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Aircraft Field Exercise to Develop Multi-Spectral and Infrared Imaging for CTBT On-Site Inspections

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Executive Summary

The Comprehensive Test Ban Treaty (CTBT) permits Multi-Spectral and InfraRed Imaging (MSIR) to be performed as part of an On-Site Inspection (OSI) for the purpose of reducing the search area for the location of a possible underground nuclear explosion (UNE). Dedicated airborne MSIR measurements have not been made in conjunction with historical or recent UNE's. Satellite data has been used to show that MSIR observables can be used to reduce the search area, but the satellite data do not have the spatial resolution or spectral and thermal capabilities desired to fully characterize the MSIR observables. Consequently, there is insufficient information currently available to confidently specify an MSIR instrument to be used on an Additional Overflight as part of an OSI.

The potential MSIR observables are known, but not well characterized. The possibility of using airborne MSIR measurements to characterize some of those observables has been assessed here for a variety of field exercise scenarios. The main challenge in making aircraft measurements is to have confidence that the field conditions will accurately reproduce the MSIR observable compared to a UNE. The four types of events expected to generate relevant MSIR observables are (1) underground coal fires, (2) road traffic measurements, (3) underground mining operations, and (4) certain carefully staged explosions, such as the Source Physics Experiment.

1.0 Background and Purpose

The Comprehensive Test Ban Treaty (CTBT) allows for Multi-Spectral and Infrared Imaging (MSIR) measurements as part of an On-Site Inspection (OSI). The objective of MSIR measurements is to help narrow the search area for the location of a potential nuclear explosion that violates the CTBT. MSIR measurements as part of an OSI would either be made from an aircraft during an Additional Overflight, or from the ground. Whether MSIR measurements might be made via other means, such as from a UAV or tethered balloon, remain under discussion.

The application and utility of MSIR measurements for OSI require further study: MSIR measurements have not been made or used to date for field exercises conducted by the CTBTO; there are few measurements with demonstrated relevance to this objective; there are no vetted requirements for the specification of equipment that might be used for MSIR; and the current level of experience is insufficient to generate CONOPS and analysis procedures for the use of MSIR to support an OSI. Analysis of satellite data taken over the sites of recent presumed nuclear tests indicates that disturbed earth and human activity observables might be used to locate the UNE [Henderson et al, 2010], but measurements with higher spatial resolution and more spectral bands would be useful to better characterize the MSIR observables and optimize the MSIR instrument specification.

One approach to better characterize the MSIR observables would be to take aircraft data at relevant locations and events. The data collected would need to have sufficient spatial resolution and spectral properties (number, location, width and sensitivity of the spectral bins) to adequately characterize the MSIR observables so a nominal equipment specification could be generated. Further, it is expected that the field exercise of collecting this data, along with the data itself and the findings from processing the data, would be useful in developing the Concept of Operations for collection of MSIR data. Ultimately, the goal is to develop the Specification for the MSIR equipment and the associated text for the OSI Operations Manual. In the medium term, it is expected that the findings from an MSIR field exercise would be used to identify relevant MSIR equipment that might be used in a subsequent field exercise to further refine the Specification and Standard Operating Procedures for the MSIR equipment.

The purpose of this paper is to outline what field exercises might be valuable to mature the application of airborne and ground borne MSIR for an OSI. The two key design parameters of the field exercise are that the scenario measured have observables relevant to an MSIR observable from a UNE, and that the equipment used have sufficient spatial resolution and spectral properties that the MSIR observable(s) can be well characterized. These two conditions are necessary to be able to confidently specify the MSIR equipment and CONOPS for an OSI.

2.0 MSIR Observables

In general, the UNE observables that might be detected by MSIR fall into five categories:

1) disturbed earth at the surface (due to the shock wave from the explosion),
2) plant stress in the vicinity of the UNE,
3) artifacts of human activity,
4) thermal effects, and
5) novel materials at the surface.

These are described in detail and relevant scientific work referenced in the MSIR Primer [Henderson, 2010]. They will be summarized here with a focus on the physical conditions necessary to generate the observable, and what measurements might be made to characterize the observable.

