Stanton Nuclear Security Fellows Seminar

PANEL 2: Nuclear Detection and Verification

1. Taylor Harvey, Texas A&M

Can a simple directional radiation detector featuring a single scintillator volume and two photomultiplier tubes be a useful tool in nuclear security and nonproliferation applications?

On what issue are you working and why is it important?

The field of nuclear security and nonproliferation seeks to stop the spread of nuclear and radiological weapons by developing institutional, legal, and technical mechanisms that could prevent the misuse of nuclear materials and technology.[1,2] Essential to the nuclear nonproliferation paradigm, especially in safeguards, is the use of measurement technologies to monitor and verify the quantity, identity, and movement of radiation sources. These radiation sources may include special nuclear materials (SNM), medical isotopes, industrial isotopes, sources out of regulatory control, or radioactive waste. Proliferation-relevant sources such as these can be monitored and identified using a variety of gamma and neutron radiation detection techniques[3,4]. A majority of these radiation measurement technologies for nuclear security and nonproliferation are based on destructive assay (DA) and nondestructive assay (NDA) techniques. Both DA and NDA techniques seek to determine the properties of radiation sources through chemical, spectroscopic, or other means to quantify the material for accountancy purposes. This suite of techniques can reveal, often in fine detail, the "what" and "how much" of a material of interest but cannot give information about the location or distribution of a source, if these facts are unknown. A class of radiation detectors, known as directional or imaging detectors, seek to further the international nuclear security technical repertoire by providing spatial information on radiation sources. In many cases, inspectors tasked with analyzing radiation sources may be unable to test the material with the standard DA or NDA techniques due to a variety of limitations. The exact location and distribution of a source may be unknown. Urgent time limitations may not allow for full material analyses. The placement of a source may be physically hard to access, for example, material holdup within the ducts or pipes. Directional detectors may also be of use when the location and identity of radiation sources are limited or completely unknown. Since 2013, 1205 incidents of radiation source smuggling, theft, or loss have been reported.[5] In many cases, these sources are never recovered, largely due to inadequate radiation detection tools that can be used to swiftly locate and secure sources. Directional detectors could additionally be used to locate widely-dispersed radioactive material in post-accident or attack

scenarios by allowing for the quick identification of strong source signals among debris and wreckage. Directional detectors have also been proposed for use in nuclear warhead monitoring during treaty verification.[6] All of these scenarios hint at the usefulness of directional radiation detection systems in creating more certainty when managing sensitive materials or searching for the source of unexplained radiation signals.

Detectors used in the international safeguards regime most commonly gather data from radioactive sources by detecting gamma and/or neutron radiation. Both gamma and neutron radiation detectors can be used in directional systems. Compton cameras with wide fields of view, which can localize and image gamma radiation sources, have been a subject of research for decades.[7] Imaging systems that rely on neutron scatters, including neutron scatter cameras, coded aperture systems, and time projection chambers, are the focus of another fertile area of research.[8-12] Many technical strides have been made in the creation of reliable directional radiation detectors, though many of the current designs are not yet field-deployable or producible on more than a single unit scale due to considerations related to system size and cost. Currently operating scatter camera designs that rely on multiple detector volumes are expensive, heavy, hard to transport, and require data to be processed from many output channels. Attempts to make compact scintillator-based directional radiation detectors have largely required the use of expensive micro-channel plates or similar pixelated fast photodetectors, pushing expenses for a single unit into the range of hundreds of thousands to millions of dollars. Many directional systems that rely on multiple scattering events or high particle fluxes have low imaging efficiencies, resulting in long measurement times to gain directional data.

These facts suggest the need for a simpler and less expensive alternative to traditional imaging radiation detectors that can “point toward” the direction of a radiation source without using complex electronics, distributed detector volume arrangements, or computationally taxing algorithms. A simple, cost-effective, and transportable radiation detector should be able to be constructed using a neutron and gamma-sensitive scintillation volume and two standard photomultiplier tubes (PMTs).

What is the big question that you are seeking to answer about that issue?

