ON THE RADAR

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Remote Radiation Detection by Electromagnetic Air Breakdown

A Technology Primer

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TYPE Sensor	**CHARACTERISTICS** Speed, Vantage	**RISK FACTORS** Predictive, Preemptive
DOMAIN Air, Land, Sea	**COUNTRY** United States, Russia, China	

Introduction

Emerging radiation sensing techniques that measure changes in the dielectric properties of air may offer ultra-long-range radiation detection capabilities with potential applications in counterforce targeting and counterproliferation. These radiation detection systems use the reflection of high-intensity radiofrequency (RF) or infrared (IR) pulses to probe the concentration of charged species produced by radiation-induced ionization in air.[1] The measurement technique is purely optical, and therefore requires no detection hardware near the radiation source. Although this family of techniques is in its infancy, lab-scale systems have been shown to be sensitive to radiation fields similar to what one would find in the immediate vicinity of a nuclear warhead or near a UF_6 storage cylinder.[2,3] With sufficient development, this technology could be used to hunt for nuclear warheads on dual-capable systems, determine the location of uranium handling facilities, and find illicit reprocessing facilities without the need for detectors deployed on the ground.

[1]Joshua Isaacs, Chenlong Miao, and Phillip Sprangle, "Remote monostatic detection of radioactive material by laser-induced breakdown," *Physics of plasmas* 23, no. 3 (2016): 033507.

[2] Dongsung Kim, Dongho Yu, Ashwini Sawant, Mun Seok Choe, Ingeun Lee, Sung Gug Kim, and EunMi Choi, "Remote detection of radioactive material using high-power pulsed electromagnetic radiation." *Nature communications* 8 (2017): 15394.

[3] Steve Fetter, Thomas B. Cochran, Lee Grodzins, Harvey L. Lynch, and Martin S. Zucker, "Gamma-ray measurements of a Soviet cruise-missile warhead," *Science* 248, no. 4957 (1990): 828-834.

Note: Dose-rate on contact with a DUF_6 tank assumed to be ~5mR/hr (based on measurements taken on a DUF_6 –filled 12B cylinder at ORNL using a H3D Polaris detector, unpublished data).

Theory of Operation

The standoff radiation-sensing platform relies on the detection of byproducts produced when ionizing radiation deposits energy in the air surrounding the source. While the details of each approach differ, the general concept is to use a source of radio waves (RF) or infrared photons (IR) to excite one of the radical species produced in air by ionizing radiation. This excitation produces a population of free electrons that can be used to seed an avalanche breakdown process. This avalanche process is created by an intense electromagnetic field generated by a secondary RF or laser sourcethat generates a small volume of plasma, the density of which evolves to reach a steady state in under a nanosecond. The initial electron population can be inferred by monitoring the time-evolution of the reflected power from the plasma. This value is directly proportional to the density of the radical species generated by the ionizing radiation and therefore to the flux of ionizing radiation in the volume.[4]

Calculations performed by Kim et. al show that this method is limited by atmospheric turbulence, which diffuses the beam used to induce dielectric breakdown. Assuming a one-meter dish transmitting 30kW of 95GHz RF to induce breakdown, the authors predict a standoff distance of up 1km. However, this value may be a massive underestimate, as the authors found that their method was approximately 100 times as sensitive as predicted by simulation.[5]

Operational Theater

The requirement for line-of-sight and the range limitations imposed by atmospheric instability (kilometers to tens of kilometers) suggests that this system is likely best deployed in aerial surveillance platforms. Surface systems (ground or boat) could also benefit from this capability, although increased turbulence because of ground features would likely limit the effective range.

The ability to quantify radiation sources over extremely long ranges could provide dramatically enhanced surveillance of nuclear weapons platforms, weapons manufacturing facilities, enrichment facilities, reprocessing plants, and weapon storage depots. If coupled with information on vehicle movement from optical observation platforms, this technology could also serve as a powerful means of finding road or rail-mobile nuclear weapons platforms, even when decoys and optical vehicle camouflage are in use. Sea-based versions of this system could be used to assess the weapons load-outs of aircraft and nearby vessels. Systems on land could be used to covertly find enrichment facilities, uranium mines, and reprocessing plants without the need to enter restricted-access areas.

State of Play

This technology is currently functional at the lab scale in both IR-laser and focused-RF form. Due to the relative ubiquity of the lasers used in the proposed IR systems, this technique is not particularly difficult to replicate. The RF-based system is likewise not difficult to replicate using the powerful ~100GHz gyrotron RF sources used by the fusion research community.

