SPO Special Projects Office

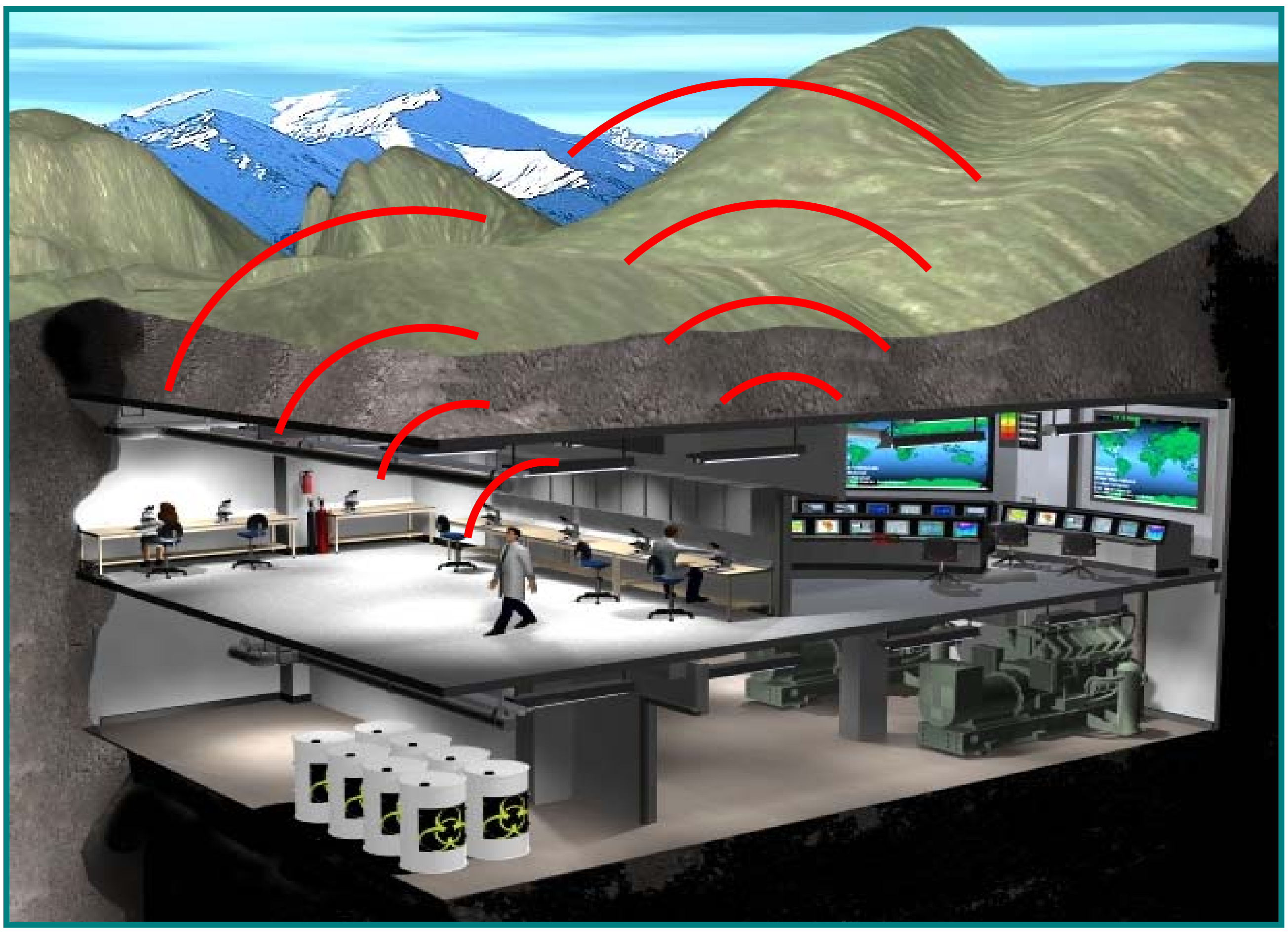
Dr. Greg Duckworth
Program Manager
Special Projects Office

The Enemy Beneath: Finding and Monitoring Unimproved Underground Facilities

Some of the most dangerous threats we face have gone underground. In a way, that's a compliment to our improving urban surveillance and warfighting capabilities. Underground is the last refuge our adversaries have to hide people and material and conceal their manufacturing and transportation operations. It is also one of the last places they can survive an attack. And DARPA is determined to deny them that sanctuary.

