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Widening the ceasefire toolkit: The promise of geophysical monitoring in Ukraine and beyond

Policy Brief

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Executive summary

Scientific advances and a growing availability of relevant data have made geophysical or 'seismo-acoustic' analysis a cost-effective means of complementing, backing up, and in some cases replacing other ceasefire monitoring technologies.

'War is the realm of uncertainty [...]. A sensitive and discriminating judgment is called for; a skilled intelligence to scent out the truth.'¹

Any monitoring mission deployed to observe an end to the hostilities in Ukraine is likely to incorporate a range of remote-sensing technologies to support its verification activities. Previous monitoring missions have relied primarily on satellite imaging, camera-drones, and stationary CCTV as technical tools to support onsite observers.

In this paper, we maintain that scientific advances and a growing availability of relevant data have made geophysical or 'seismo-acoustic' analysis a cost-effective means of complementing, backing up, and in some cases replacing other ceasefire monitoring technologies. Analysing small vibrations in the earth and/or air, a seismo-acoustic monitoring solution could help detect conflict-related explosions in all environments, including areas deep behind the prospective line of separation. Seismo-acoustic techniques could also help monitor the integrity of borders, demilitarised zones, or weapon stores.

Drawing on insights from the Norwegian research institute NORSAR's real-time monitoring of the 2022 Ukraine conflict, we show that seismo-acoustic methods can reliably detect and locate artillery and missile strikes at vast distances. More specifically, we suggest that seismo-acoustic monitoring techniques could fill at least seven roles:

1. **Base layer monitoring:** Seismo-acoustic monitoring techniques could provide continuous, basic coverage of the entire conflict zone, including areas not extensively monitored by other technologies.
2. **Redundancy and resilience:** Seismo-acoustic monitoring techniques could help back up more sabotage-prone technologies such as stationary or drone-borne surveillance cameras. Seismic sensors can be installed underground or in secure locations far from active combat zones.
3. **Early warning:** Automated seismo-acoustic monitoring could enable rapid detection of renewed hostilities or heavy bombardments, supporting early-warning systems to protect civilians, alert observers, and prevent escalation.
4. **Detection and timing of attacks:** Seismo-acoustic monitoring could help provide near-real-time identification and localisation of explosions, reducing the need for risky or time-consuming field investigations.
5. **Transparency and accountability:** Seismo-acoustic monitoring mechanisms could provide objective, time-stamped data that might be visualised as maps or event catalogues, helping verify claims, counter misinformation, and deter violations.

6. **Enhanced perimeter and facility monitoring:** Using the technique of distributed acoustic sensing (DAS), inexpensive fibre-optic cables can detect footsteps, vehicle movements, or tampering near borders, demilitarised zones, or weapon storage sites.
7. **Forensic analysis of major events:** Seismo-acoustic tools could support post-hoc investigations of events of particular importance (e.g., infrastructure damage or suspected attacks) as demonstrated in analyses of the Kakhovka Dam and Nord Stream incidents.

The potential contributions of seismo-acoustic monitoring should be further explored through political consultations and policy research.

1. Introduction

There is widespread agreement that any sustainable peace or ceasefire agreement between Russia and Ukraine would need to incorporate a robust monitoring system.² Empirical evidence suggests that ceasefire agreements that are monitored by a third party are generally more likely to last than those that are not.³ Yet, monitoring large and militarily contested areas can be costly, dangerous, and difficult. Established monitoring technologies, such as satellite imaging, short-range acoustic sensing, drone surveillance, and stationary CCTV, can each provide invaluable information but are plagued by various blind spots and vulnerabilities related to scope, reach, continuity of data, and resilience to sabotage. In this paper, we outline the potential applications of geophysical or ‘seismo-acoustic’ analysis as a cost-effective tool to complement, support, and in some instances supplant more resource-intensive monitoring techniques.

