Introduction

There are long-standing concerns that the vulnerability of nuclear forces to counterforce attack and missile defenses could increase the risk of nuclear escalation. Nuclear-armed states have sought to minimize this vulnerability by securing their arsenals against a preemptive attack—including, in the cases of China, Russia, and North Korea, by the deployment of mobile ground-launched missiles. However, a spate of technological developments in recent decades—such as improvement in missile accuracy and the development of ever more sophisticated remote-sensing technologies—have spurred a debate about whether nuclear arsenals will remain survivable.

There is little consensus on the likely outcome of this competition. One group holds that counterforce technologies have been rapidly advancing and will continue to do so, so that only the largest and most sophisticated arsenals will remain survivable.[1] Such pessimists argue that the competition between counterforce and survivability is inherently biased in favor of the offense. The second group argues that technological development also aids the defense in bringing countermeasures to bear, so that, with sensible investments, even small arsenals can be kept survivable.[2] Partially because of these different understandings, the two groups offer very different policy prescriptions on whether the United States should seek a damage limitation capability *vis-à-vis* its adversaries.

Critiquing the debate

The critical debate about the ability of remote-sensing systems—space-based radar, most importantly—to track mobile missiles has some significant flaws. At the root of most of these flaws is the lack of a framework for understanding the process of tracking mobile missiles, how the attacker forms beliefs about target positions based on remote-sensing data, and how those beliefs evolve over time as new information is gathered and old information grows stale. This deficiency manifests in an underappreciation of the scale of the challenge of tracking.

An attacker would want to destroy all of an adversary's weapons nearly simultaneously, so tracking needs to be conceptualized as a network of sensors tracking an entire force of mobile missiles—not as a single sensor against a single target. As mobile systems can hide, all these targets are unlikely to be detectable when the decision over whether to launch an attack is being made. Tracking, therefore, must take place over the course of days and even weeks before a potential attack under varying conditions of daylight and weather.

The existing debate also fails to delve deeply enough into the limitations of remote-sensing technologies, especially the conditions under which they can operate. Space-based radar, for example, operates in three different modes, each with its own limitations. One mode, for example, can detect only moving targets, while another has a limited field-of-view. A failure to understand these limitations, and the constraints they place on sensors, has led to overestimates of sensor performance.[3] Without an appreciation of the

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[1] Keir A. Lieber and Daryl G. Press, "The new era of counterforce: Technological change and the future of nuclear deterrence," *International Security* 41.4 (2017): 9-49; and Austin Long and Brendan Rittenhouse Green, "Stalking the secure second strike: Intelligence, counterforce, and nuclear strategy," *Journal of Strategic Studies* 38.1-2 (2015): 38-73.
[2] Charles L. Glaser and Steve Fetter, "Should the United States reject MAD? Damage limitation and U.S. nuclear strategy toward China," *International Security* 41.1 (2016): 49-98.
[3] Lieber and Press, "The new era of counterforce."

limitations of remote-sensing technologies, there has been no comprehensive description of how and whether an ensemble of remote sensing technologies could work in tandem to track targets over time and under all conditions.

Proposed approach

The proposed work will rectify these and other deficiencies in the current debate by providing a technically supported conception of tracking and apply it to an actively debated question with great political import: can remote-sensing systems, including space-based radar, persistently track an entire force of road-mobile missiles simultaneously? This work will address some of the poorly supported arguments in the debate that have arisen from the black-boxing of tracking and advance the policy debate about the wisdom of the United States' pursuing a damage-limitation capability. It will also provide a powerful tool for analyzing the impact of current and future remote-sensing systems.

Drawing on my background, I will produce a technically supported and policy-informed analysis that contributes four crucial insights:

1. A clear, qualitative description of tracking and how it shapes the most effective strategies that the offense and defense can adopt, and their interactions. In the description of tracking that will be developed, the attacker uses its remote-sensing capabilities to detect targets or, if they are not detected, to rule out the possibility that they have moved along certain routes. Its beliefs about the locations of those targets can be represented mathematically as a probability distribution. The attacker aims to deploy its remote-sensing systems to minimize the uncertainty around the location of the targets as much as possible. Meanwhile, the defender aims to anticipate this strategy and hence operate its mobile systems in a way that maximizes the attacker's uncertainty as much as possible. The result of this competition is that, in practice, the defender only moves its mobile systems when it is advantageous to do so—in particular during gaps in coverage, when no remote sensor is available—which has the effect of steadily growing the attacker's uncertainty.