2.1 Disturbed Earth

Airborne disturbed earth measurements not been explicitly measured for a UNE, but visible observations of earth movement, surface fissures, and measurements of surface upheaval from prior UNE's indicate that disturbed earth is possible for a UNE of sufficient size. Further, measurements for other purposes have shown that disturbed earth can be detected with MSIR imaging. Finally, analysis of satellite measurements have shown areas with spectral signatures consistent with disturbed earth, although physical access was not possible to confirm the findings [Henderson et al, 2010]. The mechanism for generating disturbed earth is the surface shock from the UNE, and the spatial extent of the disturbance is about 1.5 to 2 times the depth of burial. The disturbed earth signatures are likely to persist for days to months or more, depending on how different the sub-surface material is from the surface material, and how rapidly weathering changes the spectral properties of the newly-exposed material to become similar to weathered surface materials.

2.2 Plant Stress

Plant stress is due to the surface shock from the UNE. It was measured at the Non Proliferation Experiment (NPE) in 1993 [Pickles 1993]. Those measurements showed that the plant stress was highest nearest surface ground zero, and were approximately correlated with the surface acceleration. Plant stress peaked by 56 hours after the explosion, and then returned to pre-explosion levels after about 2 weeks. There are few other directly relevant measurements, so it is unclear whether these results apply to a variety of plant types, or only the plant types present at the NPE. Again, the spatial scale corresponds to about 1.5 to 2 times the depth of burial.

2.3 Artifacts of Human Activity

Whether the UNE is a tunnel shot or a borehole shot, there will be human activity (road traffic, buildings, cables, equipment and material movement, etc) associated with the UNE. While some of these may be readily detected in visible imagery (e.g., buildings), MSIR can sometimes provide additional information, such as whether dirt or gravel roads have been used recently. Because of the smaller spatial scale of the observables (sub-meter for tire tracks, few meter for buildings), higher spatial resolution is required to optimally detect artifacts of human activity.

2.4 Thermal Effects

Two postulated mechanisms for there to be observable thermal effects on the surface are venting of hot material from the explosion to the surface, and heating of underground water near the explosion cavity which migrates to or near the surface. The timescale for heat transfer via conduction to the surface from a depth of burial in excess of 120 m is years or more. The spatial extent of a thermal "hot spot" will depend on which of the two candidate phenomena cause the hot spot, and the extent of fracturing on the surface. Venting of material would be expected to occur shortly after the explosion, and the persistence of the thermal effects will depend on the thermal mass of material heated near the surface. Migration of hot water to the surface will depend on sub-surface water flow properties, but will likely persist for weeks to months or more, depending on the stability of the sub-surface flow.

2.5 Novel Surface Materials

There are two candidate mechanisms for novel materials to appear on the surface after a UNE. Direct venting from the explosion to the surface can deposit materials from the explosion on the surface. Also, hot gases from the direct venting can vaporize or mobilize low-vapor point materials in the soil, which might then be carried to the surface. This would result in the presence of sub-surface materials at the surface. Similarly, hot water or steam from a sub-surface water flow contacting the hot cavity from the UNE could cause sub-surface volatiles to be carried to the surface. Since the underlying mechanisms are the same, the spatial extent could be highly variable as for the thermal plume. However, the volatile materials could either condense on the surface or remain after evaporation from a liquid flow. This would leave a surface anomaly which might be detected spectrally. Persistence of this anomaly depends on whether it is covered by wind deposition of dust, return to the sub-surface by rain, or weathering. In general, it is likely that the spectral anomaly would persist for days to years.

3.0 Candidate Events for MSIR Observables

Historical UNE sites are an obvious location to conduct an overflight or ground measurements for MSIR observables. Unfortunately, all of the observables have time dependent signatures, and it has been almost 20 years since the last nuclear tests at test sites one is likely to have access to. Additionally, any work on the surface, such as for remediation of radioactive contamination, would alter the observables we are seeking to measure. This means that alternate locations must be found.