Geophysical techniques – more specifically, seismology and infrasound analysis – have for several decades formed the backbone of national and international efforts to monitor nuclear testing and its absence. Recent and ongoing scientific and technical advances have enabled the use of these and similar techniques to record the use of standard conventional weapons, such as mortars, artillery, and precision-guided missiles, in almost real-time.⁴ In a nutshell, seismo-acoustic monitoring relies on collecting and analysing waveform data – signals from small vibrations in the earth or air – to characterise and pinpoint explosions in time and space. The technology is relatively inexpensive and can be deployed at a considerable distance from any front or line of contact. New advances in ‘distributed acoustic sensing’ also allow analysts to turn standard fibre-optic cables into sensitive monitoring instruments capable of detecting footsteps or vehicles in the vicinity of the cable.

Propaganda, misinformation, and the ‘fog of war’ invariably make it difficult to establish who did what when and where in armed conflict.⁵ Digital technologies have enabled the instant transmission of enormous amounts of information from active conflict zones, but have also introduced new means of obfuscation and deception.⁶ Those monitoring or investigating conflicts need objective data to corroborate witness accounts and establish the truth. Geophysical data provided by seismometers, infrasound stations, and fibre-optic cables offer a promising new data source for conventional conflict monitors. While remote-sensing technologies cannot compensate for bad agreements or a lack of political will to maintain the peace or ceasefire agreement on the part of the belligerents,⁷ technology can help reduce costs, increase transparency, and help constrain unwanted local escalation in instances where the parties to the conflict are genuinely committed to upholding a ceasefire but concerned about potential violations by their adversary.

The article proceeds in three steps. In the following part, we discuss the rationale for, and potential uses of, seismo-acoustic analysis in a future monitoring mission in Ukraine and Russia. In the second part, we provide a more detailed technical description of the underlying geophysical monitoring techniques. Then, in the third part, we briefly discuss the politics and feasibility of the monitoring scheme presented.

2. How geophysical techniques could support future ceasefire monitoring missions

An effective monitoring regime can deter ceasefire violations by holding would-be violators at risk of being caught and then held to account by internal or external audiences.

All wars end – eventually. In ongoing policy debates over possible ceasefire options in Ukraine, many analysts argue that meaningful monitoring depends on deploying a significant number of on-site observers or peacekeepers. For example, the Geneva Centre for Security Policy (GCSP) has outlined alternative monitoring schemes with personnel requirements ranging from 15,000 monitors (the ‘light’ option) to 50,000 or ideally more (the ‘heavy’ option).⁸ Yet, it is not clear that even the lighter of these options is politically feasible given the costs and security challenges involved. At any rate, any monitoring regime is likely to incorporate various remote sensing technologies to assist and support human observers.⁹ This was also the case for the Special Monitoring Mission (SMM) deployed to Eastern Ukraine by the Organization for Security and Co-operation in Europe (OSCE) between 2014 and 2022. The SMM relied heavily on satellite imaging as well as video surveillance by drones, including long-range UAVs, and fixed CCTV posts. The SMM also trialled and deployed a limited number of short-range acoustic sensors. Unlike infrasound sensors, which can detect signals hundreds or even thousands of kilometres away, these sensors operated in the audible frequency range, requiring placement close to the line of contact. The SMM had limited success with the equipment in question and stopped using it in 2020.

High-intensity conflicts are typically marked by the widespread use of major weapons such as large-calibre artillery, heavy mortars, bombs, missiles, and, increasingly, armed drones. The explosions that invariably result from the use of such weapons generate seismic (ground) and infrasound (air) waves that can travel hundreds of kilometres, at speeds of several kilometres per second in the ground (commonly up to ~8 km/s for P-waves in the crust) and around 0.34 km/s in the air at sea level. In turn, these waves can be recorded by seismometers and microbarometers, allowing for near real-time monitoring of conflicts.

Some scholars have questioned the utility of tech-heavy ceasefire monitoring. According to one position, the remote sensing technologies deployed by the SMM in Ukraine ‘had little effect on modifying conflict party behaviour or compliance.’¹⁰ We agree that remote-sensing technologies cannot compensate for poor agreements or a lack of political will to cease hostilities. However, this does not mean that monitoring by means of remote sensing technologies cannot play a role in maintaining a ceasefire. While political will is invariably *necessary* for a ceasefire to last, it may not be *sufficient*. For example, in a tense situation, an absence of trusted information could easily create room for misunderstandings and worst-case-scenario thinking. Alternatively, local commanders or troops might carry out unsanctioned attacks or reprisals against supposed partisans, potentially triggering spirals of escalation unwanted by the respective parties’ senior leaderships.

