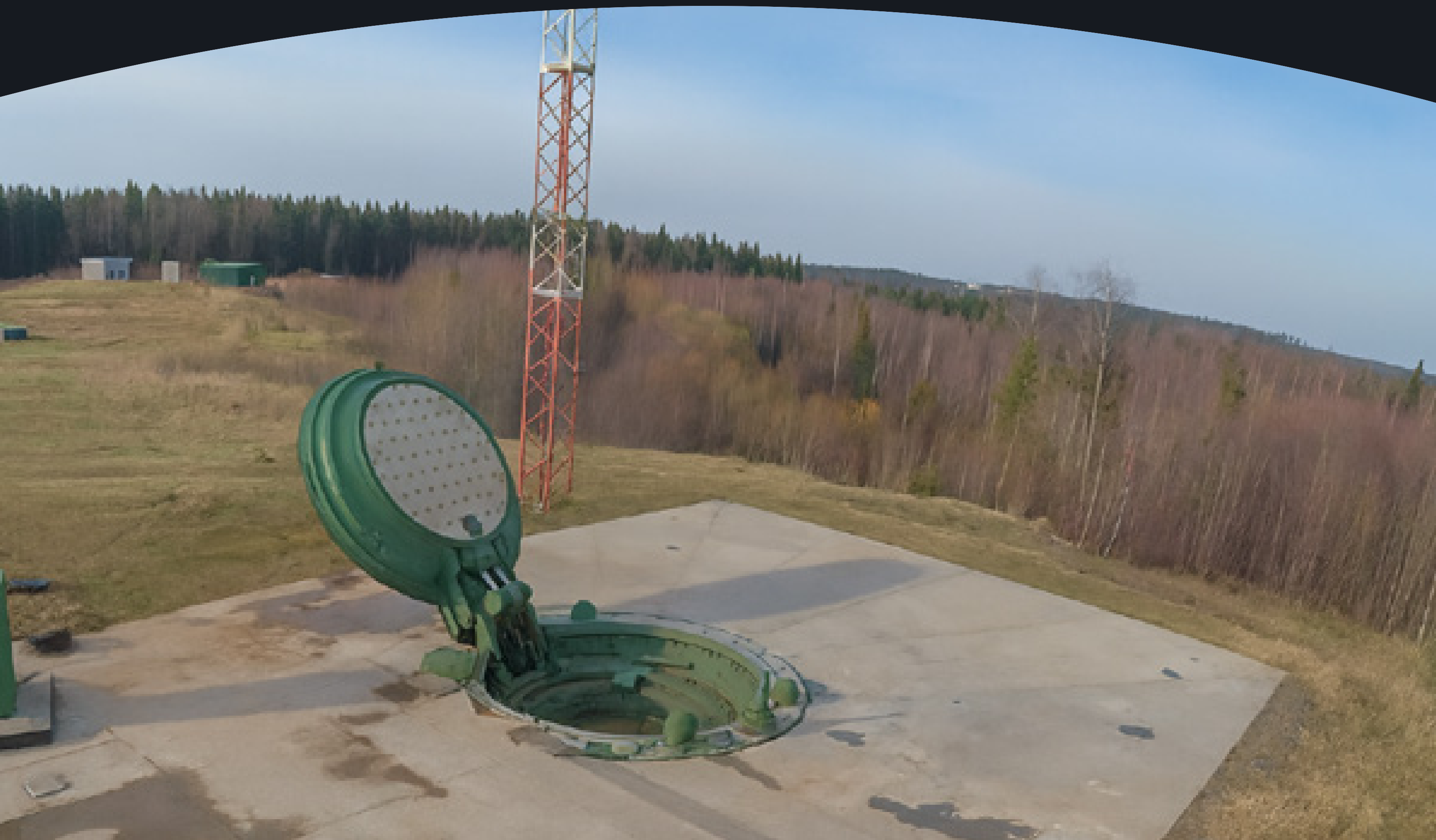
REPORT

Verification Without a Treaty

Demonstrative Verification in Arms Control, Disarmament, and Space Security

TAMARA PATTON AND PAVEL PODVIG



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About UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR) is a voluntarily funded, autonomous institute within the United Nations. One of the few policy institutes worldwide focusing on disarmament, UNIDIR generates knowledge and promotes dialogue and action on disarmament and security. Based in Geneva, UNIDIR assists the international community to develop the practical, innovative ideas needed to find solutions to critical security problems.

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Abbreviations

TPNW	Treaty for the Prohibition of Nuclear Weapons
SAR	synthetic aperture radar
ICBM	intercontinental ballistic missile
IAEA	International Atomic Energy Agency
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
HEU	high enriched uranium
TCBM	transparency and confidence-building measure
SLBM	submarine-launched ballistic missile
NATO	North Atlantic Treaty Organization

Summary

The evolving landscapes of arms control, disarmament, and space security are increasingly marked by the decline or absence of legally binding agreements and verification mechanisms, creating space for mistrust and undermining efforts to reduce risks and strengthen security. In response, this report introduces the concept of demonstrative verification—a unilateral, transparent approach by which States can actively prove compliance with disarmament or arms control commitments in the absence of formal treaties. Rather than relying on negotiated inspection regimes, demonstrative verification builds trust through proactive behaviour, open-source data, and the use of widely accessible monitoring tools. These measures can enhance stability and predictability and help to pave the way towards the renewal of bilateral and multilateral agreements.

This report begins by outlining the traditional elements of verification—national technical means, cooperative procedures, and political judgment—underscoring the limitations of formal verification frameworks in today's geopolitical environment. It then examines several historical precedents where States have voluntarily implemented commitments outside of binding treaties.

Demonstrative verification provides a structured alternative by centring on unilateral commitments, public protocols, and the use of commercially or publicly available monitoring methods, such as Earth observation satellites. The report presents three case studies that illustrate its potential applications:

A limit on deployment of silo-based missiles
A State could commit to a limit on the number of deployed intercontinental ballistic missiles (ICBMs) and periodically demonstrate empty silos using a cryptographically protected declaration system and satellite monitoring. In the absence of a treaty counterpart, open-source cryptographic tools and publicly available random number generators can support a credible, reproducible mechanism of silo selection, while optical or synthetic aperture radar satellite imagery can provide independent evidence of non-deployment.

Non-deployment of stored nuclear weapons
States can place physical barriers outside storage facilities, using satellite imagery and persistent scatterers (e.g., corner reflectors or metallic containers) to verify that weapons have not been removed. This approach offers a scalable and low-intrusion way to signal restraint both in peacetime and during crises.

Stabilizing activities in outer space

To reduce tensions over ambiguous satellite missions, States could declare their intent and share tracking data. This could include pre- or post-launch satellite descriptions, public orbital data, and practices consistent with long-term sustainability guidelines. Even without full disclosure, such transparency builds confidence in the non-threatening nature of space activities.

Overall, demonstrative verification offers an accessible pathway for States to build trust and support arms control and disarmament in an era of strategic competition, technological diffusion, and stalled progress towards formal agreements. It offers a toolset that States can use independently, alongside formal treaties, or as a precursor to future collaborative measures.

Elements of the verification process

Verification is an essential element of arms control and disarmament. In most cases, it is understood as a set of procedures included in a negotiated agreement that provides States Parties with a mechanism to assess compliance and deter violations of its terms. The procedural aspect of verification often receives the most attention, especially since all arms control and disarmament treaties the United States and the Soviet Union and then the Russian Federation have concluded since the late 1980s include thorough verification procedures, such as declarations, extensive data exchanges, and on-site inspections. The key multilateral treaties negotiated in the 1990s, namely the Treaty on Conventional Armed Forces in Europe, the Chemical Weapons Convention, and the Comprehensive Nuclear-Test-Ban Treaty, also include detailed verification provisions. The safeguards administered by the International Atomic Energy Agency (IAEA) for the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) have long been considered the gold standard for verification.

Although this approach to verification has proven its utility over time, it may overestimate the importance of technical means for supporting compliance with agreements. While technical tools and procedures, such as on-site inspections, can play an important role, they are only part of a more complex process that constitutes verification. According to one definition, which succinctly describes this process, "verification is a set of national and cooperative activities, tools, procedures, analytical processes, and fundamentally, judgments about what is happening with regard to specific activities defined in an agreement".[1] This understanding of verification includes several elements, each playing its own distinct role. Moreover, the practice of implementing arms control and disarmament agreements suggests that some elements may take precedence, and it is possible to have an effective verification mechanism that does not include all of them.

