FEDERATION OF AMERICAN SCIENTISTS

SCIENCE & GLOBAL SECURITY
PRINCETON UNIVERSITY

NOVEMBER 2025

Inspections without Inspectors

A Path Forward for Nuclear Arms Control Verification with "Cooperative Technical Means"

IGOR MORIĆ, ASSOCIATE RESEARCH SCHOLAR,
PROGRAM ON SCIENCE AND GLOBAL SECURITY,
PRINCETON UNIVERSITY

MATT KORDA, ASSOCIATE DIRECTOR,
NUCLEAR INFORMATION PROJECT,
FEDERATION OF AMERICAN SCIENTISTS

About FAS

The **Federation of American Scientists (FAS)** is an independent, nonpartisan think tank that brings together members of the science and policy communities to collaborate on mitigating global catastrophic threats. Founded in November 1945 as the Federation of Atomic Scientists by scientists who built the first atomic bombs during the Manhattan Project, FAS is devoted to the belief that scientists, engineers, and other technically trained people have the ethical obligation to ensure that the technological fruits of their intellect and labor are applied to the benefit of humankind. In 1946, FAS rebranded as the Federation of American Scientists to broaden its focus to prevent global catastrophes.

Since its founding, FAS has served as an influential source of information and rigorous, evidence-based analysis of issues related to national security. Specifically, FAS works to reduce the spread and number of nuclear weapons, prevent nuclear and radiological terrorism, promote high standards for the safety and security of nuclear energy, illuminate government secrecy practices, and prevent the use of biological and chemical weapons.

The **Nuclear Information Project** provides the public with reliable information about the status and trends of the nuclear weapons arsenals of the world's nuclear-armed countries. The project, which according to the Washington Post is "one of the most widely sourced agencies for nuclear warhead counts," uses open sources such as official documents, testimonies, previously undisclosed information obtained through the Freedom of Information Act, as well as independent analysis of commercial satellite imagery as the basis for developing the best available unclassified estimates of the status and trends of nuclear weapons worldwide. The project also conducts analysis of the role of nuclear weapons and provides recommendations for responsibly reducing the numbers and role of nuclear weapons.

The research is mainly published on the FAS Strategic Security Blog, in the Nuclear Notebook in the Bulletin of the Atomic Scientists, the World Nuclear Forces overview in the SIPRI Yearbook, as well as in magazines. As a primary source for reliable information on nuclear weapons, the project is a frequent advisor to governments, parliamentarians, the news media, institutes, and non-governmental organizations.

FAS can be reached at 1150 18th St. NW. Suite 1000, Washington, DC, 20036, **fas@fas.org**, or through **fas.org.**

About SGS

Princeton University's **Program on Science and Global Security (SGS)**, based in the School of Public and International Affairs, conducts scientific, technical and policy research, analysis and outreach to advance national and international policies for a safer and more peaceful world.

Throughout its history, SGS has worked on nuclear arms control, nonproliferation, and disarmament to reduce the dangers from nuclear weapons and nuclear power. It is one of the oldest and most highly regarded academic programs focused on technical and policy studies on nuclear issues in the world. In the past decade it also has advanced policy on biosecurity issues. SGS engages effectively and creatively with these long-standing policy issues that remain to resolved and tracks emerging challenges from disruptive technologies with the potential to transform global security. These include new biotechnologies, information and communications technologies, autonomous weapons, artificial intelligence, and space-based systems.

SGS is home to **Science & Global Security**, the leading academic peer-reviewed journal for technical arms-control analysis. The journal covers nuclear, biological, chemical, space, and cyber technologies and programs and related security issues. Its goals are to help develop the technical basis for new policy initiatives to reduce the risks from these technologies to international peace and security and to provide a resource for further scholarship and policy analysis. The journal has helped define the field of arms control, nonproliferation and disarmament science.

SGS is located at 221 Nassau St, 2nd Floor Princeton, NJ 08542. For more information on the Program, see **sgs.princeton.edu**.

Authors

Igor Morić is an Associate Research Scholar in the Program on Science and Global Security (SGS) at Princeton University. A physicist by training, his research focuses on developing technical and policy frameworks to assess and mitigate the risks that nuclear weapons and emerging technologies pose to international security. His recent work includes modeling satellite observation constellations, evaluating the impact of overhead transparency on nuclear stability, and analyzing the feasibility, cost-effectiveness, and strategic implications of deploying the Golden Dome missile defense architecture. Prior to joining Princeton, he worked as a researcher on the MIMAC and PandaX dark matter detectors at Tsinghua University in Beijing and SJTU in Shanghai. He received his PhD at CNES and Paris Sorbonne working on optimization of the space atomic clock PHARAO. He also holds an Advanced Master in space systems engineering from ISAE-SUPAERO in Toulouse.

Matt Korda is the associate director of the Nuclear Information Project at the Federation of American Scientists, and an associate senior researcher with the Nuclear Disarmament, Arms Control and Non-proliferation Programme at the Stockholm International Peace Research Institute (SIPRI). Korda's research and open-source discoveries about nuclear weapons have made headlines across the globe, and his work is regularly used by governments, policymakers, academics, journalists, and the broader public in order to challenge assumptions and improve accountability about nuclear arsenals and trends. He received his MA in International Peace and Security from the Department of War Studies at King's College London.

Acknowledgements

The authors would like to thank Carlos Villamil Lopez for his help with the acquisition and analysis of the TerraSAR-X data of the Dyagilevo air base. The TerraSAR-X images were provided under science proposal MTH4014. The authors would also like to thank Jess Rogers, David Rust, and Zia Mian for their generous time and feedback on an earlier draft of this report; Michael Wollersheim and ICEYE for sharing their SAR imagery and change detection analysis from Yelnya in Russia and Alberta in Canada; Capella Space for sharing SAR imagery of Russia's Sayda Guba Submarine Base; and Planet Labs for sharing additional imagery with us.

This publication was made possible by grants to the Princeton University Program on Science and Global Security from the Carnegie Corporation of New York and the John D. and Catherine T. MacArthur Foundation. The statements made and views expressed are solely the responsibility of the author(s).

COVER IMAGE: CHANGE DETECTION AND AI-ENABLED DETECTION AND CLASSIFICATION OF AIRPLANES AND HELICOPTERS AT DYAGILEVO AIR BASE, RYAZAN OBLAST, RUSSIA. ORIGINAL IMAGES PRODUCED BY TERRASAR-X SATELLITE IN 2020.

Contents

Executive Summary

The 2010 New START Treaty, the last bilateral agreement limiting deployments of U.S. and Russian strategic arsenals, will expire in February 2026 with no option for renewal. This will usher in an era of unconstrained nuclear competition for the first time since 1972, allowing the United States and Russia to upload hundreds of additional warheads onto their deployed arsenals if they made a political decision to do so. The removal of both the verifiable limits on nuclear weapons, as well as the agreed and proven mechanisms of information sharing about each country's nuclear arsenal, will increase mistrust, lead to nuclear military planning based on worst case scenarios, and potentially accelerate a global nuclear arms race amid a worsening geopolitical environment.

Traditional nuclear arms control, including New START, relies on the availability of on-site inspections to verify compliance. However, Russia has suspended its participation in New START and opposes intrusive inspections, while political conditions make negotiating an equally robust successor treaty improbable in the near term.

The proposal: verifiable nuclear arms control without on-site inspections

This report outlines a framework relying on "Cooperative Technical Means" (CTM) for effective arms control verification based on remote sensing, avoiding on-site inspections but maintaining a level of transparency that allows for immediate detection of changes in nuclear posture or a significant build-up above agreed limits. This approach builds on Cold War precedents—particularly SALT II, which relied largely on national technical means (NTM)—while leveraging modern Earth-observation satellites whose capabilities have significantly advanced in recent years.

The proposed interim agreement would:

- Preserve New START's central limits on launchers and warheads.
- Resume notifications and data exchanges.
- Uphold the principle of non-interference with national technical means of verification.
- Incorporate a set of cooperative measures to expose systems for satellite verification, making possible remote monitoring and counting of nuclear delivery vehicles and warheads.

Such a regime could either be a **formal, legally-binding treaty or an informal political arrangement.** A non-binding arrangement may encourage the participation of other nuclear states willing to freeze the production and deployment of new nuclear capabilties, including China, the United Kingdom, France, India, and Pakistan.

How would it work?

Significant increases in both the quality and quantity of state-owned and commercial observation satellites now allow global monitoring of missile silo fields, weapons storage sites, air bases, and ports at high resolutions, in different bands, and at actionable frequencies of observation. These developments make it possible to:

- **Count strategic launchers.** Missile silos, mobile launchers garrisoned in bases, submarines in ports, and heavy bombers at air bases are all observable by electro-optical and synthetic aperture radar (SAR) sensors. Large-scale silo construction is now nearly impossible to conceal.
- **Assess deployment status.** Cooperative measures—such as opening silo doors for satellite passes—could verify whether launchers contain missiles. AI-assisted SAR and EO imagery could detect, classify and count

nuclear bombers. Unique markings or alphanumeric codes placed on mobile launchers and bombers could facilitate counting and identification from space.

- **Estimate deployed warheads.** New START counts every nuclear bomber as carrying a single warhead. A similar counting rule could be established for other delivery vehicles. Otherwise, exposing missiles' re-entry vehicles (RV) during coordinated satellite overpasses could allow for the counting of warheads remotely. While this could not confirm if the displayed RVs are nuclear or decoys, it would set verifiable upper limits.
- **Address non-strategic and non-deployed weapons.** Novel SAR observation techniques can help detect undisclosed activity and traffic around storage facilities, ensuring weapons are not secretly moved in or out.

Why this matters

Arms control is a crucial tool for managing nuclear risks. The proposed remote-sensing verification regime could help maintain transparency, facilitate communication, and provide predictability between the United States and Russia beyond 2026, reducing the danger of nuclear arms racing without needing to tackle the politically sensitive issue of on-site inspections.

No past or present arms control regime is perfect and completely safe against cheating. An agreement fully relying on observation satellites would not fully eliminate uncertainty, but it would be relatively easier to negotiate than one with on-site inspections, and it would increasingly raise the costs of deception, providing visibility into major nuclear developments and leaving a pathway to more comprehensive arms control once it becomes politically viable in the future.

Introduction

Currently, there are over 12,000 nuclear weapons in the world, with nearly 90% of those belonging to Russia and the United States. According to the latest open-source estimates by the Federation of American Scientists, the United States and Russia deploy 1,770 and 1,718 nuclear warheads, respectively.[1] Including the arsenals of the United Kingdom, France, and China, about 4,000 total nuclear weapons are deployed with operational forces, of which more than half are on high-alert and ready to be used at short notice.[2] All nuclear-armed states are in the process of modernizing their nuclear forces, either quantitatively by increasing their stockpile sizes, or qualitatively by enhancing range, maneuverability, or upload capacities of their delivery vehicles.

The Treaty on Measures for the Further Reduction and Limitation of Strategic Offensive Arms, known as New START, is the last remaining bilateral nuclear arms control agreement limiting the size and composition of deployed U.S. and Russian nuclear arsenals. The Treaty's Protocol and Annexes include detailed verification measures to help assure each party that the other is in compliance with the agreed limits.[3] With no further legal extension possible, the Treaty will expire in February 2026.

In the current political climate, it is unlikely that an alternative agreement with the equivalent level of completeness and intrusiveness will be negotiated in time to replace New START. Until this becomes possible, an interim agreement that includes data sharing, enables structured conversations between states, and facilitates verification with a new generation of observation satellites—but excludes on-site inspections—can aid in managing the nuclear competition and mitigating nuclear risks between the United States and Russia. An agreement not focused at limiting development of capabilities, but intended for confidence-building and risk-reduction through transparency could also eventually include China, which has a much smaller nuclear arsenal.

If New START disappears without a replacement, we will collectively enter an era of unconstrained nuclear competition without any guardrails. In the absence of Treaty limitations, states could decide to upload hundreds of additional warheads onto their existing deployed arsenals, possibly doubling the number of deployed warheads in only a few years.[4] While New START is a bilateral agreement between Russia and the United States, its expiration could have far-reaching consequences on the global nuclear environment.

It is important to remember that all parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), including but not limited to the United States and Russia, are obligated to "pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament."[5]

Although arms control is not the only mechanism to regulate nuclear risk, Russia and the United States will lose even more insight into each other's nuclear force developments and activities, undermining non-proliferation efforts, and unsettling both adversaries and allies alike.[6] The Treaty's expiration will remove all constraints on U.S. and Russian nuclear force deployments, potentially reigniting a nuclear arms race in an increasingly confrontational geopolitical environment, where accelerating technological advances and lack of transparency will heighten the risk of accident, miscalculation, and runaway nuclear escalation.

1 Hans Kristensen, Matt Korda, Eliana Johns, and Mackenzie Knight-Boyle, "Status of World Nuclear Forces", Federation of American Scientists, 29 March 2024, https://fas.org/initiative/status-world-nuclear-forces/.

2 Ibid.

3 See Appendix 1 for more information about the key provisions of New START.

4 Matt Korda, "If Arms Control Collapses, US and Russian Strategic Nuclear Arsenals Could Double In Size", Federation of American Scientists, 2 July 2023, https://fas.org/publication/if-arms-control-collapses-us-and-russian-strategic-nuclear-arsenals-could-double-in-size/

5 "Treaty on the Non-Proliferation of Nuclear Weapons," United Nations, https://www.un.org/en/conf/npt/2005/npttreaty.html.

6 Center for Arms Control and Non-Proliferation, "Consequences of Failure of New START to Enter into Force", 14 December 2010, https://armscontrolcenter.org/consequences-of-failure-of-new-start-to-enter-into-force/

A nuclear war cannot be won, and security cannot be found through numbers, with bigger bombs and better missiles.[7] Given that both the United States and Russia maintain survivable nuclear retaliatory forces ensuring mutually assured destruction—and deterrence against other nuclear weapon states with inferior arsenals—there is no military necessity for a costly arms buildup that would not provide any tangible strategic advantage. While U.S. nuclear force strategy and posture does not need to remain constant, even with the recent Chinese nuclear force buildup, no analysis has shown that U.S. nuclear forces will be unable to meet required deterrence objectives by 2035 or beyond.[8] Recent statements from President Trump appeared to recognize this; during a February 2025 press conference, he stated that "There's no reason for us to be building brand new nuclear weapons, we already have so many [...] We're all spending a lot of money that we could be spending on other things that are actually, hopefully much more productive."[9] Trump also stated in July 2025 that New START is not "an agreement you want expiring."[10] While no bilateral arms control talks are currently ongoing with just over three months to go before the Treaty expires, in September 2025 President Putin offered to mutually maintain limits on the number of nuclear weapons for another year, calling abandoning the legacy of New START mistaken and short-sighted.[11]

Ultimately, arms control will need to adapt to the new geostrategic environment, acknowledging force asymmetries and non-strategic nuclear weapons, while also illuminating the rules of use of non-nuclear military capabilities, missile defense, the use of space, cyber, and artificial intelligence. However, until such agreements can be reached, an alternative to New START and formalized arms control need not be a world without transparency and dialogue.

To mitigate some of the aforementioned nuclear risks and avoid arms racing, Russia and the United States should agree to resume data exchanges[12] and commit to abide by the limits of New START on deployed delivery vehicles beyond 2026, which could be verifiable without on-site inspections. If both parties uphold the principle of non-interference with national technical means (NTM) and accommodate cooperative verification scenarios adapted to the new generation of high-resolution multispectral satellite systems, a follow-on agreement without on-site inspections could be effective enough to verify the numbers and deployment status of each country's nuclear delivery vehicles. If counting rules are used for all delivery vehicles, warhead limits could also be established.

The United States and Russia can look to the first generation of arms control as a model for such an agreement. Strategic Arms Limitation Talks (SALT) I and II introduced verification mechanisms into the U.S.-U.S.S.R nuclear weapons dialogue, establishing limits for the first time on the number of nuclear delivery vehicles that each country was allowed to possess. Even though both agreements included provisions for short-notice inspections of declared facilities, verification primarily relied on NTM mechanisms like telemetry intelligence and satellite observation.

This is especially true for SALT II, which, after being signed in 1979, was never ratified in the U.S. Senate due to the Soviet invasion of Afghanistan. Without the availability of on-site inspections, both nations observed its provisions until 1986 relying on satellite imagery, as well as on a combination of human, signals, and electronic intelligence to remotely detect new construction, monitor ICBM testing, and assess deployment of delivery vehicles. To facilitate satellite observation, both parties maintained the principle of non-interference with each other's NTM by not using concealment measures that would impede verification of the agreement.