Monitoring mechanisms generally and remote sensing technologies more specifically can help foster compliance with a ceasefire agreement in several ways, particularly if coupled with meaningful enforcement mechanisms.¹¹ First, an effective monitoring regime can deter ceasefire violations by holding would-be violators at risk of being caught and then held to account by internal or external audiences. Second, the respective parties’ agreement to third-party monitoring could be read as a sign of goodwill and intent to honour the agreement, possibly aiding in confidence-building and de-escalation over time. Third, an effective

and agile monitoring regime could support early warning systems, helping to protect civilians, facilitate humanitarian assistance, alert observers and peacekeeping forces, or enable leaders to rapidly contain unwanted local escalation; many ceasefire violations are not the result of a top-down decision to resume the fighting but local grievances or misunderstandings. While monitoring may not be a silver bullet for perpetual peace and stability, it has proved valuable in many cases.

Conflict observers have at their disposal a vast repertoire of technical supports. Satellite imaging is one of the most powerful. But spaceborne photography is not foolproof. Standard satellite imaging offers relatively poor temporal resolution – satellites provide snapshots, not continuous monitoring – and is both expensive and dependent on favourable weather conditions (synthetic-aperture radars can penetrate even thick clouds but are relatively speaking time-consuming and financially costly). In the case of the ‘ceasefire’ in Eastern Ukraine between 2014 and 2022, the parties to the conflict were also suspected of deliberately carrying out certain activities when they knew the satellite(s) from which the SMM received images were not overhead.¹² Satellite imaging can and should be complemented by human observers and video surveillance by fixed or drone-borne cameras concentrated on known or likely hotspots. In ideal conditions, cameras can provide enormously valuable, uninterrupted visual information with high visual and temporal resolution. However, as demonstrated by the SMM, both drones and fixed cameras are susceptible to sabotage and disruption. For example, SMM cameras were on several occasions taken out by sniper fire or other acts of sabotage.¹³ Finally, fixed acoustic sensors that operate in the audible range can offer valuable information, including the presence and direction of small arms fire, but suffer from similar limitations as cameras. To function properly, the sensors must be deployed and maintained above ground and close to any fighting, making them vulnerable to physical disruption.

In this context we suggest that geophysical analysis offers promising and hitherto underutilised tools for ceasefire monitoring.¹⁴ We maintain that these techniques could conceivably be used for a range of overlapping purposes.

2.1 Base layer monitoring

Seismo-acoustic monitoring could be used to provide a basic layer of continuous monitoring capability throughout the entire conflict or ceasefire area. While seismic monitoring would not be able to detect the use of small arms, it would be of great value in efforts to detect uses of ‘explosive weapons’, i.e. grenades, shells, bombs, and missiles. Seismo-acoustic monitoring techniques would also be of tremendous value in efforts to detect covert or long-range attacks in areas behind the line of separation (including underwater). The area to be monitored will, by all accounts, be enormous – far too big to be continuously covered by human observers or even drones. For reference, the approximately 700 civilian field monitors deployed through the SMM covered an area of approximately 15,000 square kilometres (along a contact line of 420 kilometres).¹⁵ The current conflict zone is substantially larger.

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2.2 Redundancy

In more intensively inspected areas, such as those closer to the line of separation, seismo-acoustic monitoring can complement and support satellite imaging, video surveillance, and onsite observation in the event of sabotage or other failures. As discussed above, seismic stations and infrasound instruments would be deployed in less exposed areas far from the contact line or in hidden bunkers protected from artillery fire.

2.3 Early warning

Seismo-acoustic monitoring may play a crucial role as an element in a broader early-warning system designed to quickly identify flare-ups in artillery exchanges or other major forms of violence. Early warning could help policymakers at the central level – i.e., senior officials in Moscow and Kyiv – contain unwanted local escalations. Like other monitoring techniques, seismo-acoustic analysis can play an important role in facilitating the rapid dissemination of trusted information, both horizontally (i.e., between parties) and vertically (i.e., within parties). A well-developed early warning system could also help protect civilians or alert monitors of ongoing hostilities and shifting front lines.