Described at last year's DARPATech were programs in progress aimed at identifying large, underground structures—structures that may serve as production and storage facilities for weapons of mass destruction, command and control centers, and storage for ballistic missiles.

Our Passive Acoustic, Seismic, and Electromagnetic Ground Sensor program and Low Altitude Airborne Sensor System (LAASS) program are exploiting and enhancing many sonar and nonacoustic technologies developed for Cold War antisubmarine warfare. They take advantage of the large seismic footprint of large underground facilities, as well as the acoustic and electromagnetic emissions from their extensive



power, ventilation, and equipment suites. In addition, our new Sub-Surface Navigation program is developing technologies that will provide robust navigation and geolocation capabilities for underground operations.

These are challenging programs. But this year we've taken on an even tougher job—finding small underground structures, such as caves, that serve as simple hiding places and tunnels for smuggling weapons and infiltrators across borders or provide secret entry into sensitive areas such as Baghdad's International Zone, or even prisons, weapons laboratories, and nuclear power plants.

Our goal is to develop ways to scan large areas rapidly with high probability of detecting small caches of weapons of mass destruction and weapons manufacturing hardware and material and low false alarm rates.

The challenge posed by small caves and tunnels is they are little more than holes in the ground. Except for the terrorists and materials they're concealing, they're basically empty places and don't emit the characteristic signatures of larger facilities with extensive infrastructure and high rates of human activity.

Although the signals from these underground features are weak, they exist and there are lots of them. The trick is to cull them from the background clutter using temporal and spatial integration.

Emptiness is a detectable characteristic. In fact, detecting emptiness is the idea behind active probing technologies such as sonar. One could say that sonar finds holes in water, holes that just happen to be submarines. Similar active probing strategies could do the same underground.

For almost a century, the geophysical exploration industry has been steadily improving active probing techniques used to remotely detect subtle geological features that indicate the presence of minerals, oil, and other resources. These techniques include ground-based and air-deployed electromagnetic sounding systems that use induced polarization, resistivity, and magnetotelluric imaging to reveal subtle changes in the Earth's conductivity and dielectric properties. They record how either seismic and electromagnetic waves or quasi-static fields interact with the medium they are in (e.g., different types of soil or rock, air, accumulated salts) to provide a picture of subterranean features.

It is time to harness these technologies for military purposes and use them to find and map the caves and tunnels used by our adversaries. The challenge is to develop scaled down versions of these geophysical and oil exploration techniques including seismic reflection, refraction, vertical seismic profiling, and borehole-to-borehole tomographic methods.

This kind of scaling has been done before in the medical arena: ultrasound for prenatal and cardiac imaging, computerized axial tomography, magnetic resonance imaging, and even positron emission tomography. All reveal the inner structures of our bodies in spectacular detail.

Where's the challenge? Why can't we just start probing the Earth's subsurface? The problem is access.

Existing technologies for geophysical imaging are invasive and have extremely slow search rates. In many cases, we have to physically plant energy sources and sensors over the area we want to scan. This is not only labor-intensive and time-consuming, it's tactically infeasible in hostile areas and under battlefield conditions.

In addition, the size of the features we are trying to find is small, and the natural subterranean environment, unlike the deep blue sea, is extremely complex. As a result, we face an immense clutter problem, calling for both high resolving power and increased capability for differentiate geotechnical anomalies from manmade intrusions. These factors conspire to require close access, sampling, and multicomponent/multimodal sensors.

But imagine the impact if we succeed. Imagine that, instead of being limited to spot searches, we were able to scan wide areas of Iraq for buried material. Imagine if we were been able to scan large swaths of Afghanistan for terrorist caves.

How can we achieve this?