Countries with active LIBS research programs, like Russia, the United States, and China, may have a significant advantage in the development of this technology.

[4] See Yurii P. Raizer, "Reviews of Topical Problems: Breakdown and Heating of Gases Under the Influence of a Laser Beam," *Soviet Physics Uspekhi* 8 (1966): 650–673; Alexander D. McDonald, "Microwave breakdown in gases." (1966); and Robert M. Schwartz, Daniel Woodbury, Joshua Isaacs, Phillip Sprangle, and Howard M. Milchberg, "Remote detection of radioactive material using mid-IR laser-driven electron avalanche," *Science Advances* 5, no. 3 (2019).

[5] Dongsun Kim, et al.

The optics/RF design required to compensate for atmospheric turbulence to increase range to the tens-of-kilometers level poses a significant challenge that will require substantial R&D expenditure to fully address.

Because of the similarity of the IR-based indirect sensing approach to laser-induced breakdown spectroscopy (LIBS), countries with active LIBS research programs may have a significant advantage in the development of this technology. Both Russia and China maintain robust LIBS research programs, suggesting that both states would likely not lag behind the United States in developing IR-based indirect-detection schemes if sufficiently motivated to do so.

The RF approach borrows significantly from technologies used by the fusion community, suggesting that countries with large fusion projects would benefit from a significant advantage in development. China, and to a lesser extent, Russia, maintain magnetic confinement fusion research projects that would help them to rapidly develop this technology.

Indirect-detection approaches are vulnerable to a variety of countermeasures, especially if deployed on an aircraft that is vulnerable to adversary anti-access/area denial systems. Although a space-based platform would provide significant advantages (by reducing perceived intrusiveness and lowering chances of detection), it is unclear if such systems are possible. Though indirect-detection systems have not been implemented in the battle space yet, these systems do not require particularly exotic hardware, and therefore are not anticipated to be expensive in comparison to existing strategic SA technologies. In contrast, systems that fulfill a similar role in observing suspected mining, enrichment, weapon manufacturing, and weapon storage facilities often require exotic optics and space-launch capabilities to properly deploy.

Strategic Situational Awareness Impacts

The main situational awareness implications of this technology are best classified as improvements to speed and vantage.[6] Fundamentally, the technology would enable platforms previously restricted to sensing in the infrared and visible bands to carry out surface radiation surveys. This primarily represents an improvement in vantage. Additionally, the ability to survey suspected nuclear facilities without the need to deploy hardware on the ground in denied areas creates an improvement in speed. Enhancements in precision also follow from the application of this technology, as radiation data can clarify otherwise ambiguous data.

Front-end facilities such as mines and UF^6 production plants would require limited sensitivity to detect and could provide evidence of proliferation activities well in advance of a country developing a fully-fledged nuclear weapons capability. The sheer volume and activity of material entering and exiting such locations would prove exceptionally hard to hide from this detection method.[7] While wholly-underground facilities could conceivably disguise this signature, that would constrain the size of the facility and increase costs dramatically. Therefore, it is likely that this technology would limit the ability of proliferators to rapidly build a weapons program while evading detection.

It is unclear if enrichment facilities would be similarly detectable because this is dependent on the design of the facility and the arrangements for delivering natural UF_6 and removing depleted UF_6. Facilities in which storage tanks or pipes are placed near exterior walls (or outdoors) may be vulnerable to this variety of intelligence gathering. Even for facilities designed to limit the dose-rate on exterior surfaces, shipments of uranium

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[6] To learn how this project defines the terms, please visit the On the Radar website glossary, https://ontheradar.csis.org/glossary.

[7] Alexander Glaser. "Detectability of Uranium Enrichment," presentation to iGSE, New York, May 10, 2010.

feedstock entering the facility would have to be well disguised and heavily shielded to avoid detection. Because of these limitations, enrichment facilities pose a more difficult target, but may in some cases prove detectable.

Plutonium production reactors and reprocessing facilities both may produce radiation signatures that are detectable by this method. In particular, the intense radioactivity of the spent fuel and reprocessing effluent would require very careful engineering to shield sufficiently to completely evade detection. Likewise, leaks of fission products are possible and are likely to produce large radiation signatures.[8] While careful design could reduce the risk of detection, this add complexity to the reactor and reprocessing plant design, thereby constraining the efficiency of these projects.