---

7 Joe Cirincione, "The dangerous new Washington consensus for more nuclear weapons", Bulletin of the Atomic Scientists, 9 September 2025, https://thebulletin.org/2025/09/the-dangerous-new-washington-consensus-for-more-nuclear-weapons/

8 Adam Mount, Defining the Two Nuclear Peer Problem, in "Understanding the Two Nuclear Peer Debate," Federation of American Scientists, September 2025, https://fas.org/wp-content/uploads/2025/09/0916-PCRN-report.pdf.

9 Zeke Miller, and Michelle L. Price, "Trump wants denuclearization talks with Russia and China, hopes for defense spending cuts", AP News, 14 February 2025, https://apnews.com/article/trump-china-russia-nuclear-bbc1c75920297f1e5ba5556d084da4de

10 "Trump says he wants to maintain nuclear limits with Russia", Reuters, 25 July 2025, https://www.reuters.com/business/aerospace-defense/trump-says-he-wants-maintain-nuclear-limits-with-russia-2025-07-25.

11 Meeting with permanent members of the Security Council, President of the Russian Federation, 22 September 2025, http://kremlin.ru/events/president/news/78051.

12 While notifications relating to New START are no longer taking place, mutual notifications relating to ballistic missile launches are still ongoing per the 1988 Agreement Between the U.S. and USSR on Notifications of Launches of ICBMs and SLBMs.

Today, to avoid the sensitive issue of on-site inspections, the verification of a successor agreement to New START could rely on remote-sensing, thereby making it easier to negotiate. While the agreement could be a formal arms control treaty, it could also be informal and non-legally binding, thus making it more likely to be negotiated in the current political environment. Such an agreement would not need to have a fixed duration, and would allow both the United States and Russia to exit the agreement and other parties to join the agreement without the political and legal hurdles of ratification.

In addition to the obligation not to interfere with satellite observation, participating states should disclose information on their arsenals and share other forms of data to help demonstrate that their declarations are accurate. They should also establish a compliance and implementation body, similar to New START's Bilateral Consultative Commission, which would allow parties to consult on technical issues, resolve disputes, and agree on practical matters related to the execution of the agreement.

To support monitoring, states could exploit their own nationally operated imaging systems or leverage commercial systems whose capabilities are quickly approaching those previously available only to governments. As demonstrated by findings from recent years, commercial satellite imagery is able to regularly detect and monitor nuclear operations and deployments, and relying upon commercial imagery could allow the sharing of unclassified data demonstrating potential violations with both treaty partners and the public.[13] This would be an added incentive for countries to participate in the agreement, as they could publicly hold violators to account without revealing classified information about the characteristics and capabilities of their national technical means, which are closely guarded secrets.

Inspired by open-source analysis, this report aims to demonstrate how satellite imagery could allow nuclear weapon states to cooperatively monitor each other's nuclear capabilities, verify the numbers of fixed and mobile intercontinental ballistic missile (ICBM) launchers and submarine-launched ballistic missile (SLBM) launchers, as well as track the number and location of their heavy bombers. It also explores how remote sensing could be the basis for monitoring of non-deployed and non-strategic nuclear warheads.

13 Igor Moric, "Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring", Science & Global Security, May 2022, https://www.tandfonline.com/doi/full/10.1080/08929882.2022.2063334.

Arms Control Verification Without On-Site Inspections

Effective arms control solutions are essential to reduce the role and number of nuclear weapons while maintaining deterrence in a multipolar world. However, perfect verification does not exist, and all arms control agreements carry risk and allow for the possibility of cheating. This includes New START, which—like all arms control agreements—had inherent verification gaps but was nevertheless successful in reducing the deployed arsenals of both the United States and Russia.

For a New START successor treaty, the National Nuclear Security Administration (NNSA) initially planned to retain the verification technologies and approaches established under New START, while additionally developing and implementing more intrusive technologies to enhance confidence in their compliance assessments.[14] However, given the tumultuous political relationship and diverging priorities of the United States and Russia (and China), any treaty that would lead to a reduction in the nuclear arsenals and involve intrusive verification mechanisms is not probable in the short term. It is also increasingly unlikely that the United States and Russia will be able to agree on a follow-on treaty that would include verification arrangements matching the degree of intrusiveness of those already present in New START, with the key issue being Russia's unwillingness to permit regular on-site inspections.[15]

To that end, it is imperative for prospective arms control partners to consider the ways in which effective verification could be maintained with minimally intrusive measures.

The solution proposed in this report is to consider verification with a greater reliance on Earth observation satellites, implementing arms control procedures allowing for monitoring and counting of nuclear delivery vehicles, without on-site inspections. This is made possible by recent advancements of state-owned and commercial capabilities, which are increasingly making it possible to provide widespread planetary coverage at actionable resolutions and with high frequencies of observation, allowing both state- and non-state actors to remotely monitor sites and track ground changes. Information provided by electro-optical sensors is complemented with data produced by novel synthetic aperture radar (SAR) systems which transmit microwave pulses and measure the backscattered signal, enabling observation under all weather and illumination conditions at high resolution.[16]

Although Russia formally suspended its participation in New START in February 2023 and the United States subsequently imposed reciprocal countermeasures, in January 2025 the U.S. Bureau of Arms Control, Deterrence, and Stability could assess "with high confidence that Russia did not engage in any large-scale activity above the Treaty limits, and "there is not a strategic imbalance between the United States and the Russian Federation that endangers the national security interests of the United States."[17] This shows that significant violations of New START's central limits—and particularly those relating to delivery vehicles—could be detected by remote monitoring for at least two years after the last on-site inspection and without cooperation of the parties.

14 Some of these aspirational verification measures involved the use of novel passive neutron and gamma detectors, as well as tamper-indicating devices. Other more advanced technologies under consideration were "template matching" gamma and neutron detectors, high explosive detectors, and active neutron measurement and imaging techniques. Government Accountability Office, "U.S. May Face Challenges in Verifying Future Treaty Goals", September 2023, https://www.gao.gov/assets/gao-23-105698.pdf.

15 Declaring his decision to suspend Russian participation in New START in 2023, President Putin accused the United States of the following: "They want to inflict a 'strategic defeat' on us and at the same time, they keep trying to get to our nuclear facilities." See "Putin suspends Russian involvement in nuclear arms pact over Ukraine tensions", PBS News, February 2023, https://www.pbs.org/newshour/world/putin-suspends-russian-involvement-in-nuclear-arms-pact-over-ukraine-tensions

16 See more on SAR in Franz Meyer, "Spaceborne Synthetic Aperture Radar: Principles, Data Access, and Basic Processing Techniques", from The Synthetic Aperture Radar (SAR) Handbook: Comprehensive Methodologies for Forest Monitoring and Biomass Estimation, April 2019, https://gis1.servirglobal.net/TrainingMaterials/SAR/Chp2Content.pdf.

17 2024 Report to Congress on Implementation of the New START Treaty, Report by Bureau of Arms Control, Deterrence, and Stability, January 2025, https://2021-2025.state.gov/2024-report-to-congress-on-implementation-of-the-new-start-treaty.

In general, even though regular on-site inspections provide for a more comprehensive overview of the other sides' capabilities, these rarely uncover direct treaty violations. A better indicator of non-compliance is a party's refusal to cooperate or provide clarification when requested. An advantage of overhead imagery is that it allows parties to promptly demonstrate their willingness to comply with their obligations. It also facilitates communication and nuclear signaling beyond declaratory measures, reflected in changes in nuclear posture immediately observable with satellites—such as mating of nuclear weapons and delivery systems.

While information provided by observation satellites has been crucial for the verification of past nuclear arms control treaties, without co-operation of all parties it cannot provide the same level of confidence in verifying compliance as an agreement including on-site inspections. Verification measures described in this report demonstrate how satellites could take on a greater role in a new arms control agreement—and if adopted and accommodated by all parties—provide the same degree of mutual transparency as New START's verification regime, even without the availability of on-site inspections.

As a first step, for a verification regime based solely on remote-sensing to be effective at detecting non-compliance at a smaller scale, the United States and Russia should take the following initial steps:

- Reaffirm their mutual commitment to the central limits of delivery vehicles and warheads established under New START;
- Resume sharing data on the number, type, and location of deployed strategic delivery vehicles and warheads;
- Resume the mutual exchange of notifications on production and elimination of strategic weapons and delivery vehicles;
- Uphold the principle of non-interference with NTM of verification.

Preserving the principle of non-interference is especially important as it would allow parties to take full advantage of observation satellites and other NTM resources at their disposal. This would not disrupt their operational procedures or endanger national security, but build on decades of established practices, enhancing predictability through transparency and promoting nuclear stability.[18]

As a second step of the proposed agreement, state parties should take on a more active role to embrace cooperative technical means (CTM) that would enable detailed remote monitoring of nuclear weapon launchers and their deployment statuses.

In contrast to national technical means of verification—which refer to a state's intelligence gathering capabilities—we define "cooperative technical means" as a series of cooperative or mutually agreeable measures that arms control partners can take to remotely monitor compliance with a specified agreement. While NTM largely relies upon the principle of *non-interference*, **CTM instead relies upon countries** *actively facilitating* **each other's remote collection capabilities.**

While initially still providing a lower probability of detection of non-compliance compared to a regime that includes on-site inspections, the availability of prior knowledge and the ability to observe operational patterns as more information is collected may allow these measures to approach the effectiveness of more traditional methods—while being much less intrusive and politically costly.

Although no verification regime is completely effective against all forms of deception, build-ups of capabilities yielding strategic advantage or of those that could undermine the retaliatory capabilities of either side would remain detectable. Technological improvements, evolving overhead transparency, and the availability of other types of open-source data would make it increasingly difficult to conceal violations, and would require the maintenance of increasingly elaborate installations of hidden infrastructure.

18 Igor Moric, "Nuclear Stability in a World with Overhead Transparency," Comparative Strategy 42, no. 4 (2023): pp. 621-654, https://www.tandfonline.com/doi/pdf/10.1080/01495933.2023.2236489.

As trust between parties is repaired—and if the geopolitical environment allows for it—eventual re-introduction of on-site inspections in a future arms control agreement would provide baseline information to facilitate improved verification of the correctness and completeness of the declarations exchanged, as well as monitoring of novel delivery vehicles and of non-deployed and non-strategic warheads. With the availability of intelligence provided by advanced remote-sensing capabilities and automated monitoring made possible by artificial intelligence algorithms, the number of further visits necessary to maintain continuity of knowledge would be significantly reduced, compared to New START or past treaties.

The following sections provide concrete examples of how remote-sensing could take on an expanded role in a New START follow-on agreement and—in addition to verifying the elimination and dismantlement of delivery vehicles—how it could be used to assess compliance with numerical limits and to monitor the deployment statuses of strategic delivery systems and associated warheads. The examples provided also demonstrate how advancing satellite observation capabilities, in combination with other forms of remote sensing, could facilitate an expanded verification regime encompassing non-strategic and non-deployed weapons.

2.1 Verifying the Number of Land, Submarine and Mobile Strategic Launchers

New START places limits on the number of deployed and non-deployed US and Russian ICBM launchers, SLBM launchers, and heavy bombers. The Treaty considers an ICBM or SLBM launcher to be deployed if it contains a missile, and non-deployed if it does not.

Whenever a launcher or a missile changes its deployment status (or is eliminated), the parties are required to notify each other and update its status. While on-site inspections were still taking place, the inspecting party could verify the declared deployment status, type, and location for a limited number of selected launchers and missiles at the inspected site.

In the absence of on-site inspections, it is critical for countries to maintain the ability to detect whether their arms control partners are adding additional strategic launchers, which in this context can take four forms: fixed missile silos, mobile missile launchers, submarine launch tubes, and heavy bombers. While all of these are observable via imaging satellites, some are easier to detect than others.

Since the latter decades of the Cold War, analysts have been able to use satellite imagery to detect the construction of new missile silos.[19] This is typically because individual missile silos, especially when constructed in large quantities within a well-defined area, have highly distinct signatures. They are typically built away from high-density population centers, which makes them easier to spot. In addition, digging abnormally large holes in the ground requires specialized equipment and generates a large construction footprint.

For instance, the United States' Minuteman missile silos were built to a depth of approximately 80 feet (~24.4 meters) and a diameter of 25 feet (~7.6 meters).[20] Excavating a silo of that size produced approximately 40,000 cubic feet (~1100 cubic meters) of dug-up earth—creating a noticeably large spoil pile for a single construction site.

Furthermore, the design of nuclear missile silos—as a nearly 70-year old technology—are relatively standardized across countries. This has helped analysts identify missile silos, even in countries that had not previously built them at scale. During a two month period in 2021, for example, multiple teams of non-governmental imagery analysts

19 Central Intelligence Agency, "New ICBM silos under construction in China", December 1976, approved for release June 2011, https://www.cia.gov/readingroom/docs/CIA-RDP78T05698A000200030065-2.pdf; National Photographic Interpretation Center, "Antiballistic Missile Silo Under Construction in the Moscow Area, USSR", April 1981, approved for release November 2011. https://www.cia.gov/readingroom/docs/CIA-RDP81T00380R000101110001-9.pdf; National Photographic Interpretation Center, "Possible CSS-4 ICBM Silos Under Construction: Jingxian, China", December 1982, approved for release February 2011, https://www.cia.gov/readingroom/docs/CIA-RDP90T00784R000100110011-1.pdf.

20 Dave Fields, "Launch Tube," Minuteman Missile, A Tribute to the ICBM Program, https://minutemanmissile.com/launchtube.html.

disclosed the construction of hundreds of new ICBM silos in northern China.[21] These high-profile disclosures were preceded and succeeded by additional disclosures of new silos at China's Jilantai training area, displayed in **FIGURE 1** and **FIGURE 2**, as well as new DF-5 silos in the mountains of central China.[22]

Whether or not any of these new silo complexes were known to the U.S. government before they were publicly disclosed by non-governmental organizations (and many likely were), these case studies demonstrate that it is extraordinarily challenging to hide both large and small scale silo construction from imagery analysts.

The construction of the three other strategic launcher types—mobile missile launchers, submarine launch tubes, and heavy bombers—is generally concentrated in a small number of specialized assembly buildings whose locations are widely known. This makes it relatively straightforward for countries to persistently monitor those buildings using satellite imagery and other remote sensing capabilities.

For example, the images below demonstrate how mobile launchers and bombers can be detected and classified by type using commercial satellite data. **FIGURE 3** shows mobile launchers detected at a complex in Pakistan, distinguishable via satellite imagery by dimensions, number of observed axles, and their alignment. As shown in **FIGURE 4** and explained in the caption, commercial SAR imagery analyzed by an algorithm allows automated monitoring of airbases, providing information if the observed objects moved by detecting subtle changes between satellite overpasses. As shown later, an algorithm is also able to count and classify the observed helicopters and airplanes, including nuclear bombers.

Since strategic submarines are large, easily-observable metallic objects, electro-optical and SAR imagery also could be used to count them by continuously monitoring ports and submarine bases, as shown in **FIGURE 5** and **FIGURE 6**. To facilitate this type of inspection, before submarines are deployed to sea from an underground base, the inspected party would be obligated to notify other parties, and expose them to satellites.

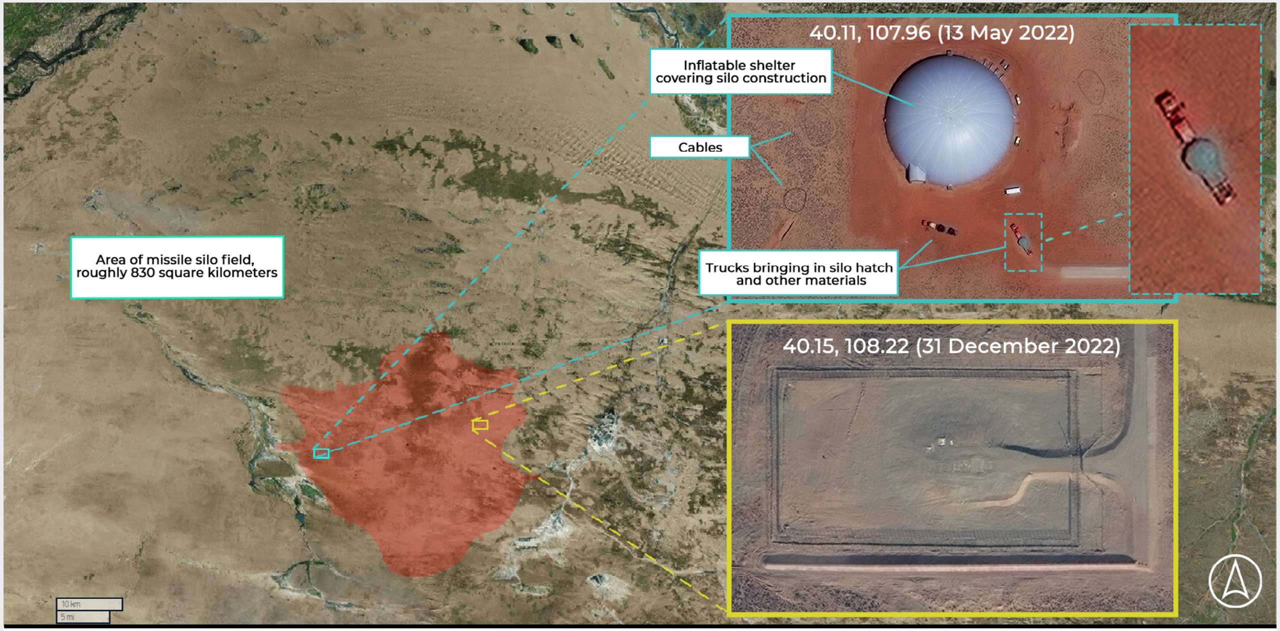
2.2 Verifying the Deployment Status of Fixed, Sea-Based, and Mobile Strategic Launchers

In addition to verifying the number of strategic launchers that each country possesses, arms control partners also could verify with satellites whether those launchers contain a missile—i.e., whether they are deployed. To facilitate this type of verification relying exclusively on remote sensors, the interiors of launchers would need to be exposed to overpassing sensors in coordination between parties. While there could be sensitivities regarding the ability to look inside launchers, these would be bounded and mitigated by the quality of sensors and the placement of coverings or shrouds over interior aspects of the launchers that are not covered by the treaty.