National activities carried out by States provide them with the capability to monitor activities in other States. These include, but are certainly not limited to, various national technical means, such as satellite observations and signals intelligence. It is important to note that monitoring by various means is an activity not normally linked to any particular agreement or an obligation. States constantly monitor each other's activities, depending, of course, on the capabilities available to them.[2]

Monitoring is also not an exclusive prerogative of States. International organizations that are tasked with supporting verification of specific agreements, such as the IAEA in the case of NPT safeguards,

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1 *Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks*. *Overview, Cultivating Confidence Verification Series* (Nuclear Threat Initiative, 2014), 5, http://www.nti.org/media/pdfs/VPP_Overview_FINAL.pdf; the Group of Governmental Experts on disarmament verification agreed on a similar working definition: "verification is a process driven by state parties to a specific treaty, agreement or arrangement, of gathering and analysing information, based on agreed technologies, methodologies and procedures, to enable assessment of compliance with relevant nuclear disarmament commitments and obligations, or an assessment of adherence to unilateral undertakings as set out in a verification arrangement"; "Final Report of the Group of Governmental Experts to Further Consider Nuclear Disarmament Verification Issues", 23 June 2023, para. 17, https://undocs.org/en/A/78/120

2 Amy F. Woolf, *Monitoring and Verification in Arms Control* (Congressional Research Service, 2011), https://www.fas.org/sgp/crs/nuke/R41201.pdf

also monitor various activities. In doing so, they can rely on capabilities provided by States or those that are available commercially. The availability of commercial technical means of monitoring provides a kind of open-source intelligence, which is usually understood as the collection of information by private citizens or non-governmental organizations using publicly or commercially available sources (States use these sources as well).[3]

An agreement can include provisions that require States to engage in cooperative activities that provide additional information about the object of verification. These can include declarations, notifications, exhibits of equipment, and on-site inspections. The procedures that States must follow in providing information and access to their facilities are defined in the verified agreement, normally in considerable detail. The role of these cooperative activities is broader than the collection of information. Compliance with the cooperative verification procedures specified in the agreement usually serves as a good indicator of overall compliance with the agreement. The specificity of these procedures also provides parties with the means to positively prove their compliance by adhering to all required procedures.

Analytical assessment of the information collected through national and cooperative processes, and judgment formed based on that assessment, are arguably the most important elements of the verification process. These can involve all kinds of information available to a State, some of which may not be directly related to the activity being verified. This includes the general transparency of the State and its decision-making structures, the record of compliance with other agreements, and its readiness to cooperate with the dispute resolution process. It should also be understood that verification is a deeply political process, and a conclusion about compliance can be part of a broader policy of a State towards a counterpart. The same set of facts could lead to allegations of non-compliance or be resolved through consultations, depending on the politics of the moment.[4]

The political nature of verification underscores the importance of ensuring that the compliance assessment process is transparent and well-defined. This is normally the case in multinational agreements, most of which have a procedure for raising and resolving compliance concerns. For example, the IAEA has a procedure for resolving questions about States' compliance with their safeguards obligations that has been used in a number of cases.[5] The situation may be different when allegations of non-compliance are made by a State that is unwilling to disclose the basis for its conclusion or to use available dispute resolution mechanisms.[6] Resolving compliance disputes becomes extremely difficult if a treaty lacks a formal verification mechanism or if the existing verification arrangements cannot adequately address the problem. In most cases like these, resolving the dispute or returning to compliance requires substantial political effort.

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3 Pavel Podvig and Decker Eveleth, "The Role of Open-Source Data in Verification", in *Exploring Options for Missile Verification*, ed. Pavel Podvig (UNIDIR, 2022), https://doi.org/10.37559/WMD/22/Misver/01

4 Pavel Podvig and Amy Woolf, *Monitoring, Verification, & Compliance Resolution in US-Russian Arms Control* (UNIDIR, 2019), 26, https://doi.org/10.37559/WMD/19/WMDCE5

5 Olli Heinonen, *IAEA Mechanisms to Ensure Compliance with NPT Safeguards*, UNIDIR WMD Compliance and Enforcement Series (UNIDIR, 2020), https://doi.org/10.37559/WMD/19/WMDCE2

6 Pavel Podvig, "Who Lost the INF Treaty?", *Bulletin of the Atomic Scientists*, 26 October 2018, https://thebulletin.org/2018/10/who-lost-the-inf-treaty; Pavel Podvig and Amy Woolf, *Monitoring, Verification, & Compliance Resolution in US-Russian Arms Control*.

Demonstrative verification

The definition of verification quoted above assumes that the activity being verified is specified in a certain agreement. However, this is not always the case, and very often the verification process can apply to obligations that States assume unilaterally, in the form of political commitments. In the absence of an agreement and a specific verification procedure, the verification process relies almost exclusively on monitoring, analysing available information, and making judgments about the nature of activities that the State can carry out.

One example of this kind is the commitment to remove nuclear weapons from surface ships that the United States and the Russian Federation made as part of the parallel unilateral pledges, known as Presidential Nuclear Initiatives, in 1991 and 1992.[7] While the initiatives did not include any transparency or accountability provisions, it can be said with certainty that the United States has indeed de-nuclearized its surface fleet. The transparency of the US military planning and acquisition process allows any independent observer to determine that no nuclear weapons are deployed on US surface ships. There are reasons to believe that the Russian Federation has removed nuclear weapons from its surface fleet as well, but the confidence in such a conclusion is significantly lower due to the lack of transparency of its processes.

A somewhat different example is the moratorium on the production of fissile materials for weapons declared by France, the Russian Federation, the United States, and the United Kingdom. In the Russian Federation and the United States, the moratorium on the production of plutonium for weapons is partially verified under the terms of a bilateral agreement that shut down dedicated plutonium production reactors. France has dismantled its fissile material production facilities and invited observers to witness the process [8] These visits provided sufficient assurances of the dismantlement in this particular case. In other situations, the assessment of compliance with the moratorium would be made differently. For example, while the Russian Federation continues to operate the uranium enrichment plants that were used to produce high enriched uranium (HEU) for weapons, the large stock of military HEU that the Russian Federation retains provides sufficiently high confidence in its adherence to the moratorium on the production of new material for weapons purposes.

These examples show that verification can take many different forms and that it may not require a detailed formal procedure specified in a treaty to provide confidence in a State's compliance with certain obligations. Quite often, voluntary transparency and confidence-building measures (TCBMs) can adequately address the concerns that States may have about certain activities. At the same time, there are limits to what TCBMs can achieve in practice. Their success depends on the degree

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7 Joshua Handler, "The September 1991 PNIs and the Elimination, Storing and Security Aspects of TNWs", Program on Science and Global Security, 24 September 2001; Susan J. Koch, *The Presidential Nuclear Initiatives of 1991–1992* (Toda Peace Institute, 2018), https://doi.org/10.21236/ADA577537

8 "Visite des anciennes installations de Pierrelatte et Marcoule", FranceTNP, 2009, https://web.archive.org/web/20180625151117/https://www.francetnp.gouv.fr/visite-des-anciennes-installations-de-475

of trust in the State that implements them. Also, since the implementing State controls the scope of transparency and the type of information released, these measures can be open to challenge.[9] Some measures, to be effective, require the active participation of counterparts, which cannot always be taken for granted. For example, a State may invite its counterparts to inspect a certain object, but they may decline the invitation.

A similar situation can occur when States are prepared to assume certain obligations, but no formal agreement is available to establish the necessary verification framework. This is, for example, the situation with the Comprehensive Nuclear-Test-Ban Treaty. While the treaty includes detailed verification provisions, States Parties cannot use their full power unless the treaty enters into force. The key US–Russian strategic nuclear arms limitation agreement, New START, has also fallen into this category. After the Russian Federation suspended the implementation of the treaty in 2023, both parties pledged to abide by the numerical limitations established by the treaty. At the same time, since both suspended all verification activities, this commitment is difficult to verify.

By all indications, in the current geopolitical context, concluding and bringing into force a new legally binding arms control agreement between the Russian Federation and the United States will be extremely difficult. It is also uncertain whether other nuclear-armed States, particularly China, can be persuaded to join a formal arms control process. Some experts have suggested that arms control and disarmament can be organized around a series of political commitments, whether unilateral or coordinated, that are supported by TCBMs.[10] This approach, however, has its limitations, as TCBMs may not provide the necessary level of confidence in States' compliance with their obligations and, as noted earlier, can be open to challenge.