2.4 Detection and precise timing of attacks

Seismo-acoustic monitoring could help reduce overall costs for the monitoring mission by enabling rapid, near-real-time detection of major attacks. Between 2014 and 2022, when called upon to assess contradictory claims of shelling across the line of contact, the SMM in Ukraine was frequently obliged to send observers out into the field to carry out bomb crater analysis by means of various forensic techniques. Seismo-acoustic analysis could go a long way towards obviating such resource-intensive tasks. As we demonstrate below, researchers have already shown the feasibility of tracking and dating attacks in real-time using seismo-acoustic techniques.

2.5 Transparency

The event catalogue associated with a seismo-acoustic monitoring solution could be visualised relatively easily – for example, by plotting individual explosions as points on a map or by generating heat maps to illustrate areas of concentrated activity – and then shared with outside observers and media organisations. Such transparency might, in turn, help deter ceasefire violations through the risk of incurring high audience costs, which has been theorised as a key causal mechanism linking the establishment and maintenance of a monitoring regime to ceasefire success.¹⁶

2.6 Enhanced perimeter monitoring

Installing fibre-optic cables along borders, demilitarised zones, or key storage sites could enable cost-effective and highly granular seismic monitoring. When fitted with interrogators, the cables

would function as extended sensors, capable of detecting a range of phenomena, from the movement of heavy vehicles to the footsteps of individuals. Distributed acoustic sensing (DAS) could be applied, for example, to permanently or temporarily ring-fence areas containing heavy weapons. Such fencing activities could be mandated through an agreed framework or, potentially, be unilaterally carried out as a confidence building measure. It should be noted, however, that DAS remains an emerging technique compared to for example traditional seismological array processing.

2.7 Analysis of events of particular interest

Finally, seismo-acoustic techniques could be used to illuminate events of particular interest. As it happens, seismological analysis played a key role in shedding light on two of the most significant and discussed events associated with the war. First, it helped to establish that the collapse of the Kakhovka Dam was almost certainly not caused by material fatigue or insufficient maintenance, as some suggested in the immediate aftermath of the disaster on 6 June 2023, but explosives.¹⁷ Second, seismology also helped establish that the Nord Stream leaks, which became apparent on 26 September 2022, were caused by explosions on the Baltic seabed in the vicinity of the Nord Stream 1 and 2 pipelines.¹⁸ While seismology cannot establish culpability on its own, corroborating whether an explosion has in fact occurred can be of enormous importance. In both cases, seismological analysis was instrumental in establishing that the infrastructure in question had indeed been attacked.

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3. Seismo-acoustic monitoring of ceasefire violations in Ukraine: Technical background

Thanks to various geophysical monitoring projects and, in particular, the Comprehensive Nuclear-Test-Ban Treaty (CTBT), the accessibility of seismic and infrasound data is steadily increasing. The International Monitoring System (IMS), a network of remote-sensing instruments established under the CTBT framework to detect nuclear explosions, now comprises over 200 seismic and infrasound stations worldwide.¹⁹ There is also a large amount of continuous and publicly available data from seismic instruments installed worldwide to monitor earthquakes and study the Earth's interior. In combination, these sources could provide extensive data for analysing events in various locations. That said, the quality and viability of geophysical conflict monitoring depend on several factors. First, the quality and viability of seismo-acoustic conflict monitoring can depend on weather conditions (infrasound) or local geological factors (seismology) that impact how well energy is propagated through the air or ground. Second, the odds of detecting an explosion with the techniques described in this paper depend on the relevant blast's yield/size and height/altitude. Third, the quality and viability of seismo-acoustic conflict monitoring depend on the proximity of the area under investigation to functioning sensors. In the case of Ukraine, the western and particularly northern parts of the country are better covered by existing sensors than the southern and eastern parts of the country. Any viable geophysical monitoring regime for a potential ceasefire would thus need, at a minimum, to incorporate new sensors covering the south and eastern parts of the front line. To be clear, existing seismic sensors in north-western Ukraine generally cannot detect smaller explosions, such as those produced by hand grenades or projectiles fired by handheld launchers or light mortars. A more sensitive detection capability in the north-west would require the deployment of a denser sensor network (also) in that area.