Can a simple directional radiation detector featuring a single scintillator volume and two photomultiplier tubes be a useful tool in nuclear security and nonproliferation applications?

How are you going to answer your question? What methods will you use and what evidence or cases will you explore?

Monte Carlo N-Particle (MCNP) modeling of simple directional radiation detectors and the corresponding radiation transport simulations will be carried out to test the validity of the

proposed technical method. Following successful simulation results, a prototype two-PMT, one scintillator volume system will be constructed and tested in measurement scenarios relevant to nuclear security, such as the ability to localize a nearby source in 3-D space. Parameters such as efficiency, time to produce and accurate vector, and distance ranges will be quantified.

What is your answer to the question you are asking? That is, what is your argument or conclusion even if it is still tentative at this point?

Work with the prototype Simplified Neutron Scatter Camera developed at the University of Florida showed the previously unobserved ability to create "guess vectors" that point in the general direction of a neutron source using only the comparison of light arriving at opposing PMTs in coincidence counting mode. The Simplified Neutron Scatter Camera is able to form guess vectors by comparing light pulses arriving at six PMTs to simultaneously pinpoint the average scatter position in the three Cartesian dimensions. In contrast, the proposed two-PMT system would find the average scatter positions in the three dimensions sequentially, requiring the system to perform a series of 90-degree rotations between the measurement in each dimension. Guess vectors can be calculated at multiple detector positions to triangulate source positions using simple trigonometric principles. The reduction from tens of separate photodetectors to just two standard PMTs in the proposed system would significantly reduce the unit costs of a directional detector.

How does your work fit into the existing work on your subject?

The concept for the two-PMT directional detector stemmed from previous work with a neutron scatter camera system. Though dozens of competing designs exist for directional and imaging radiation detectors, none has yet been widely adopted by the international nuclear security and nonproliferation community. This is largely due to the high cost and technical complexity of imaging systems, most of which are constructed with nuclear security scenarios in mind. This project seeks to build on the technical foundations of previous directional and imaging systems with the end goal of fulfilling an unexplored niche in the nuclear security regime.

What policy implications flow from your work? What concrete recommendations can you offer to policymakers?

The reliable monitoring of radiation sources is integral to the ultimate goals of nuclear security and non-proliferation. The monitoring of such material is more successful when more information can be gained from instruments without large capital investments. Spatial information about sources from directional and imaging detectors could be useful in source search scenarios, smuggling and theft prevention, inventory monitoring, safeguards inspections, treaty verifications, source transportation, or in the aftermath of nuclear accidents

or attacks. Detectors used to provide spatial source information in these scenarios need to be widely available and transportable between relevant parties, indicating the need for functional, small, low-cost, and easy-to-operate systems.

What do you think is the weakest or most vulnerable aspect of your study and what sort of feedback would be most useful to you?

It is still uncertain whether or not the average scatter interaction/guess vector technique will be successful in complex measurement scenarios that mimic real-world environments. Scenarios with high background radiation levels and many close-together sources could prove confounding for a detector of the described design. Technical feedback that would be helpful could be from experts on scintillation materials and photoelectronics that could provide insights on the best material selection for such a detector. Policy feedback could focus on the criteria for uptake of new instruments by international security and nonproliferation organizations so that the design of the detector can be better tailored to concrete policy-related needs.

References

1. International Atomic Energy Agency. Basics of IAEA Safeguards, available at: https://www.iaea.org/topics/basics-of-iaea-safeguards. Accessed June 16, 2021.

2. Doyle JE. *Nuclear Safeguards, Security, and Nonproliferation*, Burlington, MA: Butterworth-Heinmann, 2008.

3. United States Nuclear Regulatory Commission. Special Nuclear Material, available at: www.nrc.gov/materials/sp-nucmaterials.html. Accessed June 7, 2019.

4. Runkle RC, Bernstein A, and Vanier PE. 2010. Securing Special Nuclear Material: Recent Advances in Neutron Detection and Their Role in Nonproliferation. *Journal of Applied Physics,* Vol. 108, No.11, 11101. doi.org/10.1063/1.3503495

5. The cns global incidents and trafficking database. 2020. Nuclear Threat Initiative, available at: www.nti.org/analysis/articles/cns-global-incidents-and-trafficking-database/. Accessed September 13, 2021.