The inspecting party could select the launchers and provide the inspected party with a specific time window to open the silo door of a land-based ICBM launcher (the United States uses silo covers that slide open horizontally, while Russia uses upward-opening hatches), or the hatches of a surfaced submarine docked in port. Such remote inspections would be limited in number for each year and could be scheduled at regular intervals. In theory, these could be designed as surprise inspections in a similar manner to New START, although some degree of flexibility would likely need to be baked into the negotiations in order to avoid significant operational disruption.

21 Joby Warrick, "China is building more than 100 new missile silos in its western desert, analysts say", Washington Post, 30 June 2021, https://www.washingtonpost.com/national-security/china-nuclear-missile-silos/2021/06/30/0fa8debc-d9c2-11eb-bb9e-70fda8c37057_story.html; Matt Korda and Hans Kristensen, "China Is Building A Second Nuclear Missile Silo Field", Federation of American Scientists, 26 July 2021, https://fas.org/publication/china-is-building-a-second-nuclear-missile-silo-field/; Rod Lee, "PLA Likely Begins Construction of an Intercontinental Ballistic Missile Silo Site near Hanggin Banner", China Aerospace Studies Institute, 12 August 2021, https://www.airuniversity.af.edu/CASI/Display/Article/2729781/pla-likely-begins-construction-of-an-intercontinental-ballistic-missile-silo-si/.

22 Decker Eveleth, "People's Liberation Army Rocket Force Order of Battle 2023", James Martin Center for Nonproliferation Studies, July 2023, https://nonproliferation.org/wp-content/uploads/2023/07/web_peoples_liberation_army_rocket_force_order_of_battle_07102023.pdf; Ben Reuter (@benreuter_IMINT), Twitter/X, 9 January 2023, https://x.com/benreuter_IMINT/status/1612435717392838656; Hans Kristensen, "New Missile Silo And DF-41 Launchers Seen In Chinese Nuclear Missile Training Area", Federation of American Scientists, September 2019, https://fas.org/publication/china-silo-df41/; Hans M. Kristensen, Matt Korda, Eliana Johns, Mackenzie Knight, "Chinese nuclear weapons, 2025", Bulletin of the Atomic Scientists 81, No. 2 (March 2025): pp. 135-160, https://www.tandfonline.com/doi/full/10.1080/00963402.2025.2467011.



Yulin Missile Silo Field, China

40.12°, 108.13°

Satellite imagery from 2022 showing features of silo construction at the Yulin silo missile field in China. The silo field spans an area of roughly 830 square kilometers and includes 90 silos, in addition to support facilities. The right-side inserts show two different silos at different stages of construction: one while the silo was covered by an inflatable shelter, and the other after the shelter was removed and a new perimeter erected.

Satellite imagery © 2025 Vantor (Base Image via Google Earth)

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 1

Yulin Missile Silo Field: Stages of Construction

Missile silos in 2021 near Ordos in north-central China, at different stages of construction. Inflatable air dome complexes offer environmental protection and hide technical details from satellite observation.

planet. FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 2

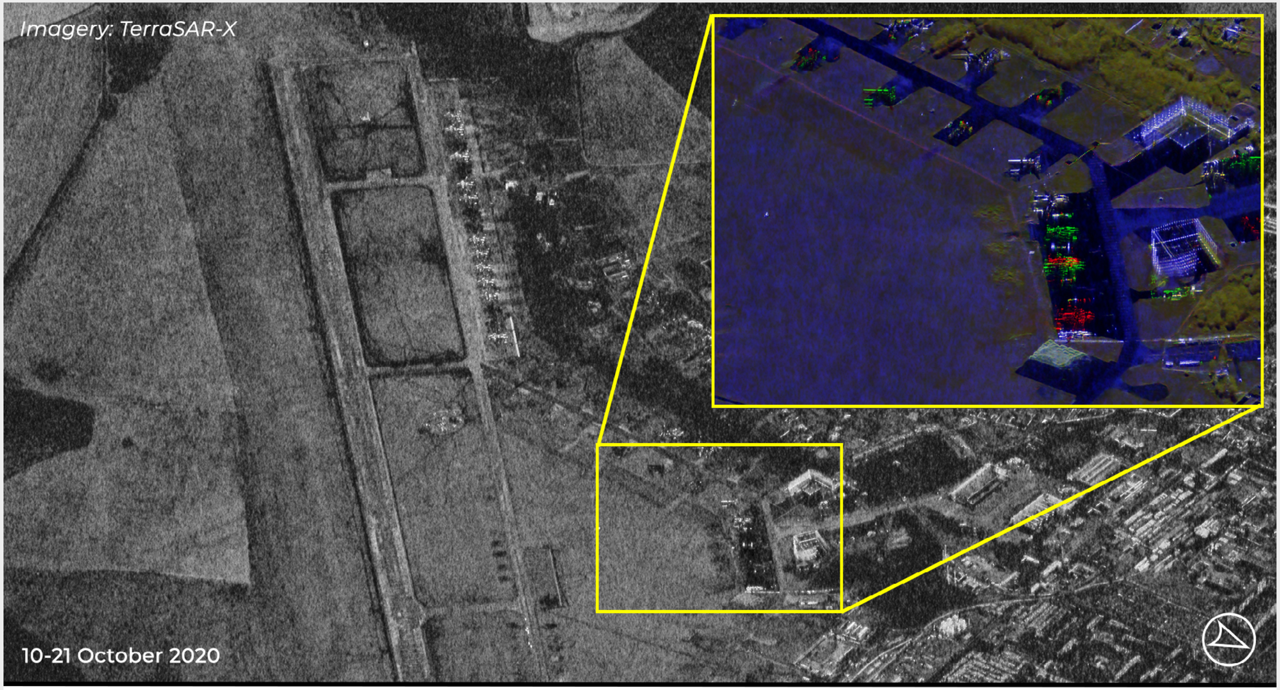
Dual-Capable Mobile Missile Launchers, Pakistan

33.63°, 72.69°

Pakistan produces its mobile missile launchers at its National Development Complex in Fateh Jang, Rawalpindi. The different launchers are easily distinguishable via satellite imagery by their dimensions, as well as the number and alignment of the axles. Through persistent monitoring, it may be possible to make an accurate estimate of the number of launchers of each type that Pakistan possesses, and monitor whether it is producing new launchers of specific types.

FEDERATION OF AMERICAN SCIENTISTS

FIGURE 3



SAR Change Detection at Dyagilevo Air Base, Ryazan Oblast 54.64°, 39.57°

Change detection analysis produced from two TerraSAR-X images of Dyagilevo air base, Ryazan Oblast, Russia. The images were collected 11 days apart on October 10, 2020 and October 21, 2020. Objects in white indicate high coherence between two acquisitions, and thus no change observed. Bright green objects were present in the first overpass, but not on the second. Bright red objects were present on the second satellite overpass, but not on the first. Blue objects were present in both overpasses and have not moved. Brown and yellow areas show objects present in both images, but that experienced subtle changes (e.g., airplanes that are parked on the same spot but have moved slightly in the meantime, or vegetation that moved or grew during this time).

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 4

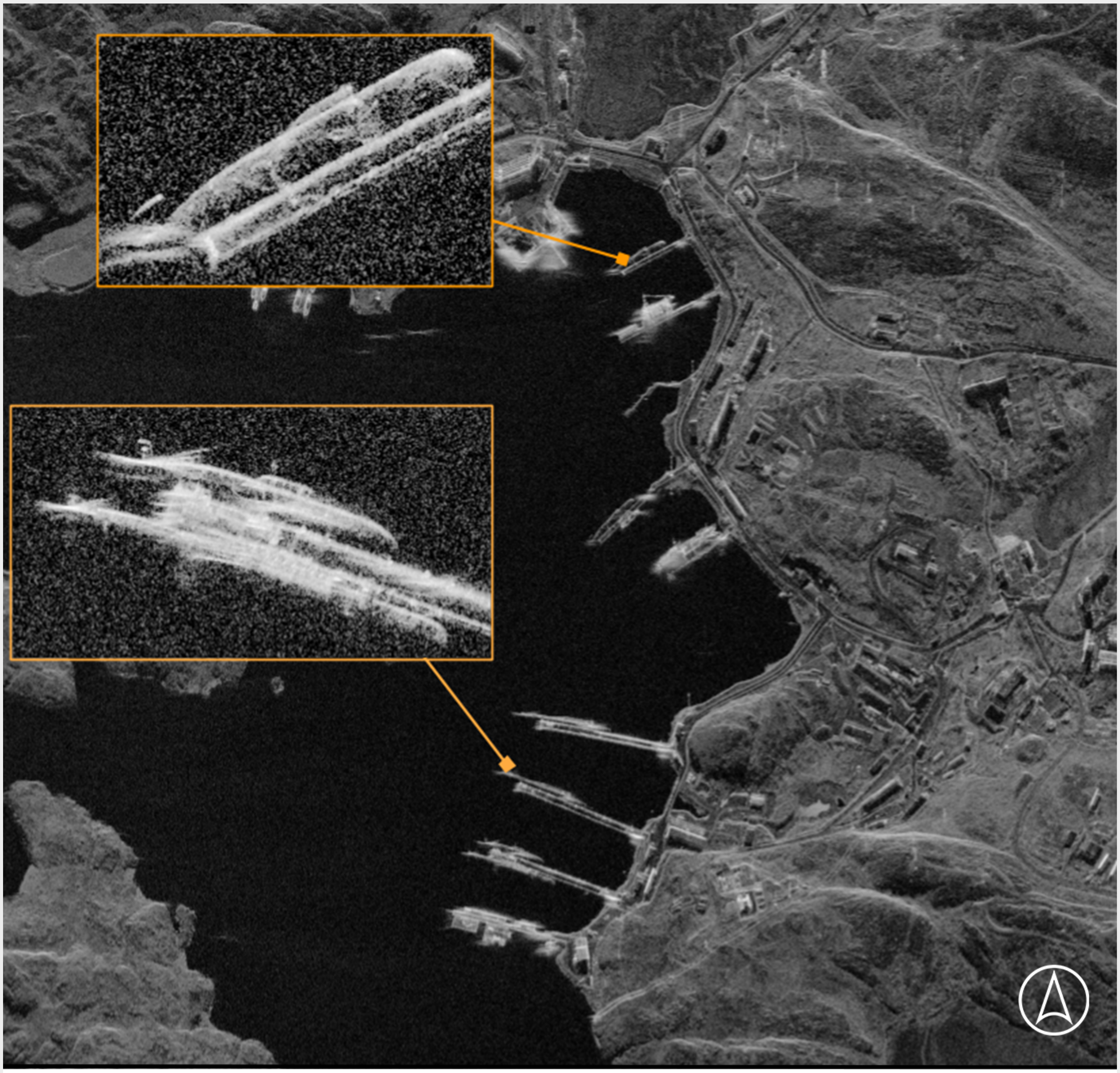
Chinese Submarine Base, Hainan Island

18.20°, 109.69°

Electro-optical imagery from August 2020 showing a Chinese submarine entering or leaving its base on Hainan Island on the South China Sea.

Satellite imagery: Planet Labs PBC

FIGURE 5



SAYDA-GUBA SSBN BASE, RUSSIA

December 2024
69.26°, 33.33°

SAR imagery of Russian ballistic missile and tactical nuclear-powered attack submarines at Russia's Sayda Guba Submarine Base, from 5 December 2024. This location is often obscured by clouds, which does not impact SAR.

Satellite imagery: Capella Space 2025

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 6

To facilitate remote verification, a standardized counting rule could be adopted for all delivery vehicles, assigning each a fixed number of warheads for treaty purposes and allowing parties to establish limits even without the presence of on-site inspectors.

In the examples provided in **FIGURE 7** and **FIGURE 8**, high-resolution commercial electro-optical satellite imagery (30-cm) illustrates how remote sensors are able to view inside exposed missile silos and submarine hatches.

It remains unknown if commercially available sensors can, with a high degree of confidence, determine whether open missile silos contain missiles. In **FIGURE 8**, for example, the five bumps that are visible inside the open missile tubes could either be loaded SLBM canisters or protective water seals; the resolution is not quite clear enough to make a firm determination.

Government and military sensors, however, are a different story. In August 2019, President Trump tweeted out a highly-classified annotated satellite image, displayed in **FIGURE 9**, of an Iranian missile launch failure that had been included in his daily intelligence briefing.[23] The satellite image—which was only formally declassified three years later following a request from NPR, was highly illuminating—not because of the content, but because of its resolution.

By cross-referencing various elements of the image—including the capture angle and shadows—with an open-source database of satellites, open source analysts were able to determine that the image was likely captured by USA 224, one of the United States' highly advanced KH-11 reconnaissance satellites.[24] The sensing capabilities of that fleet of satellites were unknown until that point; following President Trump's tweet, it became clear that they could capture imagery at resolutions of at least 10 centimeters, approximately three times sharper than most high-resolution commercially available satellites.

However, the capability gap is narrowing, as established commercial imagery providers Maxar and Airbus are now offering software enhanced electro-optical imagery they claim is equivalent to 15 centimeter resolution, while in 2021 a new company, Albedo, was granted NOAA's first license to collect and sell imagery from very-low Earth orbit (VLEO) in the 10 centimeter range.[25]

With favorable weather and imaging conditions, and with pre-agreement between parties, it seems feasible that satellites of this resolution could determine whether or not a particular missile silo was loaded. The level of confidence associated with such an assessment would largely depend upon the imagery resolution, as well as the presumed level of sophistication of adversarial decoy measures, such as placing inflatables or coverings inside the silo to falsely simulate a loaded or unloaded launcher. In turn, parties could cooperatively increase confidence of the estimate by increasing the optical visibility of missiles (e.g. painting the missile shroud in distinctive colors), by illuminating the interiors of silos, or placing radar reflectors in empty silos.