One possible solution is to design verification arrangements that a State assuming certain obligations can implement unilaterally, without the involvement of its counterparts. These arrangements could be called 'demonstrative verification', as they would allow a State to demonstrate its compliance in a manner that can withstand a challenge by its counterparts.

To be effective, demonstrative verification should be built around several principles. First, there must be a clearly stated obligation that the State assumes. Then, verification activities must follow a formal protocol that defines specific procedures and tools used in the process. A protocol like this would normally be produced during negotiations; however, there is no reason it cannot be developed unilaterally, drawing on the positive experience of past arms control and disarmament agreements. Verification procedures, however, would have to be tailored to the demonstrative nature of the process. This means, among other things, that the implementing party can take measures designed to make the procedure work.

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9 "Press Briefing with Andrea L. Thompson and Ambassador Kay Bailey Hutchison", US Mission to the North Atlantic Treaty Organization, 17 January 2019, https://nato.usmission.gov/january-16-2019-press-briefing-with-andrea-l-thompson-and-ambassador-kay-bailey-hutchison; "Russian Defence Ministry Briefs Military Attaches with Presentation of 9M729 Missile of Iskander-M Complex", Ministry of Defence of the Russian Federation, 23 January 2019, https://web.archive.org/web/20190124101632/http://eng.mil.ru/en/news_page/country/more.htm?id=12213705@egNews

10 See, for example, Amy F. Woolf et al., *Evaluating Current Arms-Control Proposals: Perspectives from the US, Russia and China* (IISS, 2024), https://www.iiss.org/globalassets/media-library---content--migration/files/research-papers/2024/10/mdi-report/iiss_mdi_evaluating-current-arms-control-proposals_22102024.pdf

Another important element of the demonstrative verification arrangement is its reliance on publicly accessible means of monitoring. Earth observation satellites can play a particularly significant role in this regard, primarily due to their capabilities, the broad availability of commercial observation tools, and the variety of providers.[11] Moreover, the verification procedures may be designed in a way that takes advantage of satellite observation capabilities. The next section suggests some examples of these procedures.

Since demonstrative verification is likely to rely on remote monitoring tools, there are limits to what it can accomplish. At the same time, if properly designed, demonstrative verification procedures can be an important tool for supporting arms control and disarmament.

The concept of demonstrative verification also offers a particularly promising contribution to the Treaty on the Prohibition of Nuclear Weapons (TPNW) as it seeks to verify disarmament in contexts where traditional adversarial models fall short. Unlike verification systems shaped by Cold War-era assumptions of distrust and secrecy, the TPNW enables a fundamentally different paradigm—one rooted in cooperation, transparency, and the visible transformation of State identity and institutions. As Mian and Philippe argue, TPNW verification processes are not just technical exercises but forms of "active reassurance", through which a disarming State demonstrates the irreversible dismantlement of its nuclear weapon programme, including the reorientation of supporting political, scientific, and military infrastructures.[12] Demonstrative verification—through public protocols, unilateral transparency measures, and open monitoring tools—can help to operationalize this model by allowing States to visibly exhibit the internal reforms and restraint that mark genuine disarmament. In doing so, it supports the emergence of new forms of accountability and could play an active role in TPNW implementation.

Demonstrative verification could also inform future discussion of a Group of Scientific and Technical Experts on nuclear disarmament verification, a concept explored by the Group of Governmental Experts on nuclear disarmament verification and subsequently supported in a First Committee resolution that recognizes that "collaborative multilateral work on tools, technologies, methodologies and procedures that could further contribute to nuclear disarmament verification can provide benefits in support of the long-term goal of nuclear disarmament".[13]

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11 Jaewoo Shin et al., "Satellite Imagery", in *Menzingen Verification Experiment: Verifying the Absence of Nuclear Weapons in the Field*, ed. Pavel Podvig (UNIDIR, 2023), https://doi.org/10.37559/WMD/23/MVE; Rose Gottemoeller, "Rethinking Nuclear Arms Control", *The Washington Quarterly* 43, no. 3 (2020): 139–59, https://doi.org/10.1080/0163660X.2020.1813382

12 Sébastien Philippe and Zia Mian, "The TPNW and Nuclear Disarmament Verification: Shifting the Paradigm", in *Verifying Disarmament in the Treaty on the Prohibition of Nuclear Weapons*, ed. Pavel Podvig (UNIDIR, 2022), https://doi.org/10.37559/WMD/22/TPNW/01; the authors draw the term "active reassurance" from Bruce Larkin, *Designing Denuclearization: An Interpretive Encyclopedia* (Routledge, 2018), https://doi.org/10.4324/9780203793459

13 "Group of Scientific and Technical Experts on Nuclear Disarmament Verification", First Committee, UN General Assembly, 17 October 2024, 3, https://docs.un.org/A/C.1/79/L.67

Potential practical applications

This section describes several scenarios that illustrate the concept of the demonstrative verification approach and its utility for arms control. Although these scenarios vary in the degree of intrusiveness and the confidence in compliance that the demonstrative verification approach can provide, they suggest that this approach to verification can be implemented in practice.

The scenarios presented in this report were developed to support field experiments that would test the practical applications of the concept of demonstrative verification. The idea of such experiments was first developed by Igor Moric, a researcher with Princeton University's Program on Science and Global Security, who suggested a series of tests to see if satellite imagery and other similar tools could support verification of arms control agreements.[14] The scenarios described here do not assume that there is a specific arms control or a disarmament treaty that is being verified. At the same time, if the approach is shown to work, demonstrative verification could potentially be used as an element of formal treaty verification provisions.

Case study 1: A limit on deployment of silo-based missiles

Elements of demonstrative verification can be introduced as expanded transparency regarding nuclear arsenals. As noted earlier, the United States and the Russian Federation have made a commitment to adhere to the New START numerical limits. At the same time, both States suspended the data exchange required by the treaty, which included biannual reports on the aggregate number of deployed warheads as well as deployed and non-deployed launchers. Resuming the publication of these data, whether unilaterally or in a coordinated manner, would be fairly strong evidence of the commitment to stay withing the treaty limits.

Moreover, the New START reporting requirements provide a ready and tested template that other nuclear-armed States could use to disclose certain information about their nuclear forces. For France and the United Kingdom, these reports would augment the information about the ceiling on the total number of nuclear warheads that these States have already published. A key feature of New START reporting is its use of definitions developed for the treaty, which adds an additional level of accountability. If this practice were extended to other nuclear-armed States, it could become an important arms control tool.[15]

14 Igor Moric, "A Few Ideas for Satellite Observations. Working Paper", Program on Science and Global Security, Internal memo, July 2021.

15 Tamara Patton et al., *A New START Model for Transparency in Nuclear Disarmament* (UNIDIR, 2013), https://unidir.org/files/publication/pdfs/a-new-start-model-for-transparency-in-nuclear-disarmament-en-409.pdf

One area where a demonstrative verification arrangement could support a move towards greater transparency is the verification of the non-deployed status of certain strategic delivery systems. New START defines a non-deployed launcher as an ICBM or submarine-launched ballistic missile (SLBM) launcher that does not contain a missile.[16] In a scenario considered here, a State decides to remove missiles from some of its launchers but does not dismantle the launchers until a later date.

ICBM silos are the best case to illustrate the demonstrative verification concept. In principle, it should be possible to apply this approach to SLBM launchers or mobile ICBM launchers. However, the arrangements in those cases would have to be different and probably somewhat more complicated.

Silo basing structures on land present openings for using the demonstrative verification concept. For example, in 2025 the United States was believed to have 450 ICBM silos, only 400 of which contained an ICBM.[17] Arguments have been made by US arms control experts to reduce or even eliminate the silo-based ICBM force, maintaining that it is no longer useful in today's security environment.[18] One could imagine a scenario where, as a unilateral arms control measure and an interim step towards reducing the role of the silo-based ICBM force, a State leaves silos intact but significantly reduces the number of deployed ICBMs. Temporarily retaining intact silos and upload potential might make such actions more politically feasible in a domestic context.

Another scenario might involve China, which is believed to have built recently 350 missile silos. Independent experts estimate that only around 30 silos have been loaded so far.[19] China could conceivably use demonstrative verification, as part of a process towards reducing threat perceptions and avoiding renewed arms racing, to show that most of its silos are unarmed in peace time.