2. An evaluation of the ability of existing remote-sensing capabilities to track both small and large numbers of mobile missiles. Currently deployed remote-sensing technologies, such as optical imaging satellites and unattended ground sensors, which are much discussed in the literature, will be surveyed to determine their capabilities and limitations. This analysis will determine which technologies can complement one another and which are redundant. It will also identify the likely gaps that could forestall tracking. Some gaps may result from insufficient deployments, which could (with sufficient resources) be overcome by fielding new sensors. Gaps could also result, however, from unpermissive conditions, such as bad weather or lack of daylight, in which case closing them would require the deployment of a complementary system capable of operating through those conditions.

3. A quantitative analysis of the conditions under which emerging technologies—space-based radar, in particular—could be used to track mobile missiles. Initial analysis suggests nighttime and clouds create crucial gaps in current tracking capabilities. Space-based radar has, rightly, been identified in the literature as the most promising way to close these gaps. Based on an analysis of the basic physical limits of radar systems deployed in optimum satellite orbits, I will estimate the minimum number of idealized radar systems needed to close the gaps in coverage for mobile missiles in Russia, China, and North Korea. Focusing on the constraints imposed by physics avoids the need to find out classified information about radar design and leads to a conservative result that likely overstates the effectiveness of real space-based radars.

4. A discussion of the conditions under which countermeasures could be decisive in defeating tracking. If a technology is uniquely capable of closing a gap or if it is the only system deployed in sufficient numbers to do so, then countering it would re-open the gap. As such, these critical technologies or systems represent potential single point failures for tracking. If deployed in sufficient numbers, space-based radars would represent one of these critical technologies, so potential countermeasures will be carefully considered. Preliminary work has identified a number of countermeasures, such as jammers and simple physical decoys, that could defeat radar-tracking outright—though further work is needed to access whether they are cost-effective and technologically accessible to potential U.S. adversaries.

Tentative findings and implications

Through preliminary research, I have identified some tentative findings that will be evaluated with further research and tested at a review workshop I will convene in Washington, DC.

First, the effect of regular coverage gaps of tens of minutes has been downplayed in the debate, with the consequence that some authors suggest, likely incorrectly, that mobile systems could be tracked with a relatively small number of satellites.[4] In reality, since satellite positions can be predicted in advance, each gap would provide mobile systems with the opportunity to move tens of kilometers without risk of detection. If there are repeated gaps in coverage, the defender can choose to move only in the gaps and hide in between. The targets thus become "lost" to the attacker, and stay lost for as long as the system can hide. Even small gaps in coverage can therefore completely undermine the attacker's ability to track mobile systems over time.

Second, space-based radar systems would be pivotal to tracking mobile missiles, as they are uniquely capable of providing wide-area monitoring to close gaps in coverage at night and through clouds. Other systems, such as optical satellites, could not contribute to tracking during these times, so a space-based radar system would need to be capable of tracking a force of mobile missiles by itself. Dozens of space-based radar satellites would likely be needed to provide sufficient coverage. Further modeling of satellite orbits is necessary to obtain specific estimates, but a constellation of 21 satellites analyzed in the current literature was found to have significant gaps.[5] As a result, small constellations of space-based radars, including those currently in orbit, having little-to-no tracking ability.

Third, since radar systems would contribute a unique capability to tracking, they would represent a potential single point of failure. Countermeasures against space-based radar systems—if they exist and are technologically accessible and affordable to the defender—would, therefore, be decisive in defeating tracking. Historically, countermeasures have not always been accessible. For example, in the case of the long-range passive sonar tracking of ballistic missile submarines, countermeasures, such as dampening motor vibrations, existed but were difficult to deploy, resulting in an extended period of vulnerability.[6] By contrast, the countermeasures to space-based radar, such as jammers and decoys, are inexpensive or are already extant and preliminary analysis suggests they are likely to be effective at defeating tracking. If

[4] *Ibid.*
[5] *Ibid.*
[6] Owen R. Cote, Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, RI: Naval War College, 2003).

further analysis bears out this conclusion, space-based radar is unlikely to undermine the survivability of mobile missiles.

Taken together, these preliminary findings highlight that survivability pessimists have overestimated the ability of plausible remote sensing systems to track mobile missiles and have underestimated the potential decisiveness of countermeasures (while the optimists have failed to identify these weaknesses with the pessimists' arguments). These results are tentative and require further research to confirm but represent an important argument in favor of the United States showing restraint and not pursuing damage-limitation capabilities.

Outputs

The proposed analysis would be written up as an academic article, my preferred publication venue being a top-tier international relations journal. In addition, I will engage with and brief my findings and recommendations to decisionmakers and their advisors within the U.S. government—the Pentagon and National Security Council, in particular. I will also communicate key findings to a broader audience through op-eds and social media, including highlighting the work through channels which have a broad reach. To aid in outreach to both policy makers and experts, I will produce a short animation that visually explains the challenges of tracking mobile missiles. I also aim to present my research at research institutions in the Bay Area.