Relying on biannual data exchanges and treaty-required notifications, New START did not require pre-notification of the addition, elimination, and uploading of strategic weapons and delivery vehicles. To facilitate observation of missile loading operations under a remote sensing verification arrangement, each side could be required to pre-notify the other side.[26]

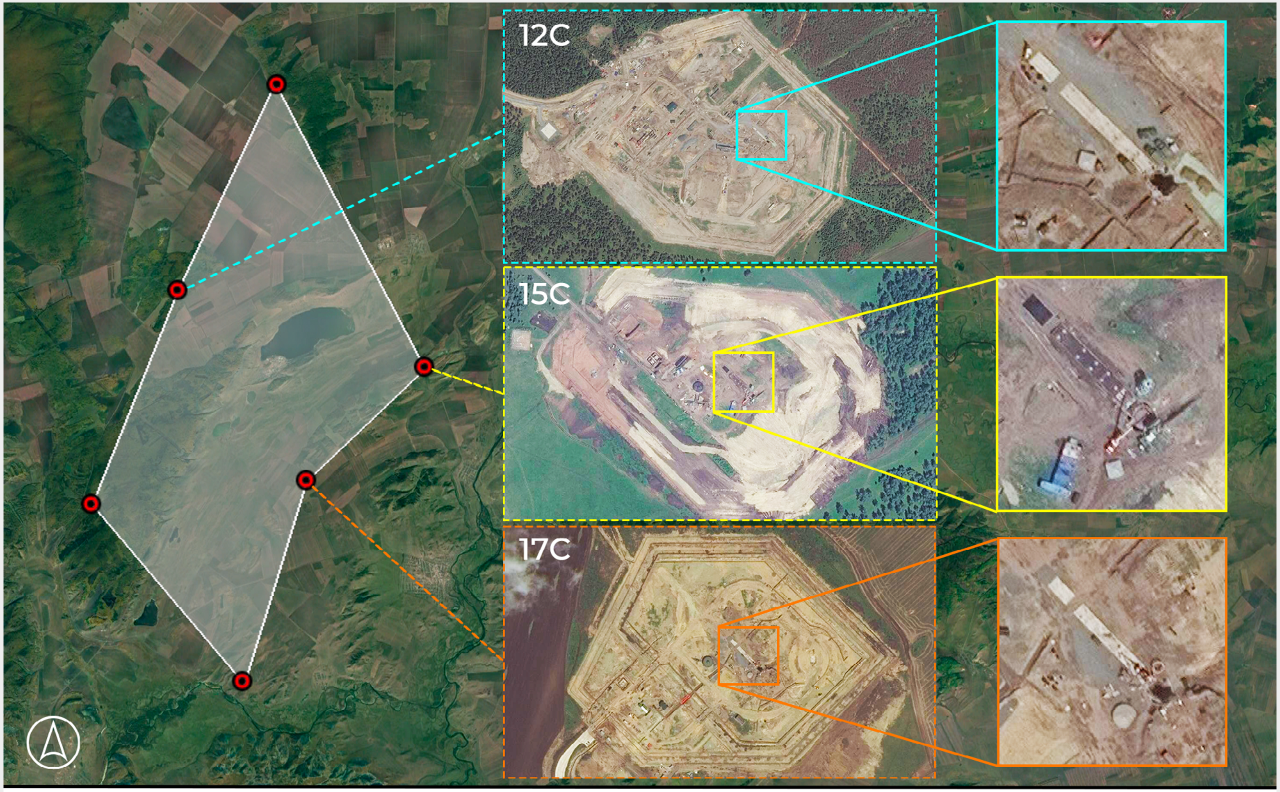
---

23 Zach Dorfman, "More than two years after Trump tweeted a classified image of Iran, former officials are divided on fallout," Yahoo News, 17 December 2021, https://www.yahoo.com/news/trump-tweeted-classified-satellite-image-of-iran-former-officials-fallout-100003879.html.

24 Geoff Brumfiel, "Amateurs Identify U.S. Spy Satellite Behind President Trump's Tweet," NPR, 2 September 2019, https://www.npr.org/2019/09/02/756673481/amateurs-identify-u-s-spy-satellite-behind-president-trumps-tweet.

25 For more information on Maxar's 15-cm imagery, see: Chris Formeller, "Introducing 15 cm HD: The Highest Clarity From Commercial Satellite Imagery," Maxar, 12 November 2020, https://blog.maxar.com/earth-intelligence/2020/introducing-15-cm-hd-the-highest-clarity-from-commercial-satellite-imagery; For more information on Airbus' 15-cm imagery, see: "Better visual rendering for Satellite Imagery | Pléiades Neo HD15," Airbus, https://space-solutions.airbus.com/imagery/our-optical-and-radar-satellite-imagery/pleiades-neo/pleiades-neo-hd15/; For more information on Albedo's 10-cm imagery, see: Topher Haddad, "Approved For 10cm," 30 December 2021, Albedo, https://albedo.com/post/approved-for-10cm.

26 Vince Manzo, "Nuclear Arms Control Without a Treaty?", CNA, IRM-2019-U-019494, March 2019, p. 70, https://www.cna.org/reports/2019/04/IRM-2019-U-019494.pdf.



Uzhur Missile Silo Field, Krasnoyarsk Krai, Russia

22 June 2023 / 55.06°, 89.68°

Satellite imagery © 2025 Vantor

Since 2021, Russia has been upgrading the missile silos under the command of the 302nd Missile Regiment at Uzhur in order to prepare for the introduction of the new RS-28 Sarmat ICBM. These upgrades involve nearly doubling the surface area of each silo complex, adding additional layers of fencing, and modernizing the silos themselves. On 22 June 2023, three of the regiment's four silos currently under construction were captured via satellite imagery with their hatches open, as seen above.

FAS FEDERATION OF AMERICAN SCIENTISTS

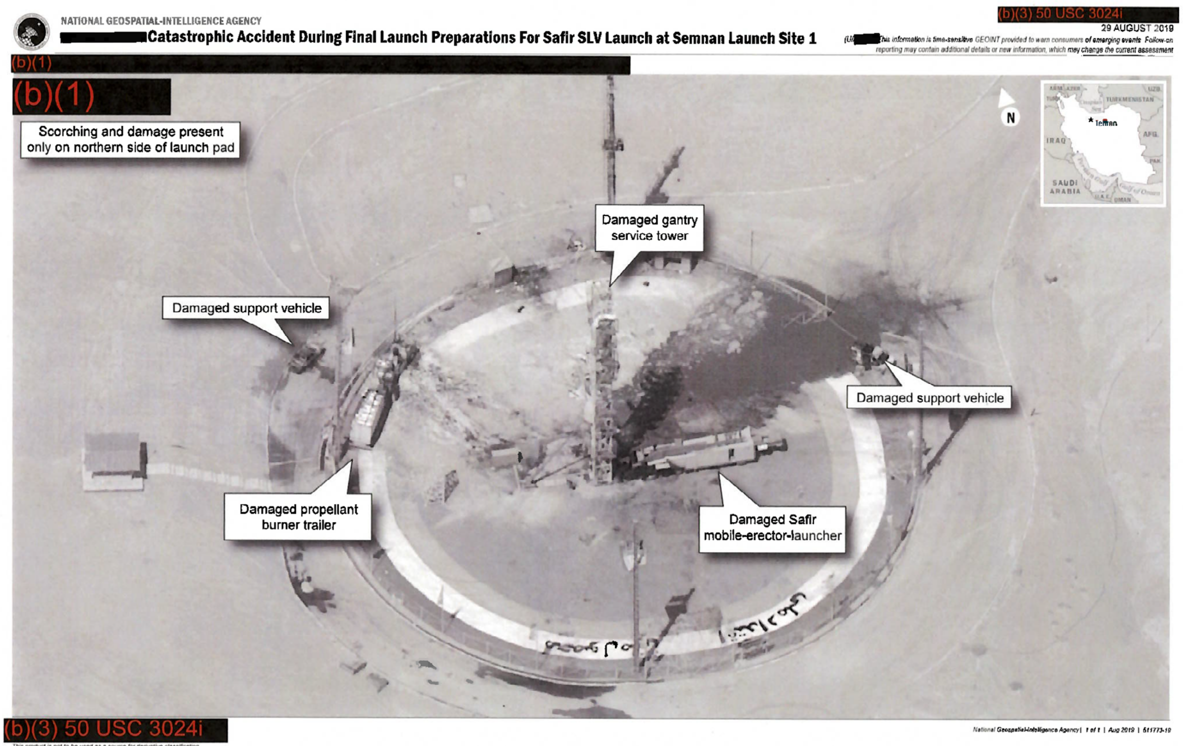
FIGURE 7

Open SSBN Launch Tubes, Okolnaya Submarine Support Base, Russia

Russia is modernizing its fleet of ballistic missile submarines (SSBNs) and associated infrastructure. This image features one of Russia's newer SSBNs—the Borei-class—undergoing maintenance at the Okolnaya submarine support base. The Borei-class has 16 launch tubes for ballistic missiles, five of which are open with either the water seals or missile canisters clearly visible with satellite imagery resolutions of approximately 30 cm.

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 8



Satellite Image of 2019 Iranian Space Launch Vehicle Accident

The image shows a declassified satellite photo of the aftermath of a catastrophic accident at Iran's Imam Khomeini Space Center on 29 August 2019. The image was originally tweeted by President Trump, inadvertently revealing the capabilities of a highly classified U.S. KH-11 optical imaging satellite known as USA 224.

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 9

Even without the notification, missile loading operations are increasingly easy to detect due to the growing number of sensors in orbit. A Sandia report from 2000 estimated that it took approximately 12 hours to load a Russian SS-18 ICBM into its silo from start to finish; this would presumably be a similar time duration for other types of ICBMs. These operations require security preparations, presence of specialized heavy equipment and a number of supporting vehicles—all easily observable with electro-optical and SAR satellites.[27]

Since orbits of observation satellites are predictable, a country could attempt to time its silo loading operations for periods when adversarial satellites are out of view of the silo. In order to mitigate this risk, both countries' would need access to satellite imagery with an observation frequency higher than the time required to load a silo.

According to the National Imagery Interpretability Rating Scale (NIIRS) and a note from the U.S. Bureau of Intelligence and Research (INR), electro-optical imagery with a resolution of 1.2m to 2.5m is able to detect an open missile silo door, while 2.5m to 4.5m resolution can observe support vehicles and equipment needed to load a silo.[28] Simulations show that even if parties were to rely solely on commercial electro-optical or SAR satellites, these provide adequate resolution and frequency of observation to detect missile loading operations.[29]

SAR is especially useful for continuous monitoring and assessments about the level of activity at specific sites. It offers high-resolution imaging capabilities at all hours of the day, and is unaffected by cloud cover. It is also particularly good at detecting metallic and human-made objects, potentially enhancing analysts' abilities to detect the presence of large vehicles, such as missile transloaders or cranes (as illustrated in **FIGURE 10**).

While in theory a country could cheat by passing actual loading or warhead uploading operations off as "maintenance" or another activity that does not affect its adherence to the central limits, doing so at abnormal rates could indicate a likely lack of compliance. As was the case with New START, verification is based on detecting inconsistencies over the long run to indicate a likely lack of compliance, rather than observing specific cases of deception In addition, other sources of intelligence would presumably be brought to bear to interrogate and assess these claims.

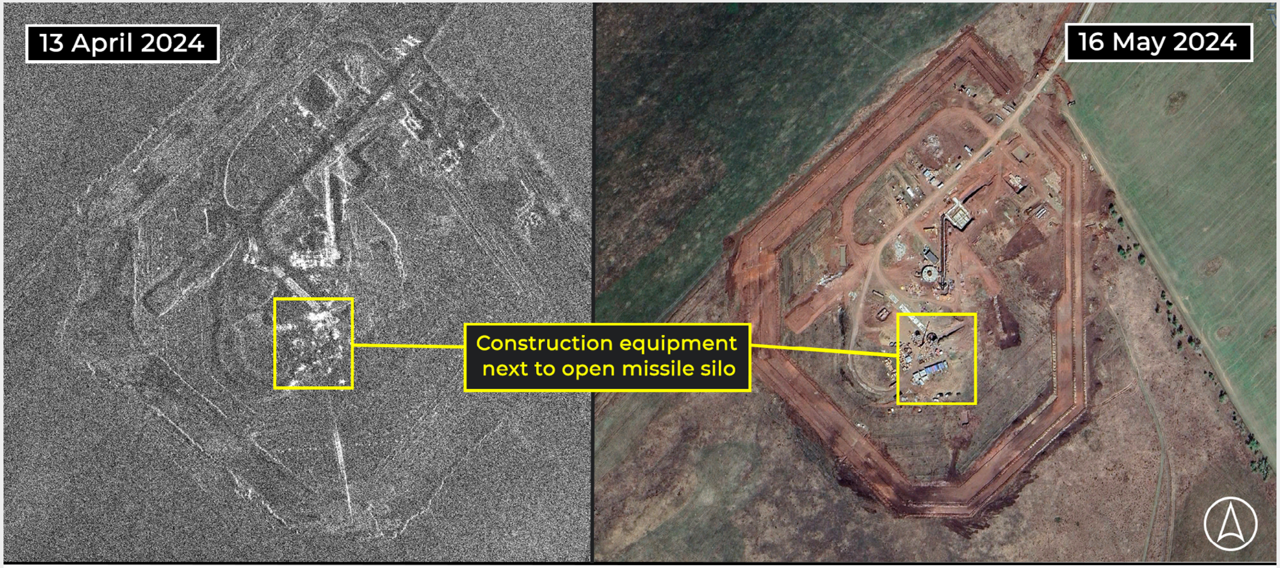
The examples provided below in **FIGURE 11**, **FIGURE 12**, and **FIGURE 13** illustrate how, with commercial electro-optical satellite imagery, remote inspectors could detect missile loaders, cranes and other equipment necessary to upload missiles into launchers. The imagery shows maintenance or loading operations observed at three distinct silo complexes housing three different missiles: two Russian ICBM silos at Orenburg and Tatishchevo, and a Chinese ICBM silo at Jilantai.

---

27 Michael W. Edenburn and Lawrence C. Trost, "Ballistic Missile Silo Door Monitoring Analysis," Sandia National Laboratories, SAND99-3173 (2000), https://www.osti.gov/servlets/purl/750347.

28 This information provides a subjective scale of the required resolution of electro-optical satellite imagery required to detect and identify different types of objects and sites. Resolution Assessments and Reporting Standards (IRARS) Committee, "National Imagery Interpretability Rating Scales (NIIRS): Overview and Methodology," Airborne Reconnaissance, XXI, SPIE Proceedings 3128 (1997). See also note by the Bureau of Intelligence, Verification and Information Management Intelligence, Arms Control and Disarmament Agency, Technology, and Analysis Division, "High-Resolution Commercial Imagery and Open-Source Information: Implications for Arms Control," 13 May 1996, https://fas.org/irp/offdocs/acda.htm, and reproduced in Appendix B of this report.

29 Igor Moric, "Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring," Science & Global Security 30, no. 2 (2022): pp. 22-49, https://www.tandfonline.com/doi/full/10.1080/08929882.2022.2063334.



Silo Maintenance Operation, Uzhur, Russia

54.95°, 89.68°

The above images show the same location approximately one month apart. The image on the left is a synthetic aperture radar (SAR) image of a Russian missile silo undergoing refurbishment, collected by Umbra. The image on the right is an electro-optical image collected by Airbus and accessed via Google Earth. SAR is particularly useful for detecting metallic and human-made objects, even through cloud cover.

AIRBUS UMBRA FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 10

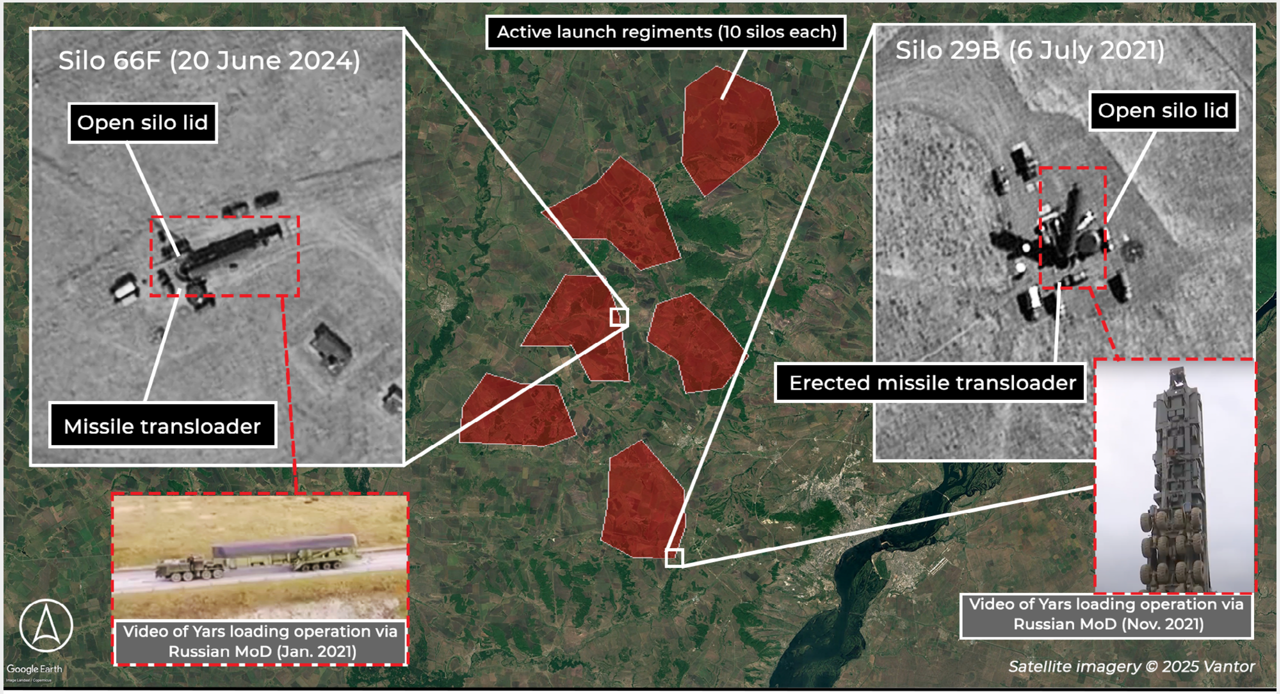
Preparations For Avangard Loading Operation, Orenburg Oblast

51.21°, 59.85°
Satellite imagery © 2025 Vantor

A small number of converted SS-19 ICBMs are being deployed with Russia's new nuclear-capable Avangard hypersonic glide vehicle. The first regiment to receive the Avangard upgrade (the 621st Missile Regiment) completed its rearmament in December 2021, and the second regiment (the 368th Missile Regiment) reportedly completed its rearmament in December 2023. Over the past five years, preparations for Avangard loading operations have been visible on satellite imagery—including at Silo 11B of the 368th Missile Regiment in October 2023 (shown above).

