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Author(s):	Peter V. Czipott
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Stand-Off Detection and Tracking of Concealed Weapons Using Magnetic Tensor Tracking

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Prepared by:
Quantum Magnetics
Dr. Peter V. Czipott
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7740 Kenamar Court · San Diego, CA · 92121 · Tel: (858) 566-9200· FAX: (858) 566-9388

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INTRODUCTION

Because the great majority of firearms and most other weapons incorporate ferrous metals, magnetic detection technology has a wide range of possible applications for law enforcement, corrections, and general security. Ferrous metals distort the Earth's magnetic field in two ways:

1. They are magnetically *permeable*, which means that they distort the Earth's natural magnetic field.
2. Some ferrous objects possess a *permanent magnetic moment* that creates its own magnetic field.

In either case, the measurement of the Earth's field can detect the presence of such objects without the need actively to generate an illuminating or probing field of one's own.[1] In some cases, such a *passive* detection modality can provide security when Fourth Amendment protections against unreasonable search preclude the use of active modalities.

In discussions with the National Institute of Justice (NIJ), Quantum Magnetics (QM) reviewed possible applications of passive magnetic detection to law enforcement. NIJ determined that a major safety threat to law enforcement personnel could be mitigated by a successful application of the technology. The following section describes the threat that QM was asked to mitigate in the funded program.

OFFICER SAFETY IN REMOTE TRAFFIC STOPS

In some areas of the United States, particularly in the Southwest, a small number of law enforcement officers must patrol large tracts of land. When stopping a vehicle for a traffic violation in a remote location, backup for an officer can sometimes be more than an hour away. Procedures in force call for the officer to call in a stop to the dispatcher and then to approach the driver of the stopped vehicle to explain the stop and request a driver's license and vehicle registration. On rare occasions, the officer may be presented not with the requested paperwork, but with a weapon drawn in anger. The threat to officer safety is evident in such a situation.

A technology to alert an officer to the presence (and, ideally, the location and type) of a weapon before he/she is exposed to the danger is highly desirable. Of course, the ideal technology would scan the entire interior of the stopped vehicle, locate and identify all weapons therein (if any), and provide the information to the officer instantly, even before the vehicles come to a rest.

Unfortunately, such technology is not feasible with the present state of science. Radar signals cannot penetrate the metallic body of a car. Magnetic fields can do so, but they are distorted by the steel in the car beyond any ability to untangle them and deduce the originating objects within.

QM posited the following scenario in which magnetic detection technology could provide an officer with information to alert him/her to the possible presence of a weapon. This alert is envisaged to provide legal probable cause that would justify a detailed weapons search. At a minimum, it would alert the officer of the need for heightened caution. The scenario plays as follows.

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[1] Metal detectors, commonly but erroneously called "magnetometers" in the security trade, illuminate the area under inspection by applying a time-varying magnetic field. This field induces electrical currents in metallic objects, which in turn produce their own, secondary, magnetic field that is detected by the system. Other technologies using actively applied fields include radar, ultrasonics, and X-ray.

1. After the patrol car and target car have come to rest and the officer has alerted the dispatcher, the officer determines whether the vehicle is occupied by a single driver or by a driver with passengers.
2. The officer assumes a safe position behind the door of his/her vehicle, and speaks to the occupant(s) of the target vehicle via loudspeaker.
3. The officer directs the vehicle occupant(s), one at a time, to exit the vehicle, walk back toward the patrol car, then turn and walk past the front bumper of the patrol car.
4. A magnetic sensor mounted on or near the front bumper of the car automatically detects whether the individual walking past has any anomalous, ferrous object on his/her person. It can also tell where the object is: at shoulder height, waist height, or near the feet.
5. An inconspicuous alarm (e.g., audio into an earpiece), that neither distracts the attention of the officer nor tips off the suspect, alerts the officer to potential danger and its approximate location.
6. The officer takes appropriate action, based on the probability of a concealed threat.

THREE-PHASE PROGRAM PLAN

This scenario was reviewed by NIJ in consultation with a few sheriffs' departments and judged to be a viable one. Accordingly, a three-phase program was embarked upon.

Phase I

The first phase of work seeks to establish the technical feasibility of detecting and locating weapons, primarily firearms, using a single magnetic sensor.[2] To save cost in this phase, QM used a system being designed and fabricated for the U.S. Navy in laboratory measurements. The end point of Phase I is a feasibility demonstration and a decision point on continuing to Phase II.

Phase II

The Phase I demonstration system, developed for a Navy application, uses the best possible magnetic sensor elements. As a consequence, it is far too expensive for law enforcement applications. In Phase II, QM is to design and develop a pre-prototype "brassboard" sensor system, making use of low-cost magnetic sensors. It is to use the system, mounted on a vehicle, and demonstrate the ability to detect and locate a weapon being carried nearby. At the end of Phase II, with a successful demonstration of the system operating in real time, a second decision point is reached, concerning continuation to Phase III.