The IMS comprises a high-quality seismic array operated by the Ukrainian National Data Centre, denoted Malyn AKASG (treaty code: PS45), located about 100 kilometres north-west of Kyiv (there are also seismic stations in nearby Romania (AS81), Czechia (AS26), the Russian province of Kaluga (AS84), and the Russian North Caucasus (AS83 and PS32). The Malyn array comprises 23 vertical component broadband seismometers and a single, three-component broadband seismometer, spanning approximately 27 kilometres with an average distance of approximately 2 kilometres between each sensor. The intended design of this and many other arrays is to maximise analysts' ability to employ traditional array processing techniques to detect nuclear tests at teleseismic distances, i.e. over 3,300 kilometres. For local or regional conflict monitoring, alternative methods must be used.²⁰ To direct the array towards local and regional seismic events, as opposed to more distant nuclear events, alternative processing techniques can be used to accurately detect and locate events closer to the array. For the Malyn array, this presents a unique opportunity to monitor conflict-related explosions in the Zhytomyr and Kyiv provinces of northern Ukraine.

Over the course of much of the year 2022, using seismic data from the Malyn array (transmitted via the Comprehensive Nuclear-Test-Ban-Treaty Organization's International Data Centre in Vienna), researchers at NORSAR implemented a continuous monitoring solution that automatically detected, located, and timed all major

Figure 1: Seismic and infrasound stations in the CTBT International Monitoring System



PS = Primary Seismic Station, AS = Auxiliary Seismic Station, and IS = Infrasound Station

explosions within north-western Ukraine. The scheme relied on a methodology developed for automatically pinpointing microseismic activity,²¹ using a so-called migration/stacking approach.²² This solution allowed the production of a comprehensive, real-time catalogue of major military attacks in north-western Ukraine, with high-precision event timings and locations. In short, the system offered an unprecedented overview of the conduct of hostilities in north-western Ukraine.²³

Specifically, between 24 February (when the full-scale invasion was launched) and 3 November 2022, the NORSAR team automatically detected and located 1,282 explosions in a region spanning approximately 300 x 220 kilometres around the Malyn array – an area covering swathes of the Zhytomyr, Kyiv, and Chernihiv provinces. In about 30 per cent of cases, the team was able to identify infrasound (low-frequency acoustic) signatures in the seismic data. By combining the analysis of both seismic and acoustic signatures, analysts can further narrow down the confidence intervals for the location and timing of the explosions.

To compare the automated seismic explosion catalogue with publicly reported attacks, the NORSAR team used conflict data provided by the Live Universal Awareness Map for the same region.²⁴ This programme tracks conflict-related events through a

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system combining artificial intelligence aggregation and manual verification of media stories. The data generated by the NORSAR team's automatic detection system proved highly consistent with the Live Universal Awareness Map. That said, the automatic monitoring solution set up by NORSAR identified a large number of attacks that were not reported in the media or, by extension, the Live Universal Awareness Map. True positives were enhanced through the adoption of a fixed, low detection threshold. In contrast, false positives were reduced through pre-processing procedures, careful parameter selection, and manual screening of the automated results. The team could thus maintain a high degree of confidence in the resulting catalogue of events.

NORSAR's monitoring system included the automatic calculation of seismic magnitudes to gauge the explosive power of the various blasts. For underground nuclear explosions at test sites, empirical connections between explosive yield and seismic magnitude are well-documented.²⁵ Yet, underground nuclear tests can be inadequate analogues for conventional surface explosions because of major differences in coupling and energy propagation. However, the NORSAR team was able to estimate the top and lower bounds of the yield for each explosion using data for land-based explosions with known yields.²⁶ The largest explosion that could be definitively linked to a military assault (and not quarry activity) had a magnitude of 1.7 and was related to a missile strike that hit Chernihiv on 10 March 2022. While the upper bound of the yield estimate is too high for any known Russian conventional weapon, the lower bound is consistent with an Iskander missile tipped with the largest available warhead (700 kilos).²⁷ The majority of the explosions detected were likely produced by standard artillery shells.