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 11



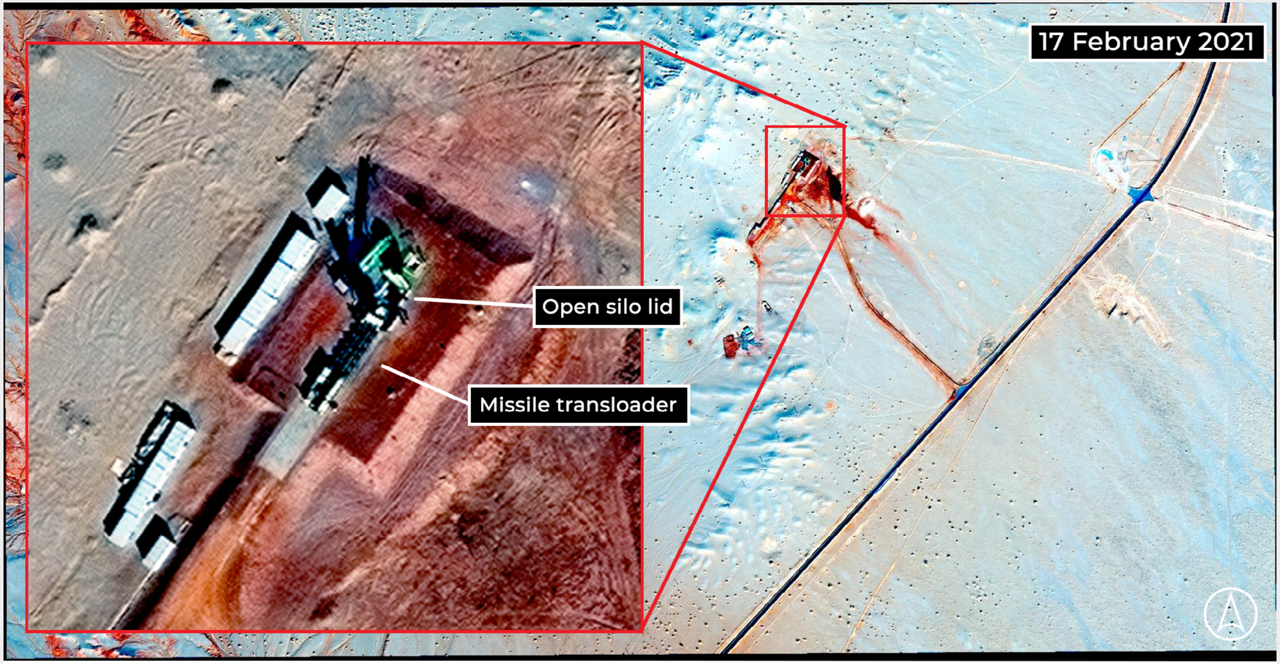
Loading Operations at Tatishchevo Missile Silo Field, Russia

51.83°, 45.41°

Russia is preparing to upgrade the intercontinental ballistic missiles (ICBMs) deployed at the 60th Missile Division near Tatishchevo, from the RS-12M1 Topol-M (SS-27 Mod 1) to the RS-24 Yars (SS-27 Mod 2). Although the bulk of the upgrades are expected to begin in 2025, loading activities have been visible at some of these silos over the past few years. In each of the above images, a missile transloader is visible, along with associated support vehicles. While the 2021 operation may have been for the purpose of regular maintenance, the 2024 operation may have been intended to removing the Topol-M from its silo in preparation for the silo's rearmament with the RS-24 Yars.

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 12



Silo Loading or Maintenance Operation, Jilantai, China

39.76°, 105.54°

A satellite image from Vantor was able to capture a silo loading or maintenance operation at the Jilantai missile training area in China. While the exact nature of the operation remains unclear, this example demonstrates the possibility of using satellite imagery to monitor such activities.

Satellite Imagery @ 2025 Vantor

FEDERATION OF AMERICAN SCIENTISTS

FIGURE 13

2.3 Verifying the Number and Basing Location of Heavy Bombers and Mobile Launchers

In peacetime, U.S. and Russian heavy bombers do not carry nuclear weapons, which are stored nearby in shelters. However, making verification easier, New START counts all operational heavy bombers as deployed launchers and each is counted to carry one nuclear warhead, regardless of their actual armament.[30]

Under the New START Treaty, heavy bombers were subject to restrictions on where they could be based. For example, while bombers equipped for nuclear armaments could be co-located with non-nuclear bombers, their number and location needed to be disclosed and they were subject to inspection and pre-inspection restrictions. Heavy bombers could be temporarily located at non-declared bases inside or outside of the national territory, but a notification had to be shared if the deployment exceeded 24 hours.

Like other launchers, heavy bombers were required to carry a unique identifier tag which the inspectors could examine during on-site visits. These tags, along with distinguishing features of the aircraft, allowed inspectors to confirm the type and the declared location of the bomber.

Remote sensing can also observe and identify externally-observable attributes, such as those used to distinguish between nuclear and non-nuclear bombers; for example, American nuclear-capable B-52s are distinguished from their non-nuclear-capable counterparts through the presence of a unique fin on both sides of the fuselage.[31] These fins are approximately 30 centimeters in length, and are thus difficult to distinguish with commercially available high-resolution 30-centimeter imagery (as each fin would be the length of a single pixel); however, they could theoretically be visible with higher-resolution imagery under proper weather conditions (particularly if the time of day casts long shadows). This represents a proof-of-concept for how remote inspections could distinguish treaty-accountable items from non-treaty-accountable items under a revised agreement.

To facilitate more detailed identification of nuclear bombers, allowing a treaty party to localize and track them remotely, the aircraft could be marked with an alphanumeric code painted on their fuselage or wings. While U.S. heavy bombers already carry a unique number on their tails or on the nose gear door,[32] the identifying code could be placed in such a way to be visible using optical sensors from space, encoding information on the bomber's type, declared location, and operational history. This information could be classified and kept in a shared database shared between treaty partners.

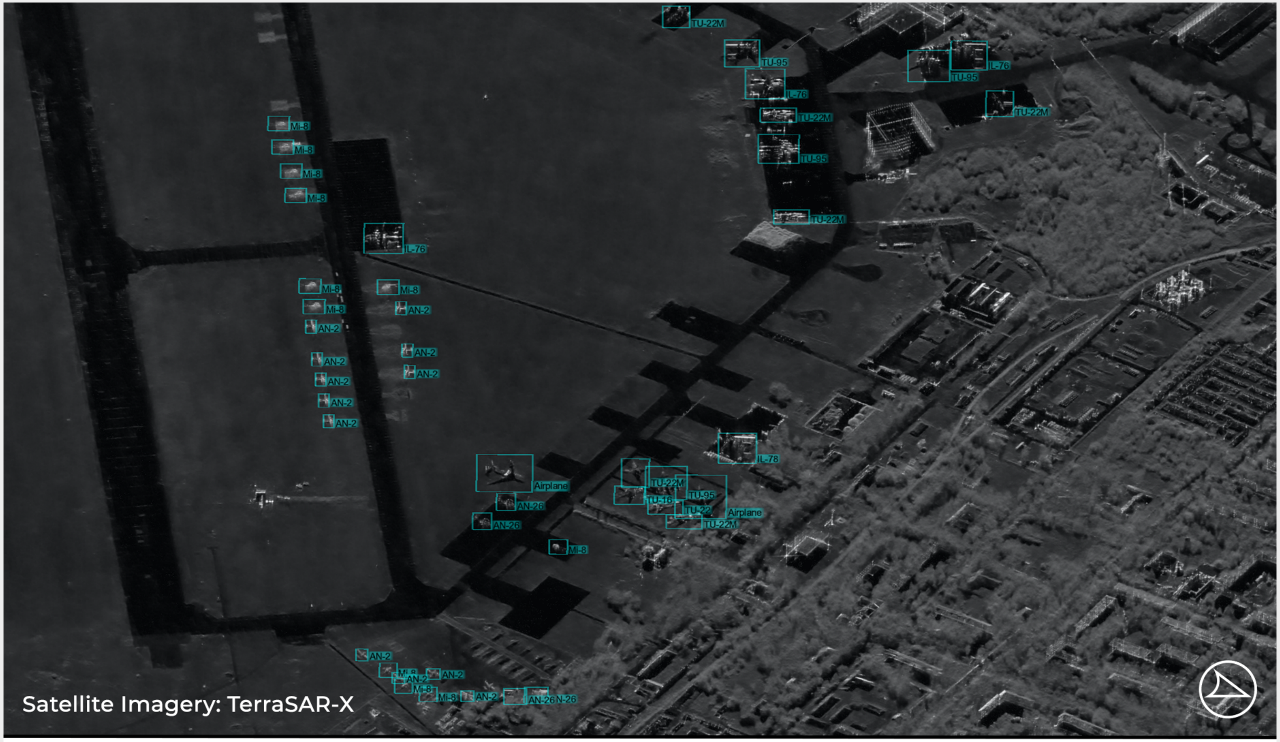
The satellite images shown in FIGURE 14 and FIGURE 15 illustrate how this could work in a proposed remote-inspection scenario. SAR sensors provide continuous, all-weather monitoring of air bases, and an AI algorithm would be employed to automatically detect, classify and count treaty-accountable nuclear bombers. Once atmospheric conditions permit electro-optical imaging, the system would cue high resolution sensors with sufficient resolution to read alphanumeric codes on exposed bombers. Remote inspectors would then use these codes to verify compliance with the agreement, by ensuring that specific heavy bombers are located where they are supposed to be, and not outside of national territory longer than allowed.

In addition to heavy bombers, Russia and China operate mobile launchers designed to transport and launch ICBMs. While New START did not require notifications for operational dispersals of mobile launchers, each launcher had a declared base when not on patrol. Russia was required to declare the number and the location of its active mobile launchers and notify the United States if they relocated to another base, as well as when new vehicles left their production facilities.

30 Nevertheless, under New START, inspectors were allowed to count the number of equipped nuclear armaments, which the host was allowed to protect with a soft cover.

31 Vince Scappatura and Richard Tanter, "Nuclear-capable B-52H Stratofortress bombers: a visual guide to identification," Nautilus Institute, 26 August 2024, https://nautilus.org/wp-content/uploads/2024/08/Nuclear-capable-B-52H-Stratofortress-Aug26-2024.pdf; Hans Kristensen (@nukestrat), Twitter/X, 18 September 2022, https://x.com/nukestrat/status/1571518011143602176.

32 U.S. Congress, Senate Committee on Foreign Relations, The New START Treaty (Treaty Doc. 111-5): Hearings Before the Committee on Foreign Relations, 111th Cong., 2nd session., April 29, May 18, 19, 25, June 10, 15, 16, 24, and July 15, 2010 (Washington: Government Printing Office, 2010), p. 82, https://www.foreign.senate.gov/imo/media/doc/New_START_hearings_111th_Congress.pdf.



Dyagilevo Air Base, Ryazan Oblast, Russia

54.65°, 39.58°
October 2020

AI-enabled algorithms trained on existing satellite imagery and 3D models applied to SAR imagery can be used for automated all-weather nuclear bomber detection. This example image, produced by the TerraSAR-X satellite in 2020 and analyzed by Carlos Villamil Lopez (DLR), shows airplanes and helicopters at the Dyagilevo air base, Ryazan Oblast, Russia.

FEDERATION OF AMERICAN SCIENTISTS

FIGURE 14

Alphanumeric Codes Visible Using Electro-Optical Imagery

22 October 2023
40.69°, -74.14°

After bombers have been detected and classified using SAR, electro-optical imagery could be used to read identifying alphanumeric codes placed o the aircraft fuselage or next to the aircraft. Military planes typically have markings on their tails, meaning that they are difficult to see using satellite imagery; however, this Google Earth image of a Boeing 777-3FX(ER) at Newark Liberty International Airport illustrates how high resolution EO imagery can read such markings ("VT-AER," on this particular plane) if they were written on top of the wings or fuselage.

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 15

A launcher was not counted as deployed if located at a space-launch facility, and there were further limitations on where non-deployed and test mobile launchers could be placed. Like with heavy bombers, New START inspectors were able to examine identification tags of selected mobile launchers to verify their numbers and declared locations. However, after announcing the inspection, the inspected party had one hour before locking down the base designated for inspection. This was often enough time for Russia to move out their mobile launchers, as was observed by U.S. inspectors.[33]

In a proposed remote-sensing agreement, verification of declared information could be performed and improved with satellites. While not on patrol, Russian and Chinese mobile missile launchers are typically housed in fixed structures inside designated basing areas (see FIGURE 16). To facilitate counting and identification from space, non-dispersed launchers could be marked with an alphanumeric code and exposed to passing observation satellites—either periodically (at designated times or as part of a surprise inspection) or continuously.

In case an alphanumeric identifier cannot be placed on the launcher due to size restrictions or security considerations, launchers could instead use simple site-specific markings, observable from space with EO or SAR satellites. The inspected party would be required to assign the markings to the stationed launchers and expose them while they are on-base, but could conceal or remove them when launchers leave on patrol. This method would not allow identification of individual launchers, but would still facilitate counting.

Even though any type of information shared remotely would not provide full confidence on verifying the location or the total number of launchers, this was equally challenging under New START due to their mobility. However, consistently marking the launchers would signal cooperative intent and—over time—build confidence between the parties, complicating and discouraging attempts at large-scale deception.

2.4 Verifying the Number of Deployed Warheads on ICBMs

The New START Treaty imposed an aggregate limit of up to 1,550 nuclear warheads that each country could deploy on their strategic delivery systems. Each party was also obliged to declare the number of reentry vehicles (RVs) on each deployed ICBM, regardless of whether they contained a nuclear-armed warhead, a decoy, or a penetration aid.

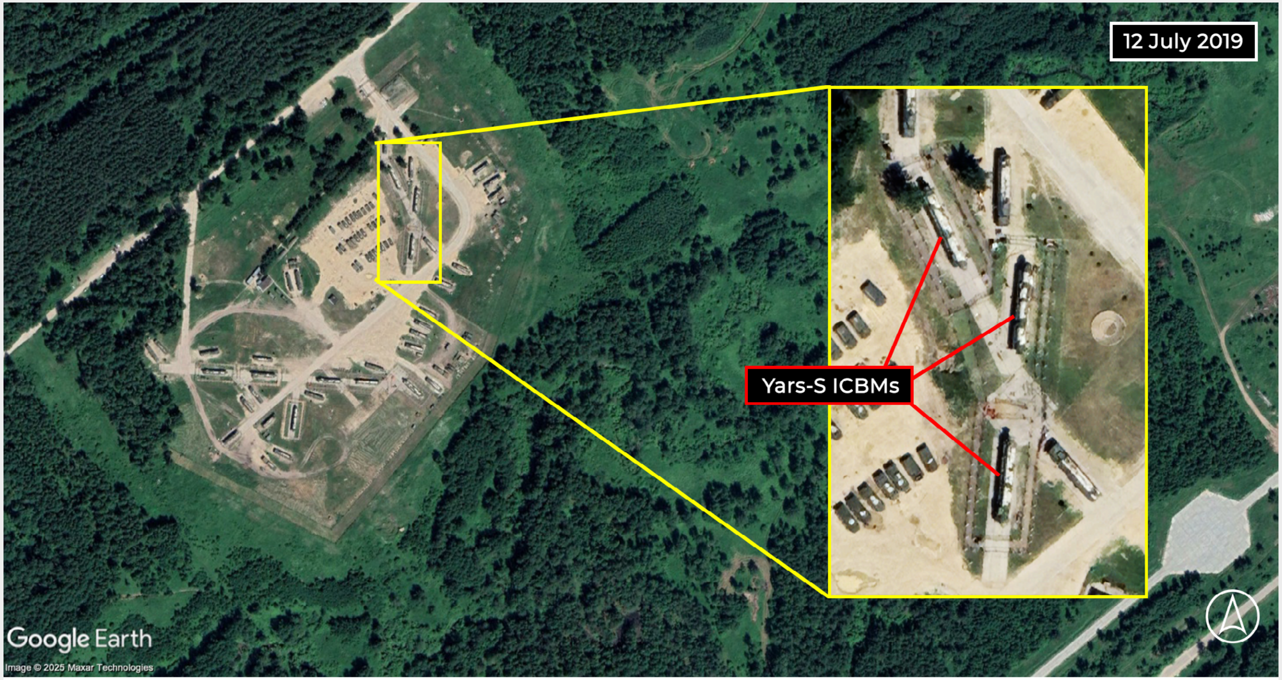
As a direct result of the Treaty, both the United States and Russia currently deploy several hundred fewer warheads than they deployed before New START entered into force. If the Treaty expires without a successor to take its place, both sides could rapidly upload hundreds of warheads back onto their currently deployed strategic launchers.