6. Harvey T, Bachner K, Enqvist A. 2020. Applications and deployment of neutron scatter cameras in nuclear safeguards scenarios. *Journal of Nuclear Material Management*, Vol. 48, No. 2, pp. 6 - 23.

7. Xu D, He Z, Lehner CE, Zhang F. 2004. 4-pi Compton Imaging with Single 3D Position Sensitive CdZnTe Detector. *Proc. SPIE 5540, Hard X-Ray and Gamma-Ray Detector Physics VI*. doi.org/10.1117/12.563905

8. Mascarenhas N, Brennan J, Krenz K, et al. 2006. Development of a Neutron Scatter Camera for Fission Neutrons. *2006 IEEE Nuclear Science Symposium Conference Record.*

9. Goldsmith JE, Gerling MD, Brennan JS. 2016. A compact neutron scatter camera for field deployment, *Review of Scientific Instruments,* Vol. 87.

10. Weinfurther K, Mattingly J, Brubaker E, Steele J. 2018. Model-Based Design Evaluation of a Compact, High-Efficiency Neutron Scatter Camera. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 883, pp. 115-135.

11. Marleau, P, Brennan, J, Brubaker, E, Steele, J. 2010. Results from the coded aperture neutron imaging system, *IEEE Nuclear Science Symposium & Medical Imaging Conference.*

12. Bowden NS, Heffner M, Carosi G, et al. 2010. Directional Fast Neutron Detection Using a Time Projection Chamber. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 624, pp. 153-161.

2. Mailys Mangin, BCSIA

Role of the IAEA's International Expertise in the Negotiations to Regulate Iran's Nuclear Activities

An important nuclear security issue. My work focuses on the role of the IAEA's international expertise in the negotiations to regulate Iran's nuclear activities. Most specifically, I am interested in exploring how the IAEA expertise has been used and misused by member-states to satisfy specific political goals and what consequences such politicization bears on the effectiveness of nuclear nonproliferation policies.

The IAEA is a technical organization, whose mandate in terms of nuclear verification is in principle a process relatively independent of political games. Yet, the years of negotiations around the Iranian "file" have generated varying degrees and forms of interest in the IAEA's expertise. In particular, there is a marked difference in the way the IAEA's expertise is mobilized (particularly with regard to the emphasis placed on the outstanding issues and the possible military dimension of Iran's activities) between the period 2003-2013 and the period 2013-2018, without it being possible to explain this transformation on the basis of a transformation of Iran's activities themselves (neither in the sense of an improvement nor a deterioration in terms of nonproliferation records). The forms of this interest, *i.e.* the importance given to the Agency's expert reports, and the way in which these reports are mobilized in the political jousts, seem to vary less as a function of the Iranian activities themselves than as a function of the international structures of the negotiations.

What explains this somewhat counter-intuitive observation?

The objective here is to focus on policies to prevent nuclear proliferation through the prism of the tactical uses of expertise in international political competition. Interest in the tactical uses of international expertise (and thus in the interpretative activity of the context of action by the actors who take part in it) makes it possible to study the processes of politicization of IAEA expertise in which the Agency has found itself, particularly because of the US domestic political stakes represented by the Iranian nuclear issue. More importantly, our research reveals how such a process has undermined the IAEA's ability to optimally implement its nuclear verification activities, and points the way forward to remedy this development.

Despite the professionalism and high competence of international civil servants, international institutions can participate in spite of their will in logics with detrimental effects to nonproliferation goals and international security.

A big question to be resolved. *How can we explain the phenomenon of politicization of the IAEA's expertise that has been observed since 2002? And what effects has this phenomenon had on the Agency's performance in terms of the implementation of its verification activities?* This phenomenon of politicization appears all the more intriguing since the technicization of issues has often had the reputation in political science of being a vector of depoliticization. This paradox opens the way to a more general questioning of the phenomenon of international politicization and the wider tactical interdependence that links certain spaces of national political competition to certain spaces of inter-state competition. Is there such a tactical interdependence between certain national political games and interstate political games? If so, how is this interdependence structured, *i.e.* what are the constraints that weigh on the calculations and actions of actors, independent of their intentions? How does the transformation of contemporary media dynamics (acceleration, fragmentation, deregulation, hyper-pluralization) contribute to modify this structuring? What are the stakes and risks that this represents for international security?