Using this technology to covertly characterize the nuclear fuel cycle has the potential to provide policymakers and military planners with information on the development of weapons programs well in advance of other data streams. In comparison to existing methods of detection (optical, signals intercepts, human intelligence) used to characterize mining, processing, and enrichment facilities, this method drastically collapses the timeline needed to detect proliferation-linked activities. Furthermore, it provides more detailed information on the scale and time-evolution of these activities, potentially allowing for more detailed intelligence estimates.

Such improvements in speed and data quality are likely to assist civilian and military responses to proliferation. Civilian government officials would likely have better constraints on the breakout timeline, intent, and potential nuclear capabilities of these states. This would reduce the probability of proliferation programs going unnoticed, provide rapid feedback on treaty violations, and improve the response time of international organizations to nuclear threats. Military decision makers would likely see improved maps and target lists for strike-planning and could expect more time for preparing kinetic options. Taken as a whole, these capabilities are expected to improve strategic situational awareness for the party deploying this technology against a proliferating state.

For governments or groups being surveilled for signs of proliferation, knowledge of this capability will constrain the scale and increase the cost of their efforts if they seek to evade detection on their path to the bomb. Activities such as overland transport of uranium ore and spent nuclear fuel would be subject to constraints imposed by shielding. Likewise, facilities would have to be designed in such a way that no external radiation anomaly (over a few times background) is detectable. Assuming proliferators wish to keep their program covert, these factors constrain behavior in a way that is advantageous to the goals of the global nonproliferation regime.

This technology would limit the ability of would-be proliferators to rapidly build a weapons program while evading detection, but its impact on strategic stability between countries that already possess nuclear weapons is not as clear-cut.

The influences on strategic stability resulting from the application of this capability against nuclear-armed adversaries are not as clear-cut. Given sufficient sensitivity, one could use a long-standoff radiation sensing platform to look for radiation anomalies occurring near nuclear weapons sites, known transportation routes, or nuclear delivery systems. This information could be used to increase the vulnerability of nuclear weapons systems and reduce warhead ambiguity when observing dual-capable systems. This enhanced ability to distinguish warhead type may improve understanding of an adversary's intent and position on the escalation ladder. It should be noted that the ability to perform such measurements would be affected by natural factors (aerosols in the atmosphere, turbulence), the observed nation's air defense capabilities, and their ability to shield their weapons.

[8] Michael Schoeppner. Remote Detection of Undeclared Reprocessing. International Panel on Fissile Materials, 2018.

Such improvements in vantage and speed are not necessarily stabilizing. On the side of the surveilling country, the decreased ambiguity regarding weapons locations might provide a false sense of certainty when making escalation decisions. On the side of the observed state, this augmented ability to find nuclear facilities and weapons could increase that state's desire to launch early, as it may come to believe that its second-strike capabilities have been degraded. Alternatively, this situation could enhance deterrence, as the state may believe that its weapons would be wholly ineffective because of this enhanced targeting and tracking capability. The interpretation of this scenario would likely depend on the posture of the state and its nuclear capabilities, as well as the security environment.

These improvements to speed and vantage are accompanied by an increase in the detectability of surveillance activity. High power pulses of IR or RF are not easily concealed, and existing systems used to detect RADAR and Light Detection and Ranging (LIDAR) systems could be repurposed to detect radiation surveys. The equipment needed to build a detection system from the ground up is cheap, widely available, and unlikely to be caught by export controls.

The precision of data resulting from radiation surveys conducted with this method will be low in comparison with direct-detection techniques, as information on the energy of the emitter is not encoded in the signal. As energy information is typically used to determine the identity of the emitter, the nature of the source material cannot be uniquely determined using this approach. An adversary could exploit this ambiguity by placing strong gamma sources in non-nuclear items, creating a false positive. Regardless of this limitation, radiation survey data powerfully augment optical imagery for proliferation detection and contribute strongly to the overall precision of measurements.

The persistence of this type of radiation sensing system is entirely dependent on the platform on which it is deployed. While most aerial systems are highly persistent, they are limited by the anti-aircraft capabilities of the state being surveilled. Countries with well-developed integrated air defense systems (IADS) could conceivably fend off or at least limit radiation survey intrusions. Nations that can detect but not defend against intrusion would likely limit the usefulness of data gathered by employing countermeasures.