The ability of analysts to apply seismo-acoustic monitoring in Ukraine – especially in the southern and eastern parts of the country – would be greatly enhanced by the deployment of auxiliary seismic and infrasound instruments in addition to the IMS. Such sensors have a minimal footprint and can be deployed in configurations that enable them to be placed at large enough distances, making them less vulnerable to potential sabotage or attacks than remote-sensing technologies that must be deployed much closer to ceasefire lines or have a significantly larger footprint. Seismic sensors have the additional benefit that they can be deployed in underground pits, deep basements, or bunkers, protecting their location. High-quality seismic and infrasound instruments cost in the region of 20,000 and 10,000 USD, respectively. Simple instruments are available for as little as 600 US dollars.

4. The politics of seismo-acoustic monitoring

While existing scholarship indicates that a geophysical ceasefire monitoring solution in Ukraine/Russia would be technically feasible, the question remains whether it would also be politically viable. A first question would be whether the parties to the conflict might object to the use of IMS data for monitoring tasks outside the scope of the CTBT. Although IMS data are already used for a range of alternative tasks – tsunami warning systems being one example – it is not unthinkable that objections could be raised on this basis. However, the techniques described in this paper would not necessarily rely on IMS data. Any serious geophysical ceasefire monitoring scheme for Ukraine would, in any case, have to be expanded by a number of additional arrays and sensors. The costs involved in constructing and operating an expansive network of geophysical sensors would be minuscule in comparison to the costs of many weapon systems. Installation could feasibly be carried out in a matter of months.

A second question would be whether the parties to the conflict would be able to shut down critical geophysical sensors and thus sabotage the monitoring scheme. In the context of the CTBT, there have been several incidents where states have been accused of hiding weapons experiments by simply closing nearby sensors for ‘maintenance’. This, we suggest, is less of a risk in the context of ceasefire monitoring, as both parties would share an interest in maintaining and sending data from the stations on their side of the contact line, as those stations would be most likely to detect violations by their adversary. The logic here is the opposite of the one in play in test-ban diplomacy, where the stations most likely to detect a proscribed or sensitive weapons experiment on the territory of Country X would be the stations on Country X’s territory. In the case of ceasefire monitoring, the stations most likely to detect any attack by Country X against Country Y – let’s say by means of artillery, armed drones, or mortars – would be those on the territory of Country Y. That said, it is not inconceivable that actors with malign intent could stage false-flag attacks to delegitimise their adversaries and/or justify aggressive ‘countermeasures’. In fairness, though, this is a general problem for most, if not all, ceasefire monitoring techniques – and, as discussed above, if the actors do not want the ceasefire to work, they will certainly find ways to resume fighting. Political will remains essential.

5. Conclusion

Seismo-acoustic analysis offers a new and potentially potent instrument in the arsenal of those seeking to understand and limit conflicts. More specifically, we have maintained that seismo-acoustic monitoring could contribute to efforts to verify a potential peace or ceasefire agreement between Russia and Ukraine. While there are obviously serious limitations with respect to what seismo-acoustic techniques can achieve on their own, they could potentially play a decisive role in either corroborating or undermining human testimonies or other sources of information. In this view, seismo-acoustic monitoring should be seen as a complementary tool to support and augment other monitoring techniques. No remote sensing technology will be able on its own to establish attribution in all cases. However, when used in combination, seismo-acoustic techniques, video surveillance, satellite imaging, and ballistic analysis could go a long way towards establishing ground truths that, in turn, could be fed into an enforcement regime designed to hold those responsible for ceasefire violations to account. Identifying and developing new sources of objective information about armed conflict is all the more important in an age where increasingly sophisticated means of deception are set to pose serious challenges to those eager to establish the truth. A robust monitoring regime could play an important role in the management of deep-seated, mutual mistrust. Any additional political implications or sensitivities should be further explored through consultations and policy analysis.

Identifying and developing new sources of objective information about armed conflict is all the more important in an age where increasingly sophisticated means of deception are set to pose serious challenges to those eager to establish the truth.

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