The more recent presumed UNE's conducted in 1998 by India and Pakistan, and in 2006 and 2009 by North Korea are clearly relevant and of interest. Preliminary work with Landsat 30 m MSIR data and GeoEye 3 m MSIR data has shown that MSIR observables were present for most of those tests in proximity to the ground zero (GZ) determined from seismic methods. (The location for GZ on these tests is typically not publicly announced.) The value of the MSIR data was in its ability to discriminate the UNE observables (disturbed earth and human activity) from visually equivalent features (plowed farmland and un-used roads), resulting in a very small number of regions of interest for detailed inspection. Work with data from other satellites (with better spatial resolution, different spectral channels, and/or different temporal sampling) may be able to demonstrate plant stress and further characterize the UNE observables. The difficulty is that the spatial resolution and number and type of spectral bands are much more limited than is likely for an OSI instrument. Nevertheless, these events are the most representative of what is being searched for in an OSI, and further characterization of them would be valuable.

Other events that generate surface disturbances may be relevant. These include earthquakes, explosive blasts for construction and mining, a variety of human activities, and underground coal fires. There is also value in making measurements on these events so their MSIR observables can be discriminated from UNE observables if necessary.

3.1 Earthquakes

Earthquakes might generate several of the features possibly associated with a UNE – disturbed earth and ground fissures are likely, and plant stress is a possibility depending on the amount of surface shock and ground movement. The difficulty with basing a field test on an earthquake is that one cannot predict the location or timing of the earthquake. This means that one would need to have arrangements made to fly an MSIR system to the site of the earthquake to take the desired data within one to two weeks of the earthquake. Recently, a team from Rochester Institute of Technology made MSIR measurements on the earthquake in Haiti [see http://www.wired.com/wiredscience/2010/01/haiti-3d-flyover/]. That example might be taken as a template for how to have resources in place to take relevant earthquake data when possible.

3.2 Explosive blasts for mining and construction

Some mining companies routinely detonate kiloton quantities of explosives, but care must be used in selecting an explosion event for data acquisition. There are three factors which might cause the observables from a large mining explosion to deviate from the observables from a comparably sized UNE. First is that the explosives are ripple-fired (i.e., detonated as a series of smaller charges rather than the entire charge instantaneously). This means that the surface accelerations and ground disturbances are smaller but for a longer time than for a UNE. Second, the explosions are either surface blasts or deep mine blasts, either of which will cause the spatial extent and magnitude of surface shock to deviate from that of a UNE. Third, areas of mining tend to be in continuous use, which means that disturbed earth and plant stress observables are more likely to be due to the accumulation of weeks of explosions rather than the most recent explosion. It is unclear whether surface accelerations reach the 0.2 g needed for plant stress or the higher levels probably needed for disturbed earth observables. We are continuing discussions with several mining companies to see what the best option for a test might be.

3.3 Human activities

This is an area where relevant aircraft data can be collected for a variety of scenarios. A key observable is to determine whether dirt or gravel roads have been used recently, and possibly to determine the level of traffic on them. Another observable is to detect the presence of buildings or structures, and possibly to determine whether they are in use, or have been in use recently.

Two scenarios have been identified for measuring the presence and level of road traffic. One is to conduct a planned experiment where roads that are known to have not had traffic for several months are measured to determine their baseline MSIR properties. Vehicles would then drive on those roads a number of times and new MSIR data acquired. This would be repeated several times to see if the MSIR properties of the roads changed with additional traffic. After stopping new traffic, MSIR data would continue to be acquired approximately once per week to see how long it takes for the MSIR properties to relax back to their original levels. Periods of rain or significant wind (which might cause dust to cover the trafficked areas of the roads) would be noted to see if they caused any significant changes in the road traffic observable. The second scenario is to observe a long-dormant mining operation, and to observe two or more operating mines with significantly differing levels of activity, and compare the observables between them. Several candidate sites have been identified, which have known amounts of vehicular traffic on long stretches of dirt or gravel roads.

The mining scenario has the additional advantage of the possibility of a tailings pile and dust and debris from the mining operation being present at the mine entrance and along the access roads. These observables are potentially relevant to a UNE conducted from an underground shaft, which might otherwise be hard to detect.