How I am answering the question: methods and evidence. In response, I am particularly interested in how political competition in the United States in the broadest sense (*i.e.* taking into account political-bureaucratic, political and media competition) affects the interstate competition for the regulation of Iran's nuclear activities. I am specifically interested in the investment of the IAEA's international expertise on outstanding issues and the possible military dimension between 2007 and 2015. In terms of method, I analyze the tactical activity (not necessarily conscious and reflexive) of actors in the US political game. In other words, I investigate how actors interpret the logic of the situation in which they find themselves, how they anticipate and calculate the possible, probable, or playable moves, and the resulting sequences of exchanges of moves. To investigate this tactical activity, I use different types of materials: interviews with actors (parliamentarians, diplomats, experts, international civil servants, journalists, ministerial officials), an analysis of the press (the proposed coverage of an event and the tactical elements exposed as to the behaviors of the various actors), testimonies of actors, Wikileaks telegrams—which are important documentary sources as to the tactical activity of the diplomatic corps—and national archives when they are accessible. Part of my work will also include an evaluation of the relevance of considering—in the framework of this analysis—the new media that can constitute certain social networks and the militant activities that take place there. The cross-referencing of these different sources allows me to reconstruct the interpretative frameworks of the political competition over the regulation of Iran's nuclear activities, and to highlight the fluctuation in the value of certain resources, in particular recourse to international law, international expertise and, more broadly, to the various resources provided by international institutions. Finally, this method allows me to show some

correlations between these variations in the value of resources and variations in the logics of the situations in which the actors are caught.

Answer to the question: argument and conclusion. My research proposes a structural explanation for the politicization of the IAEA. I account for this phenomenon by revealing the specific constraint that US political competition (*i.e.* the game of competition and bargaining, not the US as a rational unitary actor), due to its dominant position, exerts on international negotiations and the way in which the institutional resources of the IAEA are mobilized in this framework. By analyzing the production processes of US foreign policy from the logics of competition between the actors who participate in its production, I show that the politicization of the IAEA is the product of a reorientation of non-proliferation policies from an arms control logic to an interventionist logic (containment and regime change in Iran). In other words, the fluctuation in the value of the IAEA's expertise is the product of international politicization dynamics that are partly rooted in the political-bureaucratic competition of the world's leading power. This politicization stems from the mobilization by a part of the American political field of the IAEA's international expertise to support foreign policy objectives towards Iran that go beyond the objectives of placing Iranian nuclear activities under international scrutiny.

State of the art.

- ***Why my answer is superior to existing arguments:*** This research provides a better explanation than the indigenous explanations, one of the most popular of which is to blame the former IAEA's Director General Mr. Elbaradei. I place the explanation at the level of international social structures and the collective action of actors rather than the personality of an individual. This does not mean that individuals do not have a role, or an agency, but that this role must be understood from the positions that the actors occupy in relation to each other. The debate in IR has often led to the opposition of strong states to IOs in the framework of a zero-sum game between the search for a "national interest" and the search for a supranational common good. Some works show that the possible failure of an IO to move towards the production of this supranational common good is due to certain organizational pathologies. My model aims to go beyond this false opposition between states and IOs, as well as to go beyond the false opposition between social structures and social interactions to show how these two dimensions of social reality work together across national borders.
- ***How my work improves the general understanding of this issue:*** I show how some IOs can find themselves caught up in battles for control of information, and competitive strategic investment dynamics of the resources they provide. My conceptualization explains better interactions that can exists between states and OIs: it explains from a single model a greater number of behaviors and sheds light on a greater number of

implications in terms of international security. For example, this model can explain both the practices of instrumentalization of expertise, the constraints imposed on these practices, and the practices of resistance or opposition that these practices give rise to (these two terms—resistance and opposition—do not have any moral dimensions here, but designate an opposite tactical movement). It also demonstrates that international institutions are not by nature vectors of peace but that they can be caught up in belligerent dynamics just as much as the states themselves. It is important to increase our knowledge of these dynamics when it is conceivable to imagine a future in which such dynamics could develop around financial, health or environmental issues not directly related to nuclear questions, but which could present a risk of escalation toward a world conflict.