Practical considerations

This report considers a baseline scenario that assumes that a State unilaterally accepts an obligation to deploy no more than 100 ICBMs within 300 silos.[20] Note that this commitment does not require the State to reveal how many (or, rather, how few) missiles are actually deployed. It would only establish the ceiling for deployment, which can be higher than the number of deployed missiles, allowing for adjustments within the declared ceiling.

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16 Some other launchers, such as training launchers or launchers located at test sites, are also considered non-deployed. "Protocol to the Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms", 8 April 2010, paras. 49–51.

17 Hans M. Kristensen et al., "United States Nuclear Weapons, 2025", *Bulletin of the Atomic Scientists* 81, no. 1 (2025): 53–79, https://doi.org/10.1080/00963402.2024.2441624

18 David Wright et al., *Rethinking Land-Based Nuclear Missiles* (Union of Concerned Scientists, 2020), https://www.ucs.org/sites/default/files/2020-06/rethinking-land-based-nuclear-missiles.pdf

19 Hans M. Kristensen et al., "Chinese Nuclear Weapons, 2025", *Bulletin of the Atomic Scientists* 81, no. 2 (2025): 135–60, https://doi.org/10.1080/00963402.2025.2467011

20 This arrangement can include an option of moving missiles among the silos. An extreme version of this scheme, Multiple Protective Shelters, was considered by the United States in the late 1970s and early 1980s as a basing mode for the MX missile. One of the scenarios considered the construction of 5,800 shelters for the deployment of 310 ICBMs. *The MX Missile and Multiple Protective Structure Basing: Long-Term Budgetary Implications* (Congressional Budget Office, 1979), 13, https://minutemanmissile.com/documents/TheMXMissileAndMultipleProtectiveStructureBasing.pdf

The proposed concept regarding demonstrative verification involves a State making an official public commitment to limit the number of deployed missiles. This commitment would be followed by a release of a demonstrative verification protocol that describes the steps the State would undertake to prove its compliance with this commitment.

At the core of the procedure is an obligation to periodically subject a randomly selected silo to a public demonstration that could prove that the silo does not contain a missile. If the procedure is properly designed and implemented, it should demonstrate with considerable confidence that the State is in compliance with its obligation to keep a certain number of silos empty.

Strictly speaking, this procedure can only demonstrate compliance at the time of the demonstration, but from the practical point of view, it is highly implausible that a State would be able to substantially violate its commitment. For example, in the scenario considered here, a substantial violation would mean keeping, say, 150 missiles deployed as opposed to the claimed limit of 100. If the demonstration is carried out every six months, keeping 150 deployed missiles between demonstrations would require conducting 100 loading and unloading operations every six months. An operation of this scale would be quite burdensome and unlikely to remain undetected.

The choice of a six-month interval between demonstrations follows the practice of the START and New START treaties, which required parties to submit detailed data on their strategic forces twice a year. This interval is also sufficiently large to not disclose too much information about non-deployed silo launchers—even if the State does not move missiles between silos, after a decade of implementation only 20 empty silo locations would be disclosed.

The demonstration protocol would include two key elements: a procedure for random selection of a silo and a procedure that would demonstrate that the selected silo does not contain a missile. These elements are discussed in the following sections.

Selecting a silo

The first challenge in designing a demonstrative verification protocol to show that a subset of missile silos is unarmed lies in how to credibly select and reveal an empty silo for demonstration—without disclosing any information about other silos. One method to address this challenge uses a common, secure encoding technique known as a hashed-declaration scheme. Drawing on arms control applications of the scheme developed by Philippe, Glaser, and Felten, the method proposed here commits a State to a list of empty silos in a way that is cryptographically binding but operationally opaque.[21]

The process begins by preparing a list of all silos that participate in this arrangement. The list should include silo identifiers (a unique alphanumeric designation assigned to a silo) and their coordinates. This list, which in this scenario would consist of 300 entries, is released publicly.

21 Sébastien Philippe et al., “A Cryptographic Escrow for Treaty Declarations and Step-by-Step Verification”, *Science & Global Security* 27, no. 1 (2019): 3–14, https://doi.org/10.1080/08929882.2019.1573483

Separately, the State would compile a numbered list of empty silos (200 entries in this scenario), which it will keep confidential. Along with a sequence number, each entry will contain the identifier of an empty silo. The State would then use this to generate a cryptographic commitment by compiling a hash for each entry (see Appendix for details). By releasing the resulting list of hashed messages publicly, the State commits to a list of empty silos without disclosing which silos are empty. The list can be generated anew whenever the State deems necessary, allowing transfers of missiles among silos.

The next step includes the selection of a silo for a demonstration. The scenario assumes that the demonstration is carried out at a pre-determined interval, such as every six months, so that the date of a demonstration is set well in advance. Shortly before this date, the State runs the selection process that identifies the silo that will be checked during the demonstration. The selection should be made close enough to the demonstration to rule out the possibility that the State removes the missile from the selected silo. Handling procedures for silo-based ICBMs suggest that it would take at least several hours to remove the front section of a missile containing nuclear warheads. More time, also on the order of several hours, would be required to remove the missile itself.[22] This suggests that selecting a silo for a demonstration one day in advance of the demonstration date guarantees that a missile cannot be removed after the selection.

The selection process should rely on a random number generator that meets several criteria. First, it must be a true random number generator—the results must be evenly distributed and cannot be known in advance. Then, the results of the draw should be publicly retained and made accessible in a manner that rules out manipulation.

There are several possibilities for this task. For example, a number of institutions maintain randomness beacons, which produce a pulse every 30 or 60 seconds containing a 512-bit number derived from physical processes so as to be truly random. Such beacons are maintained by US National Institute of Standards and Technology, Universidad de Chile, and Inmetro Technology Lab in Brazil.[23] These services are compatible but operate independently. Since one important consideration in choosing the source of random numbers is its neutral nature, the Random UChile beacon, maintained by the Universidad de Chile, appears to meet this requirement in most circumstances. That beacon produces a true random number based on several sources that include signals registered by the Seismological Center of Chile or data from Santiago's public transportation system.[24]

Another possible source of random numbers that meets the requirements is the 'drand' distributed randomness beacon.[25] This service is maintained by a community of developers and relies on a distributed key generation protocol. The decentralized nature of the service makes it especially suitable in those applications where a single entity that controls the process is undesirable.

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22 See, for example, *START Verification Demonstration Production #610227*, directed by Association of Air Force Missileers, 2023, 10:18, https://www.youtube.com/watch?v=s0H_5p4483c

23 Information Technology Laboratory Computer Security Division, "NIST Randomness Beacon", NIST, 3 June 2019, https://csrc.nist.gov/Projects/interoperable-randomness-beacons/beacon-20; Random UChile, https://random.uchile.cl; "Inmetro's Randomness Beacon", https://beacon.inmetro.gov.br

24 "How It Works?", https://random.uchile.cl/randomness-beacon

25 "Drand Distributed Randomness Beacon", https://docs.drand.love

Finally, public lotteries provide a source of random numbers that meets all criteria. A lottery run by a multinational consortium, like EuroMillions, is public, highly regulated, and subject to constant scrutiny. EuroMillions broadcasts its draws which produce a set of seven true random numbers twice a week. The results of the draw are independently published and retained by all members of the consortium.

Using the random number generator, a State then selects entries from the list of hashed messages. To help ward against the possibility that a State entered duplicate silo entries in the list, the method proposed here uses the random number generator to select two entries from the list of hashed messages.[26] Information for those two entries is then revealed, showing two silo identifiers. One of these silos is then randomly selected for a demonstration.

Conducting the demonstration of an empty silo

Once the silo is selected, the task is then oriented towards displaying that the silo is empty through a verifiable and transparent process.

Confirmation of the non-deployed status of a silo launcher is a fairly straightforward procedure if it is done as part of an on-site inspection. In New START, the inspectors first check the geographic coordinates of the silo selected for an inspection using satellite navigation tools. After this, the inspected party opens the silo door and allows the inspectors to confirm that it does not contain an ICBM from a distance.[27] In the case of US Minuteman III ICBMs, the cover slides sideways. By contrast, ICBM silos in the Russian Federation have upward-opening hatches.

This procedure, however, cannot be implemented in the demonstrative verification arrangement, which is a unilateral set of actions and does not include the participation of inspectors. The State should instead design a procedure that would, in effect, substitute the confirmation provided by inspectors with a process that would allow outside observers to confirm that the silo is empty in a way that would withstand a challenge to this conclusion.