Likewise, the resiliency of the system mainly is influenced by the platform on which it is deployed, as the RF/IR sources and detectors themselves are in general robust and reliable devices. Important exceptions are situations in which the system is used in the immediate vicinity of a recent nuclear detonation, large fire, or reactor accident. In the case of a fire or detonation, particulates could alter the air's dielectric properties such that measurements would be impossible. In the case of a nuclear incident, radioactive fallout would render the background radiation environment too unpredictable to discern small sources. In addition, active countermeasures such false warheads with radioactive sources in them, aerosol sprays to change air breakdown properties, and laser countermeasures may also degrade the resilience and reliability of the system.

Risk Factors

This novel standoff radiation sensing system on its own is likely to be considered to be minimally intrusive and non-destructive. While the LASER/RF beams are broadcast into hostile territory, no hardware is physically deployed on the ground. As a result, it is unlikely to be as provocative as techniques that require direct radiation sensing (and therefore require placing hardware within meters of targets). However, the platform on which it is deployed may change the perceived intrusiveness dramatically. Large surveillance aircraft that could be confused with bombers could create a situation in which the surveilled party believes it is under attack. Therefore, immense care must be taken in selecting platforms and targets. Even if the action is detected and correctly perceived as intelligence gathering, it is possible that an adversary might attempt to categorize intense EM beams as munitions. This "attack" could be used as a pretext for a military response. However, such a response would be stretching the limits of credibility, as the laser cannot cause significant kinetic effects. Although the plasma peak power is high (on the order of MW), it lasts for microseconds and measures <1mm. As a result, it cannot cause significant material damage (excluding very sensitive optics).

Coupled with optical observations, long-standoff radiation sensing technologies provide predictive capabilities to anticipate proliferation-related activities. The potential application to finding weapons is primarily reactive, although the improvement in speed is significant. This ability could provide the observing state with a significantly shorter notice when responding to changes in an opponent's nuclear posture and could even provide options for preemption. However, the predictive power of this technology is closely coupled to a state's freedom to enter airspace within a few kilometers of the target unmolested (because even if given access to the target airspace, these systems would be vulnerable to countermeasures such as aerosols, decoy radiation sources, and laser jamming systems).

Indirect radiation detection is not dual-use for conventional and nuclear applications, as it is only useful to detect nuclear sources. Outside of military and national security applications, the method is of little value in the commercial sector, and therefore the technology itself is not dual-use for civilian and military purposes. Direct radiation sensing is typically more than adequate for civilian activities. However, the lasers, RF sources, and optics required for these techniques are all active areas of research for commercial applications like LIBS and fusion energy. As a result, there is significant potential for dual-use technologies originating in the private sector to allow large improvements in sensitivity and range.

Concluding Remarks: Risks Versus Rewards

Indirect radiation detection techniques may offer immense improvements in speed and vantage when dealing with nuclear-armed states and potential proliferators. The ability to detect radiation fields at ground level from distant vantage points would provide an unprecedented means of reducing warhead ambiguity and determining the purpose of suspected proliferation-related facilities. If properly implemented, this technology could be a powerful tool for both military planners and the policy community when dealing with proliferators as well as established threats.

The risks associated with the technology are primarily related to the improvement in response speed and issues with intrusiveness. Improvements in warhead identification both negate a state's ability to bluff with dual-use systems and reduce a state's confidence in its nuclear deterrent capabilities. This augmented ability to find nuclear facilities and weapons could increase that state's desire to launch early, as it may come to believe that its second-strike capabilities have been degraded. Alternatively, this situation could enhance deterrence, as the state may believe that its weapons would be wholly ineffective due to this enhanced targeting and tracking capability.

An additional risk is related to misinterpretation of intentions. In some cases, states may interpret a radiation survey with a powerful laser or RF source as the precursor to a strike. This provides ample opportunity for miscalculation, which could ultimately cause escalation.

For states applying this technology, overconfidence may be the largest threat. A positive radiation signature from an object may not be indicative of a nuclear weapon (for example, early missiles used Al-Th alloys which are mildly radioactive). Likewise, there exists a risk that an adversary might use radiation sources in conventional facilities to mislead an observing state into striking non-nuclear facilities.

Because this technology has not yet been deployed, its impact on strategic situational awareness is not yet well understood. Although the improvements in speed may prove destabilizing, these effects are common to many emerging SSA technologies (and speed, in general, has been improving for decades). However, the improvements to vantage associated with this technique have little precedent and may have a significant impact on decisionmaking for all parties involved.

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