- ***What is my most important contribution:*** My main contribution is to show why the IAEA's technical independence is important in the fight against nuclear proliferation, and how it can be strengthened. Independence is not only a matter of institutional arrangements but also of capabilities to prevent or mitigate detrimental effects of international politicization processes. My work aims at highlight ways in which the IAEA can be better insulated from the politicization and crises that occur in national contexts.

Policy implications and concrete recommendations to policy makers.

My recommendations go in three directions that I have yet to develop in more detail:

1/ The United States may be better served by preserving the IAEA as an apolitical body rather than pushing the IAEA to perform a more political role. The United States should not try to rely on political pressure to weigh on the content of IAEA's special reports on Iran; or risk weakening the IAEA's overall verification efforts, i.e. weakening the Agency's impact in Iran but also weakening the Agency's secretariat's control over the strengthening and evaluation of its verification methodologies.

2/ The IAEA should maximize its autonomy regarding nuclear verification expertise by resisting political demands that are not justified on technical grounds, the validity of which can be independently verified by IAEA safeguards staff. The IAEA should strengthen the autonomy of its analytical capabilities, and insulate their assessment and development from inter-state political competition, or from the political objectives of individual member states.

3/ As the history of nuclear negotiations with Iran demonstrates, neither the European powers nor the IAEA have the ability to reach an agreement with Iran without the support of the United States. It will also be difficult for the IAEA to fulfill its role as an investigator of outstanding issues without a stable political agreement between Iran and the United States. As part of a hypothetical new agreement between Iran and the US, the IAEA should focus on ensuring the

absence of undeclared nuclear activities in Iran, and the sustainability of that assurance, rather than on the issue of weaponization.

Weakest aspect of the study and type of feedback needed. My work is in the need to further refine the methodological setup. My objective is to refine the methodology that I have developed in the framework of my doctoral thesis. This work will also allow me to gain in finesse in terms of policy recommendations. I would like feedback and help in strengthening the policy angle to my proposal, as well on how to make my policy recommendations more relevant to a decision maker. I would also welcome feedback on how placing this study in the current policy debate regarding Iran, the way of building my puzzle, and recommendations on the types of materials that can be mobilized in a complementary way to those mentioned.

3. Tamara Patton, MIT SSP

Information and Blind Spots: Remote-sensing technology and contending arguments for nuclear force posture, arms control, and modernization

Topic and question. The rapid pace of remote-sensing technology advancement is generating new forms of information and uncertainty. Together with the emergence of new types of nuclear weapons and delivery systems, these developments have the potential to affect perceptions about nuclear security and stability, the future of nuclear force planning, and the directing of nuclear policy toward cooperation or new and potentially destabilizing forms of competition. My research therefore works to answer the question: how do advancements in remote-sensing technologies that alter the nature of information and uncertainty affect decisions about nuclear force posture and arms control in the context of restraint and cooperation versus arms build-ups and competition?

My dissertation work partially answers this question through an analysis of the use of satellite-imaging technology information and blind spots within nuclear arms control debates in the United States. Comparative case studies look at domestic debates under the Strategic Arms Limitation Talks (SALT) – including the SALT I Interim Agreement, the Anti-Ballistic Missile Treaty, and SALT II – the Strategic Arms Reduction Treaty (START I), and the Intermediate-Range Nuclear Forces (INF) Treaty. The research shows that while satellite-use contributed to the rise of arms control as a policy approach, the information and blind spots stemming from the high-resolution satellites fielded by the United States related to Soviet nuclear weapon developments were often leveraged to pursue more diverse and expansive U.S. modernization efforts, including to retain new and sometimes destabilizing weapon programs when their banning or cancellation was a possibility under debate. New information and remaining blind spots from satellites were thus co-constitutive in arms control limits (rather than bans), but also in qualitative arms build ups.