One way to design this procedure is to rely on remote observations by commercial satellites. The key advantage of commercial satellite imagery is that it provides the capability to monitor activity at a site remotely and independently from the inspected party.

Two commercial satellite imaging technologies stand out as most promising for the task of verifying the absence of a missile: optical satellites and synthetic aperture radar (SAR) satellites. Commercial optical satellites can provide high-resolution imagery (down to 30 cm per pixel or better in some systems). These images can be used to identify the presence or absence of missiles, including by allowing viewers to assess colours, textures, shadows, and physical dimensions.

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26 While the probability of finding duplicates is rather small, it is not zero, whereas it would be exactly zero if the list contained no duplicates.

27 "Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms", 8 April 2010, Annex on Inspection Activities, Part Six, § III.1, https://2009-2017.State.gov/documents/organization/141293.pdf

There are several challenges with an approach using optical satellites. One challenge includes dependence on weather and daylight conditions, which might require careful selection by a State of the timing of a demonstration period or a longer demonstration periods to allow time for suitable imagery to be captured. Another challenge involves whether the presence or absence of a missile would be detectable by observers, even under optimal lighting and weather conditions, due to the placement and depth of the missile within the silo. Optical satellite images of silos with open hatches have periodically been captured, and from these images, it is difficult to discern whether the silo contains a missile. This challenge might be addressed by proactive measures by the State conducting the demonstration, such as lighting the interior of the silo during the demonstration period.

Another approach would rely on SAR satellites for this task. SAR satellites can collect imagery independent of weather and lighting conditions, and the sensitivity of SAR to structural differences and material properties might address some of the challenges present in the use of optical imagery. Challenges with SAR, however, include the requirement of greater expertise for interpretation compared to optical images, lower commercial resolution compared to optical, and the issue that clutter and speckle can reduce interpretability.

While both optical and SAR imagery present distinct advantages and limitations, their combined use could possibly provide robust, multi-modal evidence for verifying that an ICBM silo is empty. Satellite imaging methods could be tested for this application as part of an experiment, which would include obtaining satellite imagery of an empty silo.

Confirming that a silo is empty may not have to rely on the ability of observers to see the empty interior of a silo. The very fact that the silo cover remains open for an extended period for satellites to obtain images might serve as a sufficient proof that the silo does not contain a missile. Normally, ICBMs and especially their warheads must be kept in a controlled environment, and it is highly unlikely that a State would keep them exposed to the elements. Detecting an open silo cover is a much simpler task than seeing inside the silo. Keeping the silo cover open should be possible for those silos that are built to withstand a 'hot launch', when a missile engine starts in the silo.[28]

It should also be possible to design a demonstration protocol that does not rely on favourable conditions for satellite observation and does not require keeping a silo open for an extended period of time. In this protocol, the State would livestream the opening of the silo on a public video hosting platform. This process of confirming the absence of a missile would be identical to that employed in New START, the only difference being that the role of inspectors would be played by the video operator of the inspected State.

The main challenge in this protocol is the confirmation of the time of the transmission and the location of the silo that is being demonstrated. The live nature of the transmission can be confirmed in a variety of ways, for example by playing a live radio transmission on the background. As for location, the New START method of using satellite navigation is unlikely to work, since it would require an authentication

28 This would be the case with Minuteman silos in the United States and UR-100NUTTH/SS-19 silos in the Russian Federation.

of the receiver. One option of confirming the location would require the video operator to start transmission in a reliably identifiable place, such as the garrison of the military unit, and then continuing the livestream all the way to the silo. Another option would require the video crew to position a unique object or other visible signature, such as a hand-painted pattern near the silo during the livestream. This signature can be later detected on satellite imagery of the silo. This combination—continuous livestreaming together with a unique object or signature—would allow any outside party to confirm the authenticity of the livestream and the absence of a missile in the silo. It is important to note that in this case, satellite images can be taken some time after the livestream. As long as the signature remains in place, this period can be as long as a week or even longer to allow for commercial satellite tasking times and favourable weather conditions.

Outline of a field experiment

A field experiment to test a potential demonstrative verification protocol would include several elements. These are organization of the silo selection process, coordination with the operators of the silo participating in the experiment, the work of a team on the ground, and obtaining satellite images of the silo.

The experiment would set up a dedicated web site to provide all relevant information about the demonstration. This site would host the list of all silos as well as the hashed list of empty silos. It would also contain the results of the silo selection process that will be run at the pre-selected time. In this experiment, the demonstration date will be based on the availability of the silo.[29]

Ideally, the experiment would use an actual empty ICBM silo. There are several options that could be considered. The most ambitious option would use one of the 50 non-deployed ICBM silos in the United States. Should this be impossible, a training silo could be considered. In the New START data exchange, the United States declared four training silos. It appears that some of them are open to the public.[30] Another category is silos that have been used for ICBM tests or space launches that used converted ICBMs. Two silos of this kind are located at the Baykonur space launch site in Kazakhstan. If none of these options were available, the experiment could emulate a missile silo by finding a suitable shaft or similar structure.

Once a silo for the demonstration is selected and the date of the experiment is set, the participants would travel to the site and organize a livestream of the silo inspection. The process would include opening the silo cover and placing markers around the silo during the livestream, so that the location of the site can be confirmed later. The experiment could involve a range of different markings, as long as they are in line with the requirements that may be imposed by the silo operator.

29 It should be noted that this procedure can be used to confirm the elimination of a missile silo.

30 Pavel Podvig, "New START Controversies", *Russian Strategic Nuclear Forces*, 15 April 2018, http://russianforces.org/blog/2018/04/new_start_controversies.shtml

The satellite imagery component would involve tasking optical and SAR satellites to image the silo while its cover is open. These images would be used to evaluate the feasibility of confirming the absence of a missile in a silo. Satellite images would also be used to detect the markers placed at the site during the demonstration.

The data obtained during the experiment that is required to demonstrate that the silo is empty would be published on a dedicated website, where any observer could analyse it independently.

Case study 2: Non-deployment of stored nuclear weapons

Another potential application of demonstrative verification is the confirmation of the unchanged status of certain facilities. One relevant example is that of nuclear weapon storage facilities. There are a number of cases in which nuclear weapons are kept in a relatively small number of known, dedicated storage facilities. This is the practice of storing some reserve warheads and weapons awaiting dismantlement in the United States.[31] In the Russian Federation, this practice extends to all non-deployed nuclear weapons—with the exception of warheads deployed on ICBMs and SLBMs, all nuclear weapons (strategic as well as non-strategic) are stored in a relatively small number of dedicated facilities.[32]

The practice of keeping some nuclear weapons non-deployed (that is, apart from their delivery systems) presents an opportunity for using demonstrative verification as a signalling and potentially a crisis management tool. A State could choose to provide detectable proof that it has not removed nuclear weapons from storage to demonstrate that it is not contemplating their deployment or use. This can be done, for example, by placing barriers or other physical markers in front of bunkers where weapons are stored. It should be possible to do so in a manner that would allow observers to monitor that the barriers have not been disturbed.[33]

This measure may be particularly valuable in times of geopolitical tension, when satellite-based indicators of warhead mobilization—or the lack thereof—can shape strategic perceptions and influence the pace and intensity of reciprocal military posturing. The act of visibly doing nothing, when credibly verified, becomes a strategic communication tool in itself.

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31 Hans Kristensen, "Navy Builds Underground Nuclear Weapons Storage Facility; Seattle Busses Carry Warning", *Federation of American Scientists*, 27 June 2016, https://fas.org/publication/pacific-ssbn-base; "Transparency and Verification Options: An Initial Analysis of Approaches for Monitoring Warhead Dismantlement", The Department of Energy, Office of Arms Control and Nonproliferation, 19 May 1997, https://fas.org/sgp/othergov/doe/dis/transparency.pdf

32 Observing the unchanged status of long-terms storage facilities could be an element of various nuclear disarmament verification arrangements; Pavel Podvig and Javier Serrat, *Lock Them Up: Zero-Deployed Non-Strategic Nuclear Weapons in Europe* (UNIDIR, 2017), https://unidir.org/files/publication/pdfs/lock-them-up-zero-deployed-non-strategic-nuclear-weapons-in-europe-en-675.pdf; Pavel Podvig, "Non-Deployment of Nuclear Weapons", in *Menzingen Verification Experiment: Verifying the Absence of Nuclear Weapons in the Field*, ed. Pavel Podvig (UNIDIR, 2023), https://doi.org/10.37559/WMD/23/MVE

33 Tamara Patton and Alexander Glaser, "Deferred Verification: The Role of New Verification Technologies and Approaches", *The Nonproliferation Review* 26, nos. 3–4 (2019), https://doi.org/10.1080/10736700.2019.1629072; Pavel Podvig and Ryan Snyder, "Watch Them Go: Simplifying the Elimination of Fissile Materials and Nuclear Weapons", (UNIDIR, 2019), https://doi.org/10.37559/WMD/19/NuclearVer01

In line with the general demonstrative verification approach, the placement of barriers would be done in accordance with a publicly described protocol and be accompanied by a statement in which the State concerned would describe its commitment not to remove items from the declared site. However, the act of placing the barriers, especially if it is done in a manner that clearly makes them available for monitoring, would define both the commitment and the protocol.