First, we need to develop mobile and stand-off sensors and systems that can effectively cover wide areas at high density. We want to pick up on the returns from stand-off energy sources to exploit the simple but strong intrinsic contrast between the hollow space of a tunnel and the material from which it has been carved.

We want to consider everything from actively deployed emitters and energy sources to electromagnetic waves already in the environment—from AM radio and Loran navigation system transmissions to the low frequency VLF and ELF signals used for long-range and submarine communications. We might even exploit the natural geo-atmospheric EM noise for illumination.

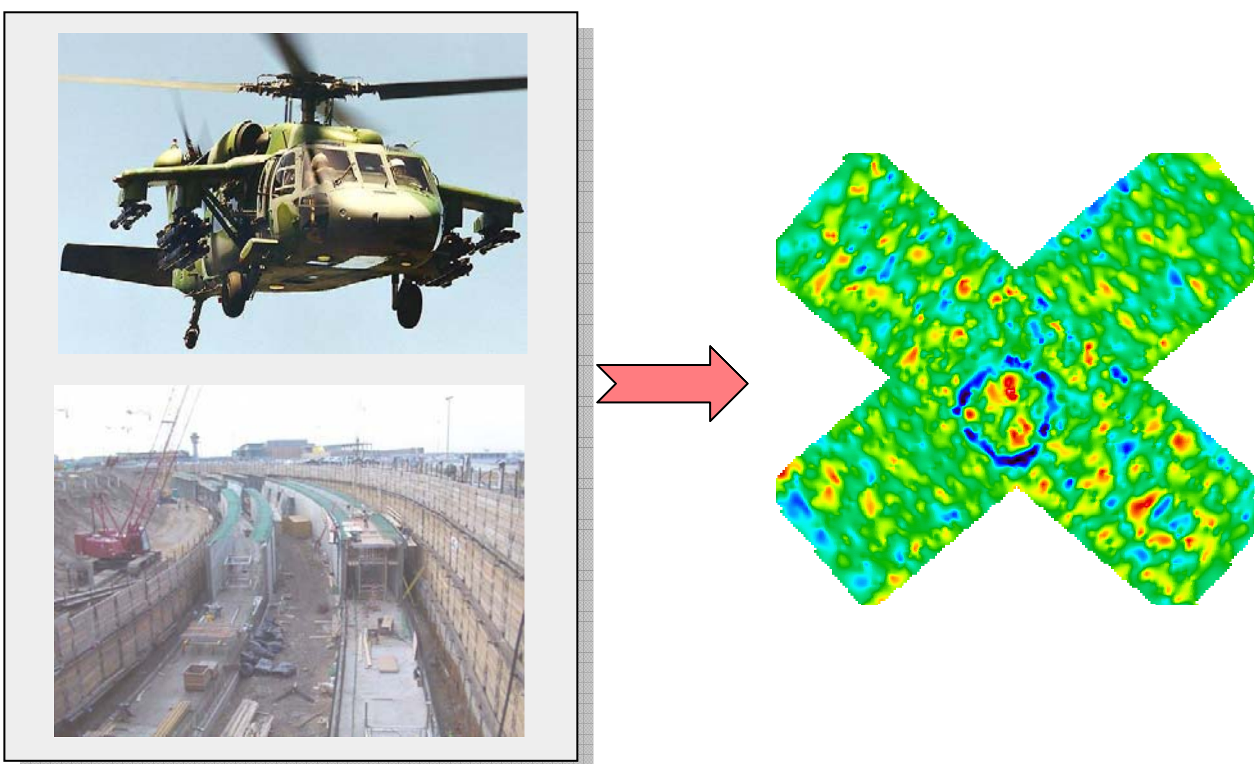
On the seismic side, natural seismic activity, traffic vibrations, exploding ordnance, or even sonic booms could be wave sources. In both cases, by using purposefully deployed or parasitic active probes, we don't have to rely on detecting human activity or signal emissions from inside a tunnel or cave in order to spot it.

Another natural candidate for a detection strategy is gravity gradiometry, which can detect the signature of empty space in the gravity field gradient. We are pursuing this with the LAASS program, and there is much to be done.