Project and Methods. As a postdoctoral fellow, I will build on this work and go beyond satellite imagery to assess the roles and impact on nuclear force posture and arms control of the broader array of remote-sensing technologies that comprise so-called national technical means of verification. This primarily includes a variety of sensing technologies involved in measurement and signatures intelligence, including radar, acoustic and other environmental sensing instruments. It also involves the integrated role of artificial intelligence in automating processes across these areas. Using recently declassified U.S. archival resources, I will assess these technologies and their various influences on the shaping of debates about nuclear force posture and arms control. I will also explore the generality of my findings on the United States by conducting shadow case studies on Russia and China, focusing on how known and estimated

remote-sensing and intelligence capabilities might affect nuclear force planning and decision-making within the unique institutional settings of each state. I intend to focus my time during the fellowship on publishing this work as a refereed journal article, and I will submit a book proposal geared to feature the historical nuances of the role of intelligence and verification technology in the politics and strategy of nuclear force posture and arms control.

Argument and contribution to existing work. This research adds to the literature new understandings of the relationship between information, uncertainty, and nuclear policy. The conventional wisdom about nuclear arms control has held that the improvement in information quality provided by satellites should increase the perceived value of cooperation with an adversary and of arms control characterized by mutual restraint as a policy choice. This argument has been made broadly within the context of international cooperation.[1] It has also been made specifically in the context of arms control.[2] This general understanding is also reflected in historical accounts of satellite technology and arms control.[3]

Next to this, the security studies literature has offered several competing explanations for the persistence of decisions to choose modernization initiatives that later result in qualitative competition over the alternatives of bans and mutual restraint. Some explanations, anchored in the realist school of international relations, have focused on external factors and the balance of power.[4] Some have focused on internal factors, emphasizing the role of bureaucratic politics and criticizing external explanations as an exercise in oversimplification that reduces complex dynamics to an action-reaction phenomenon.[5] Others have combined external and internal explanations to focus on the process of technological innovation and coalition-building.[6]

My research adds to the literature by showing that the advancement and use of precise remote-sensing technologies has so far contributed to the shaping of nuclear arms control to

---

[1] See, for example, Keohane, Robert O. "The Demand for International Regimes." *International Organization* 36, no. 2 (1982): 345. See also pp. 337-338 for how information sharing is expected to support cooperative outcomes.
[2] Kenneth W. Abbott, "Trust but Verify: The Production of Information in Arms Control Treaties and Other International Agreements," Cornell International Law Journal 26, no. 1 (Winter 1993): 4; Downs, George, David Rocke, and Randolph Siverson. "Arms Races and Cooperation." *World Politics* 38, no. 1 (October 1985): 138-139.
[3] See, for example, arms control histories such as Stuart Croft, *Strategies of Arms Control: A History and Typology*. Manchester: Manchester University Press, 1996, p. 59, and Patrick Morgan's argument about verification in the context of his chapter on "Elements of a General Theory of Arms Control," in Arms Control: History, Theory, and Policy, Volume 1, etd. Robert E. Williams Jr. and Paul R. Viotti, Santa Barbara: Praeger Security International, 2012, p. 29. Other examples include technological histories such as Burrows, William E., *Deep Black: Space Espionage and National Security*. New York: Random House, 1986, pp. viii-ix. Day, Dwayne A., John M. Logsdon, and Brian Latell. *Eye In the Sky: The Story of the Corona Spy Satellites.* Washington, D.C.: Smithsonian Institution Press, 1998.
[4] Kenneth N. Waltz, *Theory of International Politics*, Reading, Mass.: Addison-Wesley Pub. Co., 1979, p. 69.
[5] Allison, Graham and Frederic Morris, "Exploring the Determinants of Military Weapons," Daedalus 104 (Summer 1975):103.
[6] Evangelista, Matthew, *Innovation and the Arms Race: How the United States and the Soviet Union Develop New Military Technologies*. Ithaca: Cornell University Press, 1988, p. ix.