A similar demonstrative verification approach could, in principle, be applied to US tactical nuclear weapons deployed in Europe under NATO nuclear sharing arrangements. These weapons are stored at a limited number of well-known air bases in Belgium, Germany, Italy, the Netherlands, and Türkiye.[34] While most are housed within underground vaults inside aircraft shelters, it is possible to imagine an arrangement in which the weapons would be placed in separate storage bunkers.[35] In such cases, physical barriers could be placed outside those structures to signal that no access or movement has occurred. This could offer a means to demonstrate that certain weapons remain in a non-operational state.

While the United States and NATO have traditionally maintained ambiguity regarding the precise status and locations of these weapons, demonstrative verification could be considered as part of a voluntary, collective transparency measure—particularly as a good-faith measure towards renewed arms control dialogue with the Russian Federation. For example, NATO could choose to apply this approach at select, acknowledged storage locations and make SAR-based change detection results publicly available. Such adjustments in the context of demonstrative verification may be worthwhile for offering a low-intrusion yet effective mechanism for NATO States to collectively show restraint and promote stability.

Practical considerations

For demonstrative verification in these contexts to offer confidence to international observers and be an effective way for States to demonstrate positive behaviour, one would need to be able to detect whether barriers have moved after installation. While detecting the removal and replacement of small ground objects with millimetre-level precision using satellite imagery is a challenging task, such detection may be possible with the help of SAR imagery and special arrangements on the ground.

SAR satellite systems are renowned for their ability to provide quality images despite adverse atmospheric conditions, making them valuable for various remote-sensing applications. However, while SAR has been successfully employed for detecting larger-scale ground movements, such as tectonic shifts, landslides, and infrastructure subsidence, the specific application of monitoring the removal and replacement of small objects with millimetre precision is not as well-documented. Changes in environmental conditions between image acquisitions can reduce the reliability of detecting subtle object movements.

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34 Hans M. Kristensen et al., "United States Nuclear Weapons, 2025"; Hans M. Kristensen, "Non-Strategic Nuclear Weapons", *Federation of American Scientists, Special Report*, no. 3 (2012), https://fas.org/wp-content/uploads/2023/06/Non_Strategic_Nuclear_Weapons.pdf

35 Pavel Podvig and Javier Serrat, *Lock Them Up: Zero-Deployed Non-Strategic Nuclear Weapons in Europe*.

To enhance monitoring reliability, one possible solution is to use reflectors on the barriers. Depending on the design, it is possible for reflectors to better enable millimetre-scale displacement tracking using SAR imaging.

One design possibility includes the use of artificial corner reflectors mounted to heavy objects, such as concrete blocks. Reflectors come in various designs and implementations, each with specific advantages for different SAR applications. Passive reflectors represent the traditional approach, consisting of metal plates arranged in specific geometric configurations.[36]

While corner reflectors may offer fairly high accuracy, they place a certain burden on States as they must be properly fabricated and oriented. It is possible, however, that simpler arrangements could provide sufficient accuracy. For example, a simpler solution might include placing a small metal container or an arrangement of containers in front of the storage bunker. Evidence suggests that various metallic objects can be used to detect small changes. One option for such an object would be a common shipping container. Change detection work conducted on shipyards has shown the ability to determine container movement between image captures.[37]

It is also possible that other, smaller objects could be used in this role as well, which could be tested experimentally. One category of objects to explore would be those that create relatively soft surfaces. SAR is known to have the capability to detect fairly small disturbances of soil, for example those created by a heavy truck driving on an unpaved road.[38]

Outline of a field experiment

The goal of the experiment would be to check various barrier designs and the ability of SAR satellites to detect small displacements of the barriers. This experiment does not require the presence of a realistic weapon storage facility and can be carried out at virtually any sufficiently large open space that can be observed by at least one commercial SAR satellite.

Unlike the silo demonstration, the demonstrative verification arrangement in this case may not require a specific notification protocol. The assumption is that all relevant storage facilities are constantly monitored and the very act of installing a barrier would serve as a commitment not to remove weapons from storage. At the same time, the State could choose to make its actions public in a variety of ways, such as through open media. If necessary, it could also publicly signal changes at the sites, for example, when barriers are removed for maintenance.

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36 Matthew C. Garthwaite, "On the Design of Radar Corner Reflectors for Deformation Monitoring in Multi-Frequency InSAR", Remote Sensing 9, no. 7 (2017): 7, https://doi.org/10.3390/rs9070648; Matthias Jauvin et al., "Use of Corner Reflectors with Sentinel-1 SAR Images for Glacier and Moraine Monitoring", *EUSAR 2018; 12th European Conference on Synthetic Aperture Radar*, 4–7 June 2018, 1–6, https://ieeexplore.ieee.org/abstract/document/8438144

37 Valentina Macchiarulo et al., "Multi-Temporal InSAR for Transport Infrastructure Monitoring: Recent Trends and Challenges", *Proceedings of the Institution of Civil Engineers – Bridge Engineering* 176, no. 2 (2023): 92–117, https://doi.org/10.1680/jbren.21.00039

38 See, for example, S. Kuny et al., "CNN Based Vehicle Track Detection in Coherent SAR Imagery: An Analysis of Data Augmentation", *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLIII-B1-2022 (2022): 93–98, https://doi.org/10.5194/isprs-archives-xliii-b1-2022-93-2022

From a practical point of view, the experiment would involve the fabrication of several corner reflectors of proven design. In addition, the research team should explore various makeshift designs, from an arrangement of metal containers of various sizes to a collection of everyday objects, such as metal barrels or traffic barriers. The full range of objects in the experiment would depend on their availability on site.

All these objects would be placed at an open location, and a SAR satellite would be tasked to image that location. After the first image is taken, the research team would move some of the objects and then return them to their initial positions. A subsequent image would then be acquired to evaluate whether the analysis of these images could detect the objects had been moved. The experiment should help to identify promising reflector designs, reject those that do not work, and suggest new designs to explore.

Case study 3: Stabilizing activities in outer space

As outer space becomes an increasingly contested and congested domain, the risk of misperception and inadvertent escalation between major powers has grown. Satellites today serve not only scientific and commercial functions, but also critical military roles, including command and control and surveillance. The line between defensive and offensive capabilities is often blurred, particularly in systems that can manoeuvre close to other satellites or jam communications. These developments have fuelled concerns over an arms race in outer space and a growing distrust among spacefaring States.

Despite these concerns, multilateral arms control efforts related to space have made limited progress in recent years, and space verification remains challenging. This was recognized in the consensus report of the Group of Governmental Experts on Further Practical Measures for the Prevention of an Arms Race in Outer Space.[39] In this context, demonstrative verification offers a unilateral, voluntary, and scalable approach that States can adopt to signal peaceful intent. In addition to relying on negotiated treaties, States can opt unilaterally to declare and demonstrate the non-threatening nature of their satellites through a combination of transparency, restraint, monitoring, and verification measures.

Demonstrative verification in space offers a possible approach for States to exhibit positive intentions in an increasingly strategic and mistrustful domain. Through strategic transparency measures, States can proactively seek to reduce misperceptions and pave the way for future arms control initiatives. These measures can help to reward openness and discourage behaviour such as weapons-related experiments in space and provocative manoeuvring of satellites.