Under New START, the verification of deployed warheads was conducted through on-site inspections, although such inspections have not occurred since 2021. During a visit, inspectors would initially select a deployed missile they wanted to examine. The inspected party would then either view the front section—containing the re-entry system—directly in the deployed ICBM or SLBM launcher, or remove the missile's front section and transport it to a weapons storage facility to be inspected. In each case, the RVs were exposed to inspectors but covered with a soft or a hard shroud to minimize the possibility of unintentionally disclosing any sensitive information.[34] Inspectors therefore counted the "bumps" in the cover and compared this to the number of previously declared RVs for that missile. They could also use pre-approved radiation detection equipment to verify if the object is a non-nuclear decoy, if the in-country escort declared it as such.[35]

33 Rose E. Gottemoeller, "Negotiating the New START Treaty", (Amherst: Cambria Press, 2021), p. 130.

34 "START Verification Demonstration Production #610227," YouTube, The Association of Air Force Missileers (AAFM), 23 January 2023, https://www.youtube.com/watch?v=s0H_5p4483c.

35 Government Accountability Office, "Nuclear Arms Control: U.S. May Face Challenges in Verifying Future Treaty Goals," GAO-23-105698, Report to Congressional Committees, September 2023, https://www.gao.gov/assets/gao-23-105698.pdf; R. Gottemoeller, "The New START Verification Regime: How Good Is It?" Carnegie Endowment for International Peace, 21 May 2020, https://carnegieendowment.org/posts/2020/05/the-new-start-verification-regime-how-good-is-it?lang=en.



Yars-S ICBMs Visible At Novosibirsk Garrison, Russia

55.28°, 83.02°

To facilitate remote verification, mobile missile launchers could be visibly marked with alphanumeric codes and exposed periodically or continuously. The ICBMs shown above are typically covered with specialized tarpaulins, but in this image are exposed to overhead imagery sensors.

Satellite Imagery @ 2025 Vantor via Google Earth

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 16

While a counting rule could be put in place for ICBMs, it may also be possible to count the RVs remotely with very high-resolution electro-optical satellites. Under a remote-sensing agreement, the host would expose the re-entry system of a deployed missile to overpassing satellites, allowing observers to confirm the number of RVs carried by the selected missile. As with remote inspections of ICBM and SLBM launchers, the inspecting party would choose the location and observation window to deter cheating and maximize the visibility for their sensors.

Exposing the RVs would presumably allow other countries—not only the inspecting party—to also glean the same amount of information as the parties to the agreement. However, several factors may alleviate concerns of third-party intelligence collection during remote inspections. Exact timing and location of the inspection could be transmitted through secure means, and the inspection window could be limited to a very short time. Moreover, because of physical limitations of what an orbiting sensor can see from a distance of a few hundred kilometers, it would not be possible to remotely derive dimensions, details on construction, or the chemical composition of objects observed. Therefore, application of shrouds to cover RVs would not be necessary, thus avoiding the issues with counting under hard shrouds encountered during on-site New START inspections.[36]

In addition, it is not necessarily unusual for countries to publicly share images of their warheads and related loading and maintenance operations. Indeed, nuclear-armed countries occasionally publicly expose their RVs in greater clarity than would be available through such remote sensing. For example, the U.S. Department of Defense, NNSA, and the national laboratories involved in nuclear weapons production have all published images like those seen in **FIGURE 17** and **FIGURE 18**, which feature maintainers and other technical personnel alongside strategic RVs. In general, remote inspections allow the inspected country to have greater control of what information it wants to share than was the case with on-site inspections.

Without on-site visits, it would be impossible to verify if the observed RVs contain nuclear material or are decoys. However, remote inspections can still establish an upper limit and can check for inconsistencies over time throughout additional inspections and notifications. Unless a warhead is planned for dismantlement, there is little advantage for the host in declaring that an RV contains a warhead if it does not. While under New START the total number of strategic warheads was capped, a single inspection was only able to count the number of warheads on a single missile, without being able to compare this number to some previously declared value.

Under New START, inspectors were allowed to maintain visual contact with the vehicles and equipment used to lift and transport the front section. This was to ensure that the inspected party does not attempt to remove or replace RVs during transit. The remote-sensing agreement requires a different arrangement. Once the re-entry system is removed from the missile, the inspected party would uncover the missile's front section and temporarily expose the RVs to satellite observation, without transporting it to another location. If the RVs require environmental protection, they could be covered with a soft shroud until the sensor passes over it.

As with monitoring of missile uploading, large-scale deception when counting the RVs would be difficult. The inspecting party would select the observation window, and the selected missile would not be disclosed early enough to provide time for the host to modify the number of RVs from the missile's front section. While there would still remain venues for smaller-scale deception, in the long run this would require significant effort to scale up, and would become increasingly risky with higher persistence of overhead observation. The ability to remotely observe RVs without significantly disturbing normal base operations with visits of inspectors also implies that the proposed agreement could allow for a higher number of verification checks each year.

36 Concerned that it could carry more than eight warheads, Russian inspectors were unhappy with the United States using hard shrouds to cover RV's of the Trident II D-5 missile. From Pavel Podvig, "Treaty compliance controversies", Russian Strategic Nuclear Forces, 3 December 2013, https://russianforces.org/blog/2013/12/treaty_compliance_controversie.shtml.

FIGURE 17. BY REMOVING THE MISSILE SHROUD, REENTRY VEHICLES COULD BE EXPOSED TO OVERPASSING SENSORS, ALLOWING FOR COUNTING. THIS IMAGE SHOWS THE FRONT SECTION OF THE PEACEKEEPER MISSILE, WHICH CARRIED 10 RVS WITH W87S WARHEADS. THESE WERE REFURBISHED TO EXTEND THEIR LONG-TERM USE ON MINUTEMAN III ICBMS. SOURCE: LAWRENCE LIVERMORE NATIONAL LABORATORY, “ICBM WARHEADS WITH MODERN SAFETY FEATURES,” 1986, HTTPS://WWW.LLNL.GOV/SITES/WWW/FILES/1986.PDF.

FIGURE 18. A FRAME FROM A VIDEO PRODUCED BY THE 1360TH AUDIOVISUAL SQUADRON AT OFFUTT AIR FORCE BASE, NEBRASKA, DEMONSTRATING THE VERIFICATION PROCEDURES FOR THE START TREATY. SOURCE: “START VERIFICATION DEMONSTRATION PRODUCTION #610227,” YOUTUBE, THE ASSOCIATION OF AIR FORCE MISSILEERS (AAFM), 23 JANUARY 2023, 0:58, HTTPS://WWW.YOUTUBE.COM/WATCH?V=S0H_5P4483C.

2.5 Verification of Non-Strategic and Non-Deployed Weapons

One of the arms control goals that has been established and reaffirmed across successive U.S. administrations has been for any New START follow-on agreement to address all nuclear weapons, including nonstrategic nuclear weapons and weapons in storage.[37]

While parties to New START were required to store non-deployed warheads separately from deployed launchers, report their number and location, and label them with unique identifiers, inspectors were not permitted to enter storage facilities and verify any of the information disclosed.[38] The Treaty also did not cover nuclear weapons deployed on non-strategic delivery vehicles. The United States maintains approximately 200 non-strategic nuclear weapons, while Russia possesses between 1,000 and 2,000, according to the latest unclassified and open-source estimates.[39] Russia claims that these weapons are stored in centralized facilities, separate from delivery systems, but this is not currently verifiable. In reality, many regional storage sites are located relatively close to their launcher garrisons, allowing warheads to be transferred to their launch units on short notice.

Recent advancements of Earth observation capabilities can enhance arms control by allowing for novel verification approaches beyond just replacing and supplementing the procedures established in previous arms control agreements. As demonstrated, existing satellite capabilities currently allow for monitoring of delivery vehicles, and the gradual introduction of persistent multi-band overhead transparency may make it possible for remote inspectors to also monitor the separation of nuclear weapons from their launchers.

As long as all sides continue accommodating the proposed remote-inspection verification scenarios, the trust established between them may eventually lead to the resumption of some form of on-site inspections. However, to verify separation of launchers from warheads, in the proposed scenario, inspections would not occur at the weapons storage sites, but on locations declared not to have nuclear weapons. In the first step—somewhat similar to a Type Two inspection in New START—verification of non-deployment of nuclear weapons would focus on confirming that warheads were absent from storage sites that were declared not to hold them.[40]

Since inspectors would presumably not have contact with weapons or sensitive equipment, both sides may be more willing to accept these initial visits; although the inspection protocols would have to be carefully negotiated, given the likely disruptions caused by comprehensive absence verification inspections, as well as the potential opportunities for intelligence collection by inspectors. After inspectors validate the absence of weapons and the necessary infrastructure to hold them, inspections could continue on a fully remote basis—with regular satellite monitoring confirming there is no new construction on the site, and that there are no large-scale transfers of weapons to the facility.

In the second step, facilities declared to actually store non-deployed and non-strategic warheads would be locked down, prohibiting non-disclosed traffic of large vehicles and equipment. While this would disproportionately affect the Russian side, as the country with significantly larger numbers of non-strategic nuclear weapons and storage sites, as long as the warheads remain separated from their launchers, what the host does with them within the storage locations would need not be regulated by the remote-sensing arms control agreement. The continued absence of observation that the weapons are removed from storage or mated to delivery vehicles would serve as a stabilizing factor in the relationship between parties to the agreement.

---

37 Government Accountability Office, "Nuclear Arms Control: U.S. May Face Challenges in Verifying Future Treaty Goals," GAO-23-105698, Report to Congressional Committees, September 2023, https://www.gao.gov/assets/gao-23-105698.pdf; Bureau of Arms Control and Nonproliferation, "2023 – Report to the Senate on the Status of Tactical (Nonstrategic) Nuclear Weapons Negotiations Pursuant to Subparagraph (a)(12)(B) of the Senate Resolution of Advice and Consent to Ratification of the New START Treaty," 16 April 2024, https://www.state.gov/report-on-the-status-of-tactical-nonstrategic-nuclear-weapons-negotiations.

38 As a compromise, parties also agreed not to produce, test or deploy systems designed for the rapid reload of launchers.

39 Defense Intelligence Agency, "Nuclear Challenges 2024," 23 October 2024, https://www.dia.mil/Portals/110/Images/News/Military_Powers_Publications/Nuclear_Challenges_2024.pdf ; Kristensen, Korda, Johns, and Knight-Boyle, "Status of World Nuclear Forces."

40 Pavel Podvig, ed., "Menzingen Verification Experiment: Verifying the Absence of Nuclear Weapons in the Field," UNIDIR, 2023, https://unidir.org/wp-content/uploads/2023/09/UNIDIR_Menzingen_Verification_Experiment_Report.pdf.

While satellites have occasionally detected security convoys accompanying transfers of nuclear weapons, current satellite observation capabilities lack persistent real-time monitoring and it is unlikely such movement can be regularly observed.[41] Therefore, remote sensing would not be able to detect all forms of deception, especially involving only a few nuclear weapons. However, larger scale deceptions would be harder to conceal, requiring an increasing amount of logistical effort as the number of imaging systems in orbit increases and observations become more frequent, gradually augmenting confidence in the assessment.

Even though with currently available observation capabilities remote-inspectors are not able to directly observe all site traffic, traces of human activity and deviations from normal patterns of behaviour may remain detectable with SAR satellites. A signal that is transmitted by a SAR system antenna is reflected from the surface and returned to the sensor, which records its phase and amplitude. The sensor resolution depends on the wavelength and bandwidth of the transmitted signal.[42] The amplitude indicates the strength of the signal returned, and the phase describes the distance between the sensor and the target. Phase information of the signal is particularly sensitive to detecting activity on the surface; high temporal coherence of the phase signal suggests minimal changes in the signal between acquisitions, while the loss of coherence suggests that physical change has occurred.

Phase-based SAR change detection is particularly useful for observation of surface deformations, with the precision ultimately depending on the amount of SAR data analyzed and the complexity of the processing applied. For example, by comparing information from two separate acquisitions, coherent change detection (CCD) analysis can reveal disturbed terrain, vehicle tracks, and more subtle ground changes not otherwise visible with electro-optical imagery.[43] **FIGURE 19** shows military vehicle tracks observed via CCD analysis performed over a period of few days on fields near a military base in Yelnya in Russia, prior to the Russian invasion of Ukraine. **FIGURE 20** demonstrates how CCD can be used to monitor different traces of human activity at a particular site, even without directly observing it with persistent monitoring capability.

Even more accurate deformation analysis—with precision up to the millimeter level—can be achieved with a longer time-series and more complex techniques. This type of analysis can even detect thermal expansion of infrastructure and surface subsidence indicative of underground activity. The IAEA uses time-series SAR phase imagery to track signal coherence, allowing detection of undisclosed activity at nuclear facilities in the periods between observation. A similar approach could be applied in nuclear arms control for detecting traces indicative of a transfer of weapons and equipment from weapon storage facilities.

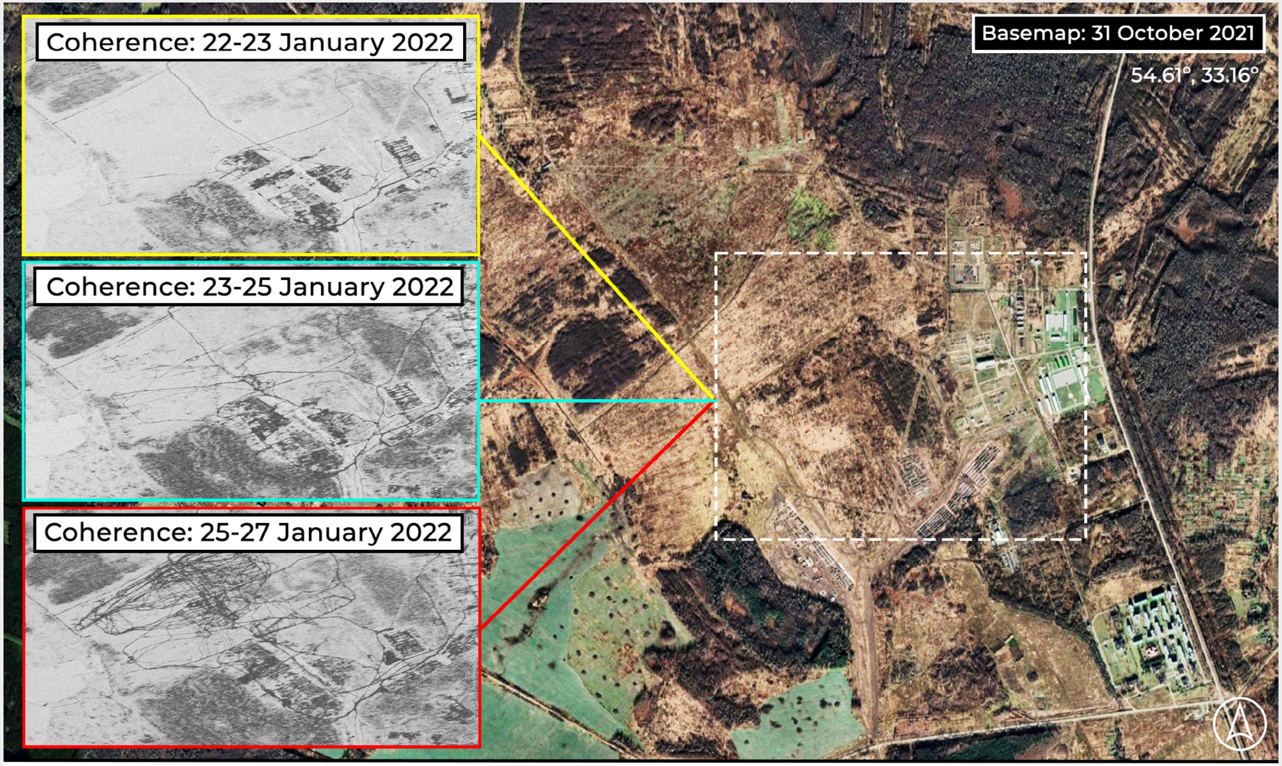
Surface deformations between each pass of the SAR satellites could be analyzed by AI-supported algorithms, alerting remote inspectors in case of anomalous activity. Monitoring could be aided by requiring the inspected party to place corner reflectors on nearby roads, with any displacement detectable remotely at at the millimeter level. Alternatively, to avoid impacting regular operation of the base, roads could be covered with compacted sand, making vehicle movement more traceable with SAR satellites, as shown on **FIGURE 20.** Another possibility would be to lay a number of metallic chains across the access roads. Chains are heavy enough not to be moved by wind, while allowing vehicular access to the facility in case of emergency. The movement of trucks, however, would displace the chains, producing a unique pattern observable by SAR satellites.