focus on limits over bans and to strengthening the case for modernization and qualitative build-ups. It shows how both new information and uncertainty were instrumental to this process. New, precise information is used to add depth and nuance to arguments for modernization under the heading of seeking strategic stability rather than overt arms-racing. At the same time, as a state acquires more information about an adversary through remote-sensing, the information it does not have becomes more powerful. Remaining blind spots are used to make the case for new weapons with stories of worst-case scenarios of covert research, development, or deployment efforts by an adversary. Unlike existing explanations that focus on "windows of opportunity" for nuclear innovation and modernization, my work shows that more important are the persistent political narratives built up over time, formed and exercised in spaces like the National Security Council, Congressional appropriations debates, and in the arms control epistemic community. Actors in these spaces utilize information and uncertainty from remote-sensing technologies to disseminate the understanding that nuclear modernization is essential on the basis of threats to deterrence, the pursuit of parity, and the importance of strategic stability. The result so far has been a transformed realization of arms control from the vision of its originators: one that is consistently and increasingly characterized by qualitative build-up, including in destabilizing weapon areas, rather than restraint.

Policy implications. Today the landscape of remote-sensing technology has changed, particularly with the expansion and advancement of capabilities within the commercial sector. High-resolution imagery is now widely and publicly available. Temporal capabilities are advancing with commercial deployments of large constellations of capable small satellites. In addition to optical cameras, these constellations are including the use of synthetic aperture radar, a technology that can allow an imagery analyst to better bridge the temporal blind spot through all-weather and night-capture capabilities, as well as through new methods of change detection. Signals and environmental sensing advances add further qualitative dimension to imagery information. On top of these collection technologies, advances related to artificial intelligence in the context of data analysis will also present opportunities for verification together with challenges to stability by approaching real-time intelligence in ways that are still rife with blind spots.

By connecting historical analysis to current political developments and technology advancements, the research will speak to contemporary policy debates about nuclear force posture and arms control. I will address how the integration of small satellite constellation imagery, signals and environmental sensing, and artificial intelligence is likely to resolve some perceived verification challenges related to small or hard-to-track weapons or components while at the same time deepening avenues of competition, increasing the risk of build-ups in new areas, and introducing potentially severe strategic stability concerns. I will highlight the

patterns that emerge in arguments and debates over the pursuit of new types of nuclear weapons that are illustrative of the constructed and subjective nature of nuclear force posture requirements.

Initial policy recommendations that emerge from this work include sensitizing policymakers and the public to the historical tendency to treat new information about adversary nuclear force advances together with intelligence uncertainty stemming from technological blind spots as justification for pursuing new nuclear weapon programs within U.S. appropriations debates. Within this context, a more balanced approach would include ensuring that the policy option of a verified, mutual ban on a potentially destabilizing type of weapon system is adequately detailed and represented at the Congressional level next to contending options to develop and compete in new areas. In addition to representing historical cases, the work will therefore offer details about what such mutual verification measures would look like by juxtaposing contemporary remote-sensing technology developments with active areas of research and development related to nuclear weapons, including nuclear hypersonic cruise missiles, nuclear torpedoes, and missile defense.

Feedback. My research has thus far focused on the United States based on relevant scholarship that the emergence and embedding of many ideas about nuclear security and arms control were primarily driven by domestic factors.[7] While I plan to retain a U.S. focus for these reasons, analysis at the domestic level presents clear limits for the analysis of international cooperation and competition. As I plan to address this deficiency by extending the analysis through shadow case studies on Russia and China, I would particularly welcome any advice about appropriately translating this research framework to these different institutional settings and perspectives.

[7] See for example: Adler, Emanuel. "The Emergence of Cooperation: National Epistemic Communities and the International Evolution of the Idea of Nuclear Arms Control." *International Organization* 46, no. 1 (1992): 101-45; Evangelista, Matthew, *Innovation and the Arms Race: How the United States and the Soviet Union Develop New Military Technologies*. Ithaca: Cornell University Press, 1988, p. 52.