There are many opportunities to observe buildings and structures, but the challenge is to make sure they are relevant to the conduct of a UNE. The Source Physics Experiment (SPE) is a planned explosives detonation at the Nevada Test Site which will have many aspects that should be similar to the conduct of a UNE.

3.4 Underground coal fires

Underground coal fires can result in subsidence and surface fissures as the coal burns and the overburden collapses. The surface cracks can be 20 cm to several meters in width, have lengths up to hundreds of meters, and are typically 10 to 20 m in depth. Underground coal fires are known to generate hot regions on the surface, and airborne thermal measurements are a well-established method of detecting them. A good summary article with references to airborne thermal measurements in a variety of countries is Zhang, 1999. That reference describes the use of multi-spectral data in conjunction with thermal data to identify regions where active coal fires are present. An advantage of aircraft data over satellite data is better spatial resolution. A concern is whether the spatial scale of the thermal signature of coal fires is relevant to thermal observables that might result from a UNE.

Underground coal fires have the possibility of generating novel materials on the surface, and hence are a good candidate to develop the anomaly detection techniques that would be needed [Zhang 1999]. These novel materials might be due either to material that has migrated from the sub-surface (e.g., sulfur), or from spectral changes induced in the local material due to heating.

3.5 General comments on candidate events

3.5.1 Plant stress

The two drivers to conduct airborne measurements versus using satellite data are the possibility of obtaining higher spatial resolution and the ability to acquire more detailed spectral information. Plant stress is an area where spatial resolution might make a significant difference.

Plant stress is of significant economic interest for agriculture, and there is a large amount of literature on the subject. Here the published literature may be sufficient to specify the optimum spectral properties of an MSIR instrument. The optimum spatial resolution is less clear, with useful measurements being made from Landsat (30 m), whereas some authors claiming the spatial resolution needs to be 0.5 m or less to ensure individual plants are resolved. It is likely that the required spatial resolution will depend on the sparseness of the local vegetation. Additionally, many areas of mining are arid, so the plants may be initially stressed due to lack of water. The main value of observing plant stress due to a surface shock is that the most recent relevant measurements were taken during the Non Proliferation Experiment in 1993. Plant stress was not observed in a preliminary analysis of satellite data for the six recent presumed nuclear tests [Henderson et al, 2010].

3.5.2 Thermal Effects

There are some operational challenges of looking for thermal anomalies in the context of an OSI. The main one being that the few hours around dawn are the best time to look for hot spots on the surface because the ground has had all night to cool, and solar heating of the surface has not yet begun for the day. In the context of an Additional Overflight, where Visual Observation is the primary goal and the flight(s) will occur throughout the day, it is likely that very little, if any, of the Inspection Area will be observed with a thermal camera during this prime time. The objective of a field test is therefore to determine whether hot spots might be observed under non-ideal conditions, and to develop the CONOPS for such measurements. A simple test, such as flying over a thermal hot springs, might be used for these measurements.

4.0 Conclusions

Underground coal fires appear to be a have many of the same qualitative features that might be present after a UNE – surface subsidence and disturbed earth, surface cracks, thermal hot spots, and anomalous materials on the surface. A region where one or more underground coal fires are present might be a good choice for a field exercise since there are several observables that might be detected by visual observation and MSIR. Because airborne measurement of coal fires is a well-established technique, it should be possible to obtain existing data to explore the required spatial resolution and spectral capabilities desired for an MSIR system and prepare for a dedicated field test.

There appear to be several good options to characterize the observables associated with the presence and level of traffic on dirt and gravel roads. A dedicated experiment or measurements made on carefully chosen mining or construction operations should provide useful information. Additionally, mining operations may be relevant to an underground tunnel scenario for a UNE, so the observables there are directly relevant to an OSI.

Planned events which have activities analogous to those of a UNE, such as the Source Physics Experiment, are prime events to make observations on human activities observables.

Earthquakes are likely to generate relevant observables, but are not compatible with planned data acquisition on a rigorous schedule. Mining and construction explosions have the possibility of generating relevant surface shocks, resulting in disturbed earth and plant stress signatures. In practice, these events may have limited utility for characterizing OSI MSIR observables because they are ripple fired and tend to occur over an extended period of time in a localized area.

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