39 "Report of the Group of Governmental Experts on Further Practical Measures for the Prevention of an Arms Race in Outer Space", UN General Assembly, 20 September 2024, https://docs.un.org/A/79/364

A wide range of measures have been considered to increase transparency and stability in outer space. Some have argued for adopting 'safety zones', or minimum safe distance between satellites.[40] Critics of this approach assert that it introduces the challenge that the establishment of such zones, in achieving exclusive control of an area, may be regarded as appropriation of space, which would conflict with the Outer Space Treaty's principle of non-appropriation.[41] Others have put forth that instead of a minimum distance between satellites, the focus should be on improving situational awareness, risk assessment, and communication among satellite operators.[42] One set of suggestions includes learning from the legal regimes regulating maritime behaviour.[43] These lessons include careful use of signalling and notifications, established practices for communication and manoeuvre in situations of unplanned proximity, and exchange of key information on movements or operations to deconflict situations.[44]

It is recognized that self-imposed limits could prevent misunderstandings during proximity operations, especially around sensitive national security assets. Aggressive manoeuvres—whether for intelligence, testing, or show-of-force—carry high escalatory risks. Voluntary restraint can build trust, especially when coupled with measures such as a stated commitment to openness to tracking by independent observers. This is especially important since multilateral agreements in outer space have remained elusive, hindered by fundamental disagreements over the scope of obligations and enforcement, as well as the unwillingness of certain States to constrain their operational freedom.

Demonstrative verification in space may offer an accessible pathway towards greater transparency and stability. Two broad areas stand out where States could implement demonstrative measures: (1) mission intent transparency, through public declarations affirming the satellite's non-threatening purpose; and (2) operational transparency, through the release of orbital data that enables independent verification of a satellite's activity in line with that declaration.

Mission intent transparency

Demonstrative verification would be most useful in situations where a State deploys a satellite in a manner that may raise questions about its mission but insists that the satellite is not threatening. These situations may be rather rare, and if they occur, it may be difficult to find a way to demonstrate convincingly the non-threatening nature of the satellite.

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40 See, for example, "The Artemis Accords. Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes", 2020, § 11.7, https://www.nasa.gov/wp-content/uploads/2022/11/Artemis-Accords-signed-13Oct2020.pdf

41 Lucas Mallowan et al., "Reinventing Treaty Compliant 'Safety Zones' in the Context of Space Sustainability", *Journal of Space Safety Engineering* 8, no. 2 (2021): 155–66, https://doi.org/10.1016/j.jsse.2021.05.001

42 Thomas G. Roberts and Carson Bullock, "A Sustainable Geostationary Space Environment Requires New Norms of Behavior", *MIT Science Policy Review*, 20 August 2020, https://sciencepolicyreview.org/2020/08/a-sustainable-geostationary-space-environment-requires-new-norms-of-behavior

43 Almudena Azcárate Ortega, "TOPIC 4: Applicable Elements of the Legal Regimes Governing the Sea in the Context of Threats Arising from State Behaviours with Respect to Outer Space", Open-ended working group on reducing space threats through norms, rules and principles of responsible behaviours, May 2022, https://documents.unoda.org/wp-content/uploads/2022/05/20220512+OEWG+Law+of+the+Sea+%26+Space+Law+copy.pdf

44 Some of this work is done on the industry level; see, for example, Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), https://satelliteconfers.org

One of the most foundational measures a State can take to demonstrate the non-threatening nature of a satellite is the prelaunch disclosure of mission intent. While this information ideally would be verified prior to launch also, prelaunch inspections of satellites have been considered to be both impractical and ineffective. Modern construction rates and increasingly short integration times for putting satellites on rockets make the implementation of on-site inspections challenging. It is also unclear if it would be possible to conduct inspections without revealing sensitive information about a satellite. Furthermore, inspections are not necessarily an effective verification instrument in some cases, as functionality could change after launch or the same capability can be used for different purposes.[45] There is also the challenge that inspectors would be hard pressed to pick up on deceptions: offensive space-based jammers could look like high-powered communications payloads, offensive lasers could be portrayed as experimental deep space communications terminals, and orbital kinetic kill vehicles will have features that could allow them to be described realistically as inspector satellites. Weapons designed for use in space could look very different compared to those designed for use on Earth.[46]

Under the demonstrative verification approach, a State need not disclose the full operational capabilities of its satellite, and the satellite would not be subject to prelaunch verification. The State's declaration and commitment could merely be that the satellite is not intended to threaten satellites of other States and commercial entities. This can include notifying the United Nations Office for Outer Space Affairs in accordance with the Registration Convention and General Assembly resolution 1721B (XVI). This would also mean acting in accordance with the published guidelines of the Committee on the Peaceful Uses of Outer Space for the long-term sustainability of outer space activities.[47]

A State could choose to go further by offering a more detailed description of the satellite than is required by the Registration Convention. This disclosure may include images of the satellite or a diagram of its basic layout. Strictly speaking, the correctness of this declaration is virtually impossible to verify. At the same time, the willingness of a State to provide a description of a satellite would in itself be a fairly strong indication of its non-threatening nature. In some cases, the State may also decide to disclose information post-launch, especially if the satellite mission raises concerns.

Operational transparency

Once a satellite is in orbit, the information about its mission comes primarily from its activity. Some of these activities could raise legitimate concerns about the nature of a satellite mission. This would be the case, for example, if a satellite is deployed in the same orbital plane as another satellite or if it

45 See, for example, Almudena Azcárate Ortega, "Not a Rose by Any Other Name: Dual-Use and Dual-Purpose Space Systems", *Lawfare*, 5 June 2023, https://www.lawfaremedia.org/article/not-a-rose-by-any-other-name-dual-use-and-dual-purpose-space-systems

46 "Verification of legally binding measures for the prevention of an arms race in outer space (PAROS)", Group of Governmental Experts on Further Practical Measures for the Prevention of an Arms Race in Outer Space, GE-PAROS/2023/WP.15, 6 December 2023.

47 United Nations Office for Outer Space Affairs, *Guidelines for the Long-Term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space* (United Nations, 2022), https://doi.org/10.18356/9789210021852

approaches a functioning satellite. Rendezvous and proximity operations, even those carried out by satellites owned by the same State, also may raise questions about their purpose.[48]

An argument can be made that the best way to avoid misunderstanding in most cases is to refrain completely from certain activities that can be construed as threatening. For example, it is difficult to imagine a non-threatening mission that would require deploying a satellite in a manner that allows it to trail another satellite. At the same time, there are missions that may be within the limits of what is considered acceptable military or intelligence activity. These could be approaches with the intent to collect intelligence or proximity operations that a State carries out with its own satellites. In these cases, a State may choose to provide evidence of the non-threatening nature of its satellite.

One way of providing such evidence would be to share satellite orbital data at regular intervals to enable independent tracking of the satellite. From a practical point of view, this measure may seem redundant, as the orbital characteristics of virtually all satellites and other space objects are being published by the US military.[49] While the United States withholds information about certain US military satellites, information about those satellites that the United States does not consider sensitive and about the military satellites of other States is publicly available. Nonetheless, the publication of orbital data by the owner of a satellite would be a valuable verification tool.

First, the publication itself would help to support the claim about the satellite's non-threatening nature. The State could go further and publish orbital data with higher accuracy than public data already available. While the orbital characteristics made publicly available by the US military are based on the data provided by the US Space Surveillance Network, satellite operators normally obtain their information from telemetry, which provides much higher accuracy.[50] However, the State decides the accuracy of the information it provides. Another important advantage of declared data over the Space Surveillance Network observations is that they would help to correctly identify satellites in multi-satellite launches.

The publication of orbital information would be particularly important for those satellites that conduct periodic manoeuvres and approach other satellites, especially those belonging to other States.[51] An agreement to limit these operations is unlikely, but the publication of orbital information could introduce a degree of predictability in these manoeuvres. For example, when a satellite begins a manoeuvre, most space surveillance networks would lose track of it and would need time to resume

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48 Sandra Erwin, “China’s Orbital Maneuvers Blur the Line between Peaceful and Provocative”, *SpaceNews*, 10 July 2025, http://spacenews.com/chinas-orbital-maneuvers-blur-the-line-between-peaceful-and-provocative; for a detailed analysis of current counterspace capabilities, see *Global Counterspace Capabilities. An Open Source Assessment* (Secure World Foundation, 2025), https://drive.google.com/file/d/1FxYfoY9eqUew3xL2LD__xgHVIOFVvASA/view

49 The orbital elements that describe orbits of satellites can be obtained at space-track.org which is currently operated by the 18th Space Defense Squadron of the US Space Force; “18th Space Defense Squadron”, United States Space Force, April 2024, https://www.spaceforce.mil/About-Us/Fact-Sheets/Fact-Sheet-Display/Article/3740012/18th-space-defense-squadron

50 See, for example, Cyrus Foster et al., “Orbit Determination and Differential-Drag Control of Planet Labs Cubesat Constellations”, preprint, arXiv, 10 September 2015, https://doi.org/10.48550/arXiv.1509.03270

51 For an overview of these operations by the United States, Russian Federation, and China, see *Global Counterspace Capabilities. An Open Source Assessment*, 01-10–13 (United States), 02-11–14 (Russian Federation), 03-06–10 (China).

tracking. For satellites on geosynchronous orbit this time can be hours and sometimes days. The publication of orbital information by the operating State would facilitate other States and independent observers to reacquire the manoeuvring satellite. A State may also choose to issue a public notification before the manoeuvre, informing observers about its purpose. Some States, however, may find these notifications excessively intrusive.