In addition, the time window to detect activity could be prolonged by extending the time required to remove the weapons from storage bunkers. This could be done by placing obstacles such as concrete blocks in front of gates.

41 Hans Kristensen, "Urgent: Move US nuclear weapons out of Turkey", Federation of American Scientists, 16 October 2019, https://fas.org/publication/nukes-out-of-turkey/.

42 Valentina Macchiarulo, Pietro Milillo, Chris Blenkinsopp, Cristian Reale, and Giorgia Giardina, "Multi-temporal InSAR for transport infrastructure monitoring: recent trends and challenges," Proceedings of the Institution of Civil Engineers - Bridge Engineering 176, no. 2 (2022): 92-117, https://doi.org/10.1680/jbren.21.00039.

43 Michael Wollersheim, "Beyond Change Detection: Measuring the Changes that Matter", ICEYE, 2 March 2022, https://www.iceye.com/blog/beyond-change-detection-measuring-the-changes-that-matter. See also Rose Njambi, "How persistent scatterer interferometry is used to predict and prevent infrastructure damage", UP42, 22 March 2022, https://up42.com/blog/how-persistent-scatterer-interferometry-is-used-to-predict-and-prevent



SAR Coherence Images Indicate Vehicle Movement, Yelnya, Russia

ICEYE's synthetic aperture radar (SAR) images of a Russian military depot near Yelnya indicate significant vehicle movement in weeks prior to the invasion of Ukraine. As these images were collected with the exact same parameters on different dates, the coherence between the images can be measured to highlight minute changes.

Imagery sources: Basemap: Google Earth / SAR: ICEYE

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 19

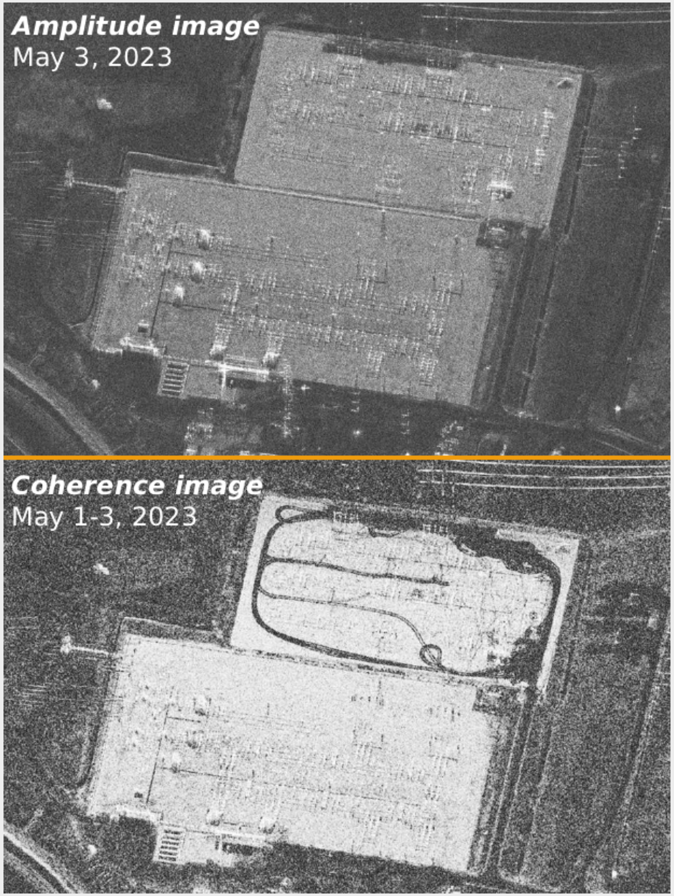


FIGURE 20. THESE FIGURES ILLUSTRATE A TIME-SERIES AMPLITUDE AND PHASE SAR ANALYSIS OF AN ELECTRICITY SUB-STATION IN ALBERTA'S OIL SANDS. THE TOP IMAGE SHOWS THE AMPLITUDE IMAGE, WHILE THE BOTTOM IMAGE IS THE PHASE DATA FOR THE SAME LOCATION, BOTH PRODUCED IN MAY 2023. IN THE BOTTOM IMAGE WHITE INDICATES FULL COHERENCE (NO CHANGE) OF THE SIGNALS BETWEEN THE TWO ACQUISITIONS, WHILE BLACK TRACKS OBSERVED IN THE UPPER HALF OF THE SITE INDICATE LOSS OF SIGNAL COHERENCE RESULTING FROM VEHICLE MOVEMENT, AND POSSIBLY HUMAN MOVEMENT FROM CONSTRUCTION AND MAINTENANCE ACTIVITIES. THE OBSERVED SURFACE MATERIAL IS IMPORTANT FOR DETECTING CHANGE, AS SOME MATERIALS (INCLUDING COMPACTED SAND, AS IS PRESENT IN THESE IMAGES) WILL MAINTAIN BETTER COHERENCE THAN OTHERS WHEN UNDISTURBED AND WILL REFLECT DISTURBANCES MORE CLEARLY. IMAGERY AND ANALYSIS PROVIDED BY ICEYE.

To remove the blocks and transfer the weapons, the host would need to use heavy equipment, easily observable from space.

Remote inspectors could further enhance their site monitoring capabilities by employing cameras with pre-approved angles, host-provided but remotely-operated inspection drones, observation balloons, perimeter monitoring systems, or simple movement detection sensors placed on doors and gates of the storage site. Unlike the more intrusive sensors used at production facilities under the Intermediate-Range Nuclear Forces (INF) Treaty, these devices would not contain weight sensors and X-ray scanners; instead, they would only have the ability to inform remote operators about undisclosed movements.

For example, Russia already uses microwave and fence disturbance sensors at their warhead storage sites,[44] and both Russia and the United States employ systems to monitor and identify traffic and measure radiation to prevent unauthorized transfer of nuclear materials.[45] Much of this information could also be shared between parties, without any impact on national security or disruption of base operations.

While experience from New START shows no evidence of either side attempting to hide nuclear storage facilities, parties may still choose not to declare all their locations. However, commercial satellites have proven effective at finding previously unknown nuclear sites. Furthermore, to have military value, hidden stockpiles would need to have a significant number of warheads which must be stored safely and securely in the longer term, producing characteristic signatures observable from space.

The examples shown in **FIGURE 21** and **FIGURE 22** illustrate how commercial electro-optical imagery was able to identify construction and adaptation of nuclear storage facilities in Belarus and the United States. Distinctive signatures of weapons storage facilities observable from space include storage bunkers and site layouts similar to known nuclear weapon storage sites, including addition of multiple layers of fencing and characteristic sheltered loading areas.

Looking ahead, the establishment of persistent observation capabilities could unlock new possibilities for arms control. Parties to the agreement could be allowed to transfer non-deployed warheads freely within a closed network of declared sites or a designated geographical area. Transporting weapons outside would not be permitted, unless other parties are notified that the weapons are to be deployed or dismantled.

Satellite monitoring of all traffic coming in and out of the facilities could enable immediate detection of the adversary's intent to deploy the weapons, and also expose locations of undeclared weapons sites.[46] Tracking warheads within a closed system could additionally be supported by placing remote sensors on equipment used to handle and transport warheads, which would not be allowed to leave the designated areas.[47]

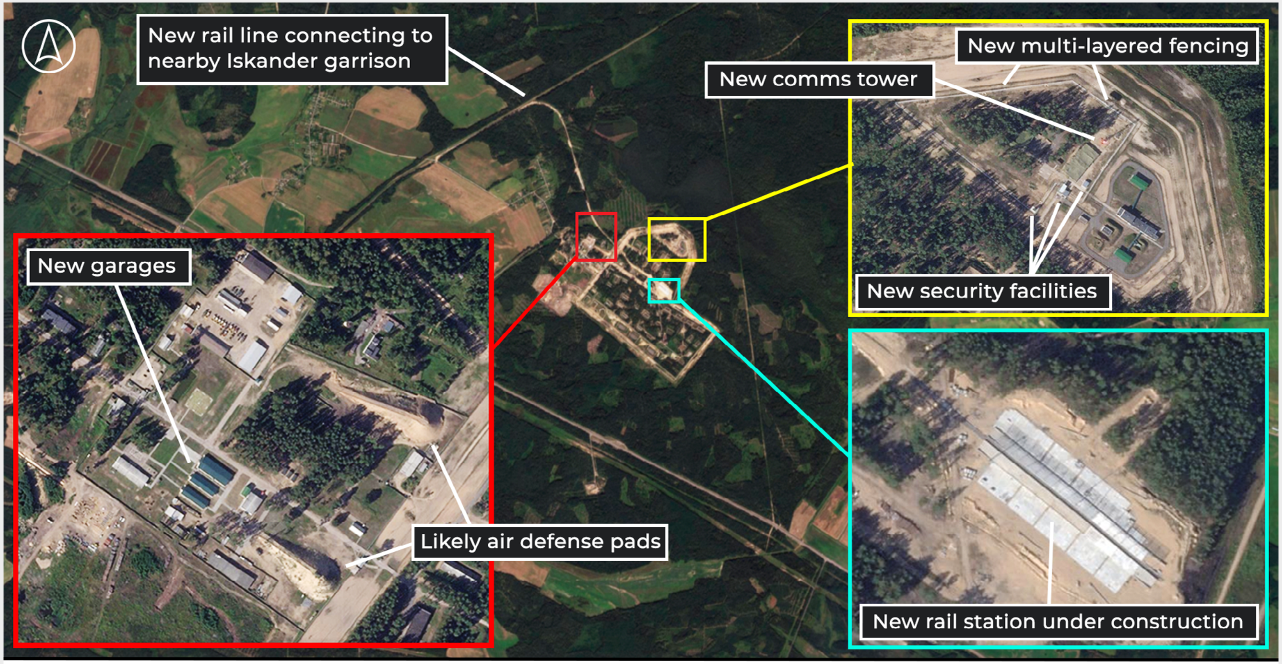
---

44 William M. Moon, "How the War in Ukraine Could Go Nuclear—by Accident," Foreign Affairs, 5 November 2024, https://www.foreignaffairs.com/ukraine/how-war-ukraine-could-go-nuclear-accident

45 Miles Pomper, William Moon, Marshall Brown, Ferenc Dalnoki Veress, Dan Zhukov, Dick Gullickson, and Yanliang Pan, "Nuclear Verification's Holy Grail: Verifying Nuclear Warheads — a new approach", James Martin Center for Nonproliferation Studies, CNS Occasional Paper #64, December 2024, p. 32, https://nonproliferation.org/wp-content/uploads/2024/12/nuclear_verifications_holy_grail_12162024b.pdf

46 Persistent monitoring capabilities could also aid verification with regards to the demating of nuclear weapons, wherein nuclear weapons are dismantled and geographically distributed. The inspected party maintains the capability to use the weapons, but requires a longer time to assemble them back into operational state. Depending on the agreed level of disassembly, weeks or months may be needed to prepare the weapons for use.

47 Pomper, Moon, Brown, Dalnoki Veress, Zhukov, Gullickson, and Pan, "Nuclear Verification's Holy Grail."



LIKELY NUCLEAR STORAGE UPGRADES AT ASIPOVICHY DEPOT, BELARUS

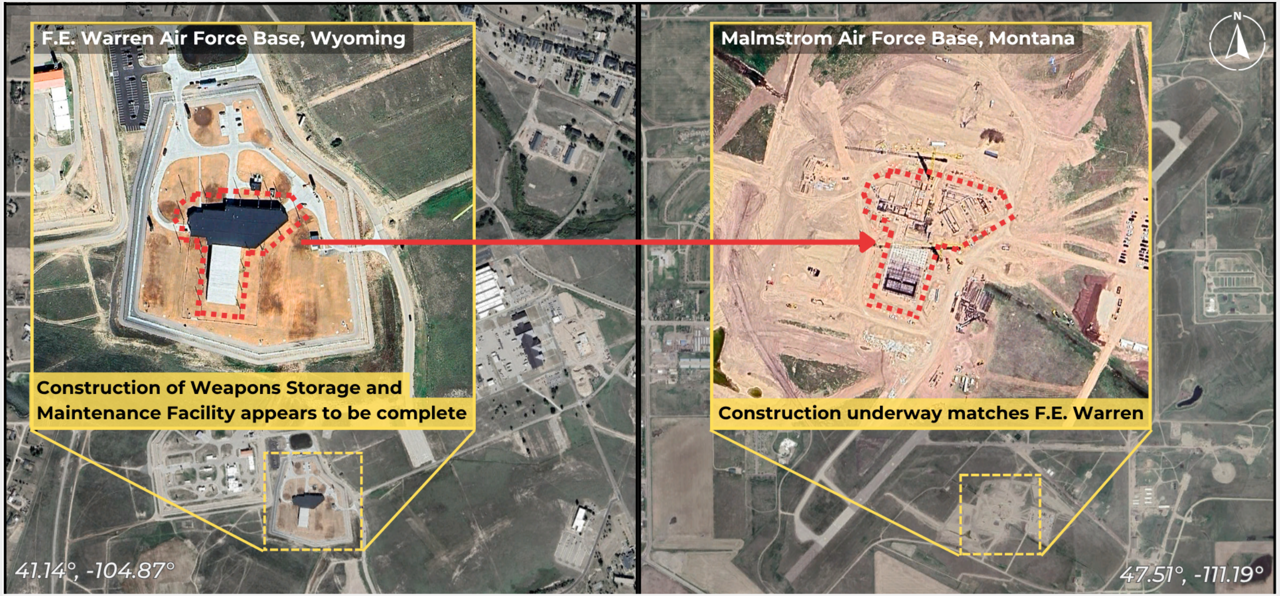
53.31°, 28.67°
September 2025

Substantial upgrades are taking place at a munitions depot near Asipovichy in Belarus. These upgrades, which include new multi-layered security perimeters, air defense platforms, communications equipment, and a new rail station, are consistent with signatures found at nuclear storage sites inside Russia.

Satellite imagery © 2025 Planet Labs PBC

planet. FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 21



NEW WEAPONS STORAGE & MAINTENANCE FACILITIES FOR THE SENTINEL ICBM PROGRAM September 2024

Satellite imagery from 2024 reveals that the new Weapons Storage and Maintenance Facility (WSMF - or Weapons Generation Facility) at F.E. Warren AFB in Wyoming is substantially complete. Construction visible at Malmstrom AFB in Montana is a perfect match of the WSMF at F.E. Warren, coinciding with the groundbreaking ceremony for the new WSMF in March and confirming the facility's location.

Satellite Imagery © 2025 Airbus via Google Earth

FAS FEDERATION OF AMERICAN SCIENTISTS

FIGURE 22

Conclusion

Arms control is a critical tool to manage the global nuclear arms race, helping establish a balance between competition and cooperation while defining observable limits for responsible behavior. While not infallible, and unable to provide full knowledge on the adversary's activities or intentions, arms control agreements provide an invaluable method of communication, help reduce the risk of miscalculation, and—should deterrence fail—limit the consequences of nuclear war.

Several factors have contributed to the demise of nuclear arms control, including the degradation of domestic support for cooperation, worsening international relations, and the proliferation of disruptive technologies.[48] The previous Trump administration considered returning to nuclear testing, withdrew from multiple arms control treaties, and encouraged nuclear arms racing.[49] While the second Trump administration may be even more focused on geopolitical confrontation, recent statements by President Trump— calling for defense budget cuts and renewed denuclearization talks with Russia and China—could signal a window for new arms control opportunities.[50]

As the last active arms control treaty, New START set numerical limits on U.S. and Russian strategic delivery vehicles and the total number of weapons they could carry. It also outlined mechanisms and procedures for verifying these limits. This has limited the buildup of nuclear arsenals, moderated arms-racing, and stabilized the nuclear relationship between state parties.

In the midst of the most strained geopolitical environment since the Cuban Missile Crisis—and with the Treaty's upcoming expiration in February 2026—both Russia and the United States will likely default to mutual distrust and worst case thinking amid fewer verifiable data points. Transparency and mutual disclosure of data is especially important for the United States, which lacks an alternative window into the much more opaque Russian (and Chinese) nuclear weapons program, that does not publicly share comparable information on the development and capabilities of its systems.

Both countries have meticulously planned their respective nuclear modernization programs based on the assumption that neither will exceed the force levels dictated by New START. Therefore, to avoid an unnecessary arms race after the Treaty's expiration, the United States and Russia should re-affirm their commitment to its central limits on nuclear warheads and delivery vehicles, and resume exchanging data on accountable weapons and launchers, as well as notifications on force deployment and relocations.