The DARPA challenge is to come up with sensor and platform combinations that are effective and can be deployed in hostile areas.

Hopefully, these mobile and stand-off systems will support the electromagnetic, seismic, and gravity gradiometry techniques mentioned earlier.

But there is another class of passive techniques: advanced signal processing of images from visible and IR hyperspectral sensors. We envision algorithms that exploit the spatial and temporal correlation structure of time sequences of these images. For example, caves and tunnels breathe; gases enter and leave through the entrance as temperature, humidity, barometric pressure, and



other factors change. Can we pinpoint the breathing signature of a cave or tunnel entrance using hyperspectral sensors? Can we correlate activities at one end of a tunnel or cave with activities at another spot? An analogy is matching the number and frequency of cars disappearing into a tunnel on Manhattan Island with the traffic reappearing in New Jersey in order to determine that both entrances are connected by the Holland Tunnel.

We believe there are three fundamental keys to exploiting active and passive signatures.

The first is persistent temporal surveillance; i.e., continuous and consistent observation over time. To identify small structured changes, we need long-duration series of images; for example, images from wide-view infrared sensors that can record air temperature and barometric pressure changes throughout the day. By cross-correlating each coordinate (or pixel on the IR image) with barometric pressure over time, we can spot very slight localized anomalies that could indicate air escaping from tunnels or caves. Such a strategy requires persistent staring sensors and survivable platforms to support them.

Similarly, human activity may create coherent variations that we can detect. Correlated or semiperiodic patterns of use (like the Holland Tunnel at rush hour) may reveal signatures that are statistically different from other human activity, especially if we can used spatial cross-correlation, too.

That brings us to our second key to success: persistent spatial surveillance. This requires developing highly mobile sensors that provide wide-area coverage, without gaps, or sensors with wide fields of view and high resolution.

As an initial step, we have to develop a solid statistical picture of the background clutter, both naturally occurring and manmade, so new, anomalous features will stand out. This is crucial for such techniques as electromagnetic scatter and gravity gradiometry, both of which have to deal with large amounts of variation in the environment. With an accurate, detailed picture of the spatial clutter background, we should be able to apply matched filters to detect characteristics such as the size and shape of an underground hollow and differences in phase and polarization between the hollow and surrounding material.

Again, critical to this approach is the development of sensor systems that can obtain both sets of data (background and anomalous) with speed and stealth to be operationally useful.

The third key is to fuse observations of many different phenomena to enhance the accuracy of our analyses and eliminate false alarms. The geophysical industry has made great strides in this type of processing for mineral exploration, and we must adapt these techniques to exploit their advantages.

For example, a tunnel generates a gravity anomaly due to its lower mass, an electromagnetic scatter due to its dielectric or conductivity differences, and temperature and vapor anomalies at its endpoints or along its length, if it is shallow enough or its cover is porous. It's also possible we can pick out hyperspectral or electromagnetic signatures of the ground and foliage above it or around its portals.

Again, the signals from unimproved tunnels and caves may be weak, but they are there and they are detectable.

We need miniaturized sensors coupled with platforms that can deliver these sensors into the theater and maintain persistent observations over time and space. In many cases, these sensor-platform packages must get very close to the area under observation because phenomena such as gravity and electromagnetic scatter lose signal strength at a high geometric, or even exponential, rate.

Passive ground sensors have proven effective for spotting vulnerabilities and monitoring activities in larger underground facilities. However, the kind of active seismic imaging needed to detect small subterranean structures, that is operationally practical, is still elusive. We can't go around planting sensors and sources in the ground everywhere we want to look. We need new algorithms to take advantage of these sensors.

The threat posed by small tactical tunnels and caves and buried caches of weapons and materiel is very real. Defeating this threat requires overcoming limitations imposed by low performance, slow scan rates, small footprints, and minimal temporal persistence. It requires a combination of existing and new, active and passive sensing technologies. These technologies must be developed simultaneously with innovative platforms that are survivable and enable a high search rate.

We have ideas in mind, but we know we can't think of everything. More likely than not, the person with the best approach to solving this difficult problem is reading this right now. If you can help, SPO wants to hear from you.