A State could decide to share more data about certain segments of its satellite fleet. It could choose to release data only for satellites that have a non-threatening purpose but the operations of which may raise concerns (such as satellites with refuelling missions or satellites intended for debris removal). It could choose to go further by releasing data on other segments of the fleet, possibly including both civilian and military satellites. If such a pathway is chosen, there are a number of emerging tools and approaches available to observers to manage such data and detect when a satellite operates in unusual ways.[52] A State would not necessarily have to commit to a particular set of norms, although this would certainly add value. Rather, by openly sharing orbital information, the State would contribute to international transparency, stability, and predictability in the space domain. Data-sharing enables other actors to assess independently whether a satellite's actions align with its stated purpose, reducing uncertainty, misperception, and the risk of conflict in space.

Practical considerations and outline of an experiment

The goal of the demonstrative verification experiment for space assets would be to test the entire chain of handling of orbital data and verify the information provided by a State.

In the experiment, the State would be represented by a commercial satellite company willing to participate. In consultation with the research team, the company would select a satellite for the experiment and determine which data can be publicly released and in what format.

The most straightforward way to publish orbital data for a satellite is to follow the example of the companies that do so already. Among these are the US companies Planet and Starlink which maintain dedicated online portals that provide access to orbital data in several formats, both as orbital elements that describe the parameters of satellite orbits and as state vectors that provide position and velocity of satellites.[53] These data are also used by independent services, such as CelesTrak, to generate orbital elements in the format similar to that distributed by the US military.[54]

Once the data-release mechanism is set up, the research team would validate the data. First, the operator's information would be compared to that provided publicly by the US military which, as noted previously, publishes orbital elements for virtually all satellites. Some elements, however, may not be updated regularly and the accuracy of orbital parameters varies. It should also be kept in mind that

52 Thomas G. Roberts et al., "End-to-End Behavioral Mode Clustering for Geosynchronous Satellites", *Advanced Maui Optical and Space Surveillance Technologies Conference* (AMOS), 2023, https://amostech.com/TechnicalPapers/2023/Poster/Roberts.pdf

53 "Planet Labs Public Orbital Ephemerides", https://ephemerides.planet-labs.com; "Starlink Ephemerides", https://www.starlink.com/public-files/ephemerides/README.md

54 "Supplemental GP Element Sets", Celestrak, 29 July 2025, https://celestrak.org/NORAD/elements/supplemental

this service is operated by the US Space Force. Thus it would be important to demonstrate the possibility of validating the information provided by a State using an independent monitoring service. This would be the next stage of the experiment, in which independent observers would use this information to locate the satellite.

There are several independent organizations and companies that could confirm the accuracy of the orbital data provided by the operator. One example is LeoLabs, which operates its own network of space surveillance radars that can track objects on low Earth orbit.[55] Satellites on geosynchronous orbit are usually tracked with optical sensors. There are several commercial companies, such as COMSPOC, that provide such services. There are also academic networks, such as the International Scientific Optical Network (ISON), that operate telescopes around the world.[56] Finally, the validation could be done by private individuals who have experience with such observations.[57]

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55 "LeoLabs Space Radar Coverage Map", LeoLabs, https://leolabs.space/radars

56 Igor Molotov, "International Cooperation in Field of Observations of the Near-Earth Objects within ISON Project", presentation at Fifty-seventh session of Scientific and Technical Subcommittee COPUOS, February 2020, https://www.unoosa.org/documents/pdf/copuos/stsc/2020/tech-63E.pdf

57 See, for example, the website of Dr. Marco Langbroek at https://langbrom.home.xs4all.nl

Conclusion

Demonstrative verification cannot replace traditional treaty-based verification mechanisms. However, it offers an accessible and potentially powerful complement—particularly at a time when formal agreements are increasingly difficult to negotiate and maintain. Unilateral, well-documented actions that are designed to withstand external scrutiny can serve as strategic signals, promote transparency, and reduce the risk of misunderstanding or escalation.

Taken together, the case studies presented here illustrate that demonstrative verification is not only theoretically viable but also practically implementable. By drawing on available technologies, open data, and proven transparency methods, States can actively shape a more stable and secure strategic environment—even in the absence of formal treaties. As such, demonstrative verification represents a timely and adaptable tool for advancing arms control and disarmament.

Appendix. Silo selection process

As the first step in the demonstrative verification process the State prepares a list of all silos that are covered by the arrangement. In the scenario considered here, the State would prepare and publicly release a list of 300 silos. Each entry will include a unique identifier of a silo and its geographical coordinates. The next step is the preparation of a list of empty silos. The list will include 200 entries, corresponding to the number of silos that the State committed to keep empty. Entries in the list will contain identifiers of all empty silos, as shown in table 1. To protect the list from brute force attacks, each entry also includes a long random number to strengthen the hashed values that are to be publicly released. These protected values are then used to generate the hashed public list of empty silos. Entries in this list are values produced by the SHA-256 algorithm. The algorithm returns 32-bit values, truncated here to eight characters. By a public release of the list of hashed values, the State commits to the list of empty silos.

Table 1. Structure of the list of empty silos

PUBLIC	CONFIDENTIAL		PUBLIC
No.	**List of empty silos**	**Protected list of empty silos**	**List of hashed values**
1	Silo A-1	Silo A-1*3847291650	43f445d8
2	Silo C-28	Silo C-28*9274638105	0a68a57f
	...	...	...
138	Silo D-96	Silo D-96*8096460246	9967533a
	...	...	...
142	Silo E-15	Silo E-15*5294817063	f30c7150
	...	...	...
200	Silo B-39	Silo B-39*6831947250	e456862e

The public list can be generated as often as needed. What is important is that it accurately reflects the status of empty silos on the day that was preselected for demonstration. In this example, the demonstration date is 18 June 2025.

The demonstration date also determines the timing of the silo selection procedure. For example, the silo selection procedure takes place at 19:30 UTC on the day before the demonstration. In this scenario, this will be 19:30 UTC on 17 June 2025.

The subsequent silo selection process uses the random 512-bit value contained in the pulse generated by the UChile beacon at 19:30 UTC on 17 June 2025. Once the pulse is generated, it can be obtained online using the following request:

https://random.uchile.cl/beacon/2.1-beta/pulse?timeGE=2025-06-17T19:30:00Z

The 512-bit random value contained in this pulse is then used to generate two further random numbers, n1 and n2, in the 1–200 range (for the number of empty silos) as follows:

r1 = integer of first 32 bits. n1 = (r1 mod 200) + 1

r2 = integer of next 32 bits. n2 = (r2 mod 200) + 1

This yields the numbers 142 and 138. The State then reveals lines 142 and 138 in the protected list of empty silos:

138. Silo D-96*8096460246

142. Silo E-15*5294817063

Once these entries are revealed, any observer can verify that these are the values contained in the public list. This can be done by calculating SHA-256 hashes of the revealed entries and checking these values against the values in the public list, as shown in table 2.

Table 2. Checking correctness of revealed entries

No.	CALCULATED HASH VALUE	PUBLISHED HASH VALUE
138	SHA-256(Silo D-96*8096460246) = 9967533a	9967533a
142	SHA-256(Silo E-15*5294817063) = f30c7150	f30c7150

Only one of the two silos is then selected for the actual demonstration. This selection can be based, for example, on the least significant bit of the random value contained in the UChile beacon pulse mapped to the 1–2 range. Even numbers (ending in 0, 2, 4, 6, 8, a, c, e in hexadecimal) would select the silo with the lower sequence number, 138 in this case. Odd numbers would point to the second silo, 142 in this example. In this scenario, the output value of the pulse is even, selecting Silo D-96 for the demonstration.

As a result of this selection process, the State would be committed to demonstrate that Silo D-96 is empty. In this scenario, the demonstration will take place on 18 June 2025.

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