While the process of verifying declared data is itself highly technical, the framework underpinning it is largely political. The New START negotiators, for example, decided that 18 on-site inspections would be sufficient to meet the standard for "effective verification," but that number is neither sacred nor immutable, and standards can change to match the changing geopolitical reality.

China has maintained a high level of secrecy related to its nuclear force numbers, locations, and operations, and has so far refused to engage in risk reduction talks. Due to its smaller arsenal and inferior nuclear capabilities, China has traditionally rejected arms control initiatives, perceiving them as a way for nuclear superpowers to restrain its growth. The recent modernization and expansion of its forces have far-reaching consequences, and if continued will trigger worst-case speculations about Beijing's long-term intentions, reducing the probability for a nuclear deal between the United States and Russia. However, as China is bridging the capability gap and strengthening its confidence in the survivability of its nuclear forces, Beijing is also more likely to de-emphasise its focus on national

48 Ulrich Kuhn, "The crisis of nuclear arms control", Zeitschrift für Friedens- und Konfliktforschung 10 (March 2022): pp. 314-344, https://link.springer.com/article/10.1007/s42597-022-00069-5.

49 Ed Pilkington and Martin Pengelly, "'Let it be an arms race': Donald Trump appears to double down on nuclear expansion," The Guardian, 24 December 2016, https://www.theguardian.com/us-news/2016/dec/23/donald-trump-nuclear-weapons-arms-race.

50 "Trump proposes nuclear deal with Russia and China to halve defense budgets," The Guardian, 13 February 2025, https://www.theguardian.com/us-news/2025/feb/13/trump-nuclear-russia-china.

defense modernization and recognize shared interests in nuclear risk reduction by being more willing to engage in dialogue.[51]

If a more comprehensive solution is not currently feasible, the United States and Russia—possibly joined by China, France, and the United Kingdom—should pursue a novel, less-intrusive New START successor. Inspired by the first generation of nuclear arms control agreements—SALT I and SALT II—the framework proposed in this report would not be dependent on intrusive on-site inspections but would instead be reliant on remote-sensing. Such a framework is now made possible by novel satellite Earth observation technologies that were unavailable when previous arms control treaties were negotiated. By upholding the principle of non-interference to satellite observation and by co-operatively exposing their arms to overpassing satellites, continuity of knowledge could be maintained and nuclear risk reduced with Cooperative Technical Means described in this report.

While no verification regime can detect all forms of cheating, and although remote-sensing verification approaches may initially carry more uncertainty than if on-site inspector visits were included, an agreement based upon remote sensing would still enable detection if any party is attempting a strategically meaningful break-out in the number of weapons or their capabilities. In addition, if co-operative measures proposed in this report are accommodated by all sides, satellites could—with a degree of confidence that would in the long run approach those of New START verification techniques—enable monitoring and counting of nuclear delivery vehicles: ground-based ballistic missile silos, heavy bombers, mobile missile launchers, and strategic ballistic submarines.

Agreeing to participate in such an agreement would not be politically costly for any nuclear weapon state since it would not include on-site inspections, and unintended disclosure of sensitive information would be bounded by the physical limitations of what a digital sensor can see from orbit. None of the proposed verification scenarios would significantly interfere with the routine operation of nuclear facilities or require changes to operational practices of nuclear forces. Procedures established and maintained over time would lead to an increase of confidence and trust between parties, and information obtained could provide predictability between parties and help ensure that no side is left completely in the dark.

In the best case, this could lead to more complete arms control agreements in the future, paving the way towards a resumption of on-site inspections when geopolitical conditions allow it. In the worst case, the capacities developed and information obtained would narrow the knowledge gap between worst-case scenarios and the adversary's actual capabilities—even if nuclear relations further degrade, other channels of communication fail, and all guardrails on nuclear weapon deployment are removed.

51 Wu Riqiang, "Keeping Pace with the Times: China's Arms Control Tradition, New Challenges, and Nuclear Learning," International Security 50, No. 1: pp. 82–117, https://doi.org/10.1162/ISEC.a.6.

Appendix 1 — New START Treaty at a Glance: Obligations and Verification Procedures

New START is an agreement for nuclear arms reduction between the United States and Russia. The Treaty is the continuation of a series of arms control treaties, starting with the Anti-Ballistic Missile (ABM) Treaty and the Strategic Arms Limitation Talks (SALT I) agreement in 1972.

Following the expiration of START I in December 2009, New START was signed on 8 April 2010 and entered into force on 5 February 2011. Initially set to last 10 years, the Treaty included an option to extend it for an additional five years, which was triggered in 2021. The Treaty officially remains in force until 5 February 2026.

New START imposed three central limits for each side:

- No more than an aggregate of 700 deployed ICBMs, SLBMs, and heavy bombers;
- No more than an aggregate of 800 deployed and non-deployed launchers and heavy bombers;
- No more than 1,500 deployed warheads and nuclear warheads counted for heavy bombers.

Launchers carrying missiles were counted as deployed; those without missiles were considered non-deployed. This does not apply for active nuclear bombers, which were always counted as deployed and assumed to carry one warhead each, unless located at production or repair facilities. The number of strategic ballistic missile submarines (SSBNs) was not limited. The Treaty also did not regulate non-deployed and non-strategic nuclear warheads.

In the initial Treaty declaration, both Russia and the United States provided coordinates for their ICBM bases, mobile launcher bases, submarine bases, air bases with heavy bombers, and key nuclear facilities. This included locations of nuclear production, maintenance, storage, repair, training, test and elimination facilities. They also submitted site diagrams and maps, as well as types, numbers, assigned locations and deployment status for nuclear weapons and launchers.

All accountable items were required to carry unique identifier tags. This included heavy bombers capable of delivering nuclear weapons, deployed and non-deployed ICBMs, warheads deployed on ICBMs, and deployed and non-deployed launchers of SLBMs with their associated warheads.

The New START treaty implementation documents also described procedures involved with the verification of the obligations assumed. Measures included were:

- National Technical Means (NTM), including satellite reconnaissance, signals, and electronic intelligence, and other sources of information;
- Biannual data exchanges;
- Notifications upon establishment of new facilities, re-location and deployed status changes of weapons and delivery vehicles, new launchers coming out of production facilities, as well as those eliminated or converted;
- On-site inspections to verify that the data provided was accurate.

To enhance transparency, the Treaty also required sharing pre-launch notifications on launches of treaty accountable ballistic missiles,[52] as well as telemetric information for up to five launches per year.

Article X of New START defines obligations of the parties not to interfere with verification by NTM. Known as the principle of non-interference, it was first mentioned in the ABM Treaty and SALT I. It survived in subsequent treaties, and was maintained in New START in similar form.

52 This is also consistent with both Parties' obligations under their 1988 Agreement on Notifications of Launches of Ballistic Missiles.

Systems constituting NTM have been left undefined to protect sources and methods, to allow flexibility in how they are used, and to produce some uncertainty about the capabilities themselves.[53] NTM included signals, geophysical, and atmospheric intelligence, as well as satellite imagery, which has been a vital verification tool for inspectors since the first generation of arms control treaties. Satellites played a key role in New START verification, enabling monitoring of strategic delivery vehicles at ICBM bases, submarine bases, and airfields. By mutual agreement, imagery was also used to monitor new ICBMs and SLBMs leaving production facilities and to verify elimination of dismantled launchers by exposing them to satellites (see **FIGURE 23**).[54]

Under New START, each party was permitted up to ten "Type One" on-site inspections per year at selected ICBM bases, submarine bases or air bases. Once there, inspectors could examine a limited number of selected launchers and count the number of nuclear weapons they carried. While random and on short-notice, inspections were not comprehensive enough to detect all attempts of deception, but were intended to gradually build confidence on the accuracy of the data provided.

To confirm the absence of deployed strategic systems or confirm launcher conversion or elimination, inspectors could also conduct up to additional eight "Type Two" ground inspections annually. They could examine non-deployed strategic launchers in facilities declared as decommissioned or at locations with eliminated ICBM launchers. Inspectors could also visit loading, storage, and repair facilities, as well as test ranges and training facilities with test launchers.

For converted or non-nuclear launchers—including ICBMs, SLBMs, mobile launchers and converted heavy bombers—inspectors could verify that they were incapable of delivering weapons. They were also allowed to confirm that non-deployed launchers and canisters declared to be empty do not contain RVs. In addition, inspectors could examine any structure large enough to contain treaty accountable items.

At the time of publication, the verification provisions of New START were de facto no longer in force. Russia "suspended" its participation in February 2023, and the United States responded with reciprocal countermeasures, involving withholding biannual data exchanges, notifications regarding treaty-accountable items, on-site inspections, and telemetric information.[55] Both countries claim that they are continuing to abide by the Treaty's central limits; however, without the regular data exchanges this is increasingly difficult to verify.

53 Richard A. Scribner, Theodore J. Ralston, William D. Metz, The Verification Challenge: Problems and Promise of Strategic Nuclear Arms Control Verification, Birkhäuser, January 1985.

54 Before exposing to NTM or ground inspectors, the inspected party needed to make a hole, cut or crush the first stage of an ICBM or SLBM, remove the silo door, excavate and fill the hole of an ICBM launcher, cut the erector-launcher and paint the eliminated TEL to distinguish it, remove the submarine tube hatches and reduce the dimensions of the launcher to render it incapable of launching the smallest SLBM, cut the sections of the heavy bombers and modify the weapon bays and external attachments.

55 U.S. Department of State, "U.S. Countermeasures in Response to Russia's Violations of the New START Treaty," 1 June 2023, https://www.state.gov/u-s-countermeasures-in-response-to-russias-violations-of-the-new-start-treaty/.

FIGURE 23. AERIAL IMAGE OF DISMANTLED B-52 STRATOFORTRESS BOMBERS EXPOSED TO SATELLITES IN THE EARLY 1990S, IN ACCORDANCE WITH START I PROVISIONS. UNDER NEW START, THE ELIMINATION OF HEAVY BOMBERS INCLUDES CUTTING UP THE FUSELAGE AND EXPOSING IT FOR A PERIOD OF AT LEAST 60 DAYS. IMAGE: JIM GARAMONE, “U.S., RUSSIA EXTEND ARMS REDUCTION TREATY,” U.S. DEPARTMENT OF DEFENSE, 4 FEBRUARY 2021, HTTPS://WWW.DEFENSE.GOV/NEWS/NEWS-STORIES/ARTICLE/ARTICLE/2493593/US-RUSSIA-EXTEND-ARMS-REDUCTION-TREATY/.

Some New START Definitions

A **ballistic missile** is a weapon delivery vehicle with a ballistic trajectory most of its flight path. An **ICBM (Intercontinental Ballistic Missile)** is defined as a ballistic missile with a range exceeding 5,500 kilometers (3,418 miles) that is launched from land-based platforms. It can be a fixed silo-based launcher, or a mobile launcher.

Mobile ICBM launchers are defined as having an erector-launcher mechanism for launching ICBMs and the self-propelled device on which they are mounted. A deployed mobile launcher carries an ICBM, and is counted as one toward the aggregate limit.

An **SLBM (Submarine-Launched Ballistic Missile)** is defined as a ballistic missile with a range greater than 600 kilometers (373 miles) that is launched from a submarine. An **SLBM launcher** is a submarine able to launch SLBMs. A training model of a missile or a launcher is a full-scale model that is not capable of being launched or launching weapons, and can be distinguished based on external and functional differences visible during inspection.

An **ICBM base** is a location with silo-based ICBM launchers and at least one maintenance facility. A **basing area** is an area reserved for mobile launchers and their fixed shelters. An **ICBM loading facility** is a facility outside of an ICBM base or a test range, where ICBMs for mobile launchers can be loaded and unloaded. A **repair facility** is a facility outside of an ICBM, submarine base or air base used for repair of ICBMs, SLBMs or mobile launchers. A **weapons storage facility** is a facility outside of a base used to store weapons.

A **heavy bomber** is an airplane that can deliver nuclear weapons to a range greater than 8,000 kilometers. Operational bombers are always counted as deployed and carrying a single nuclear warhead. A **test heavy bomber** is not equipped with nuclear armament, and is only used for testing and based at a flight test center.

Appendix 2 — Imagery Resolutions Necessary for Different Elements of Arms Control Analysis

The following table is adapted from an intelligence brief, entitled "High-Resolution Commercial Imagery and Open-Source Information: Implications for Arms Control," published on 13 May 1996 by the Arms Control and Disarmament Agency. It was archived by the Federation of American Scientists and the original document can still be found online in FAS' archives.[56]

Although the table is approximately three decades old and much of the underlying data is even older, it remains extremely useful as a resource for identifying the necessary resolutions needed to analyze nuclear-related elements from space. The 1996 version of the table highlighted those resolutions that were commercially available at that time; the following republication highlights which resolutions are commercially available today at the time of publication.

Imagery resolutions (in meters) necessary for different levels of analysis on targets of interest to arms control.

Red = imagery resolution commercially available in 1996; blue = imagery resolution commercially available in 2025; white = imagery resolution not yet commercially available.

TARGET	DETECTION (a)	GENERAL ID (b)	PRECISE ID (c)	DESCRIPTION (d)	TECHNICAL ANALYSIS (e)
BRIDGES	6	4.5	1.5	1	0.3
RADAR AND RADIO SITES	3	1-1.5	0.3	0.15	0.015
SUPPLY DEPOTS	1.5-3	0.6	0.3	0.03	0.03
AIRFIELD FACILITIES	6	4.5	3	0.3	0.15
ROCKETS AND ARTILLERY	1	0.6	0.15	0.05	0.045
AIRCRAFT	4.5	1.5	1	0.15	0.045
MISSILE SITES (OFFENSIVE AND DEFENSIVE)	3	1.5	0.6	0.3	0.045

a Location of a class of units, objects, or activity of military interest.
b Determination of general target type.
c Discrimination within general target type.
d Size/dimension, configuration/layout, components construction, equipment count, etc.
e Detailed analysis of specific equipment.

Table generally developed from the following sources: US Senate. 1978. Senate Committee on Commerce, Science, and Transportation, NASA Authorization for fiscal year 1978, pp. 1642-1643; McDonnell-Douglas Corporation. 1982. Reconnaissance Handbook, p. 125; Florini, Anne M. 1988. "The Opening Skies: Third-Party Imaging Satellites and US Security," in International Security, Vol. 13, No. 2 (Fall 1988), pp. 91-123.

56 Bureau of Intelligence, Verification and Information Management Intelligence, Arms Control and Disarmament Agency, Technology, and Analysis Division, "High-Resolution Commercial Imagery and Open-Source Information: Implications for Arms Control," 13 May 1996, https://fas.org/irp/offdocs/acda.htm.

TARGET	DETECTION (a)	GENERAL ID (b)	PRECISE ID (c)	DESCRIPTION (d)	TECHNICAL ANALYSIS (e)
SURFACE SHIPS AND SUBMARINES	10-30	4.5-6	0.6-1.5	0.3-1	0.3-0.045
NUCLEAR WEAPONS COMPONENTS	2.5	1.5	0.3	0.03	0.0015
VEHICLES	1.5	0.6	0.3	0.06	0.0045
MINEFIELDS	3-9	6	1	0.03	n/a
PORTS AND HARBORS	30	15	6	3	0.3
RAILROAD YARDS AND SHOPS	15-30	15	6	1.5	0.4
ROADS	10-20	5	1	0.6	0.4
URBAN AREAS	60	30	3-5	1	0.75
TERRAIN	90+	30-90	4.5	1.5	0.75

a Location of a class of units, objects, or activity of military interest.
b Determination of general target type.
c Discrimination within general target type.
d Size/dimension, configuration/layout, components construction, equipment count, etc.
e Detailed analysis of specific equipment.

Table generally developed from the following sources: US Senate. 1978. Senate Committee on Commerce, Science, and Transportation, NASA Authorization for fiscal year 1978, pp. 1642-1643; McDonnell-Douglas Corporation. 1982. Reconnaissance Handbook, p. 125; Florini, Anne M. 1988. “The Opening Skies: Third-Party Imaging Satellites and US Security,” in International Security, Vol. 13, No. 2 (Fall 1988), pp. 91-123.

About the Federation of American Scientists

The Federation of American Scientists is dedicated to democratizing the policymaking process by working with new and expert voices across the science and technology community, helping to develop actionable policies that can improve the lives of all Americans. For more about the Federation of American Scientists, visit **FAS.org.**

About the Program on Science and Global Security

Princeton University's **Program on Science and Global Security (SGS)**, based in the School of Public and International Affairs, conducts scientific, technical and policy research, analysis and outreach to advance national and international policies for a safer and more peaceful world.