Phase III

The Phase III work plan is to render the Phase II "brassboard" pre-prototype into a prototype system suitable for deploying on actual patrol cars. Up to four prototype systems are to be developed and then deployed in several different jurisdictions for testing in actual use. Results are to be monitored and the users' comments noted. At the end of Phase III, QM would have the data needed to decide whether to pursue commercialization of this application and to determine any modifications needed to render the system commercially viable.

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[2] NIJ had separately funded the Department of Energy's Idaho National Engineering and Environmental Laboratory (INEEL) to develop a weapons detection portal using passive magnetic sensors. However, that portal uses an array of 16 separate sensors.

SUMMARY OF RESULTS

Phase I

In Phase I work, QM successfully demonstrated the ability to detect and locate ferrous objects, including a small selection of firearms. Target localization was demonstrated in the form of a target bearing, namely, the direction to the object from the sensor. However, localization as demonstrated in Phase I was subject to the following two ambiguities.

1. Range-moment ambiguity, wherein a small nearby target cannot be discriminated from a larger, more distant target.
2. "Ghost solution" ambiguities, wherein the localization algorithm yields four mathematically correct solutions, only one of which is the correct one.

Resolution of these ambiguities was shown to be feasible, but not yet demonstrated, falling outside the scope of Phase I work. However, the results of Phase I fully justified proceeding to the next phase.

Phase II

In Phase II, QM successfully completed development of a pre-prototype magnetic sensor system that uses low-cost, thin-film sensor elements based on the principle of MagnetoResistivity (MR). The system was assembled by leveraging results from a sensor development program funded by the U.S. Air Force. QM mounted the system on a vehicle and compared system noise levels, in the QM parking lot, to those obtained using the expensive Navy sensor. Noise levels were found to be environmentally dominated, so that using the MR technology involved no sacrifice in performance. Interference was measured from a patrol car made available for the purpose by the San Diego Police Department (SDPD). Signal processing methods were devised to mitigate sources of interference emanating from the vehicle itself and from passing traffic, as well as to achieve better detection and localization performance. The system was demonstrated to detect and track a screwdriver (substituting for an actual firearm) being carried in front of the test vehicle.

Operational and Commercial Viability Assessment

At the same time and using its own funds, QM began a more intensive investigation of the commercialization issues surrounding the conceptual patrol car-mounted system. Interviews were conducted with representatives from the SDPD, the Los Angeles Sheriffs Department (LASD), and the California Highway Patrol. Simultaneously with this study, NIJ and the Office of Law Enforcement Technology Commercialization (OLETC) also investigated the operational feasibility of the proposed usage scenario.

The result of these investigations was not so encouraging. Both QM and OLETC found, in discussions with law enforcement personnel, that Fourth Amendment protection precludes requiring a vehicle occupant to exit the vehicle at all, without prior probable cause. Conversely, if prior cause exists, then the officer already presumes that the suspect may be armed, and acts with appropriate caution. This eliminates the main usage scenario initially proposed by NIJ.

QM determined that other potential uses of the patrol car-mounted sensor exist. They include:

1. Officer protection during down time. In particular, the system could alert officers while they were performing record-keeping duties and other activities that remove their focus of attention from the world outside the car.

2. Scanning a pedestrian or groups of individuals on a sidewalk, while cruising by. Since the individuals being scanned are not being asked to behave in any specific way, this usage may not constitute a Fourth Amendment breach.
3. Scanning arrestees as part of the arrest procedure. In particular, if two officers are faced with controlling multiple individuals in a group arrest, they can lead individuals past the sensor and deal first with the ones concealing potential threats.

Unfortunately, none of these applications represents a sufficiently pressing need to make the system commercially viable at the anticipated sales price, between $1,000 and $3,000. The first application is of such low priority that the system would need to sell for no more than a few hundred dollars in order to be installed on patrol cars that are already perceived as being "too gadget-heavy". The second application represents a severe technical challenge, since the system would have to reject not only the interference of the patrol car itself, but also that from buried pipes, steel reinforcing, and the like, that contribute a temporally variable signal when the measurement is made in motion. The third scenario seems technically feasible but is of marginal interest to law enforcement.

For these reasons, NIJ has decided not to proceed to Phase III prototype development. QM has likewise decided not to invest in commercializing this technology for this application.

Program Value

Nevertheless, the program has been of significant value. The MR sensor element technology developed under this effort has gone into the sensors used in the weapons detection portals developed by INEEL and now being commercialized under license to an Idaho firm, Milestone Technology. The patrol-car sensor configuration is also under investigation, using QM funds, as an inconspicuous, stand-alone security sensor. Finally, it underpins an innovative concept for building security for which QM is presently attempting to secure development funding.

Some the localization algorithms first developed and investigated under the NIJ program have since been implemented in a vehicle detection and tracking effort for the U.S. Army, which may lead to technology that obviates the need for antipersonnel mines. Under Army funding, the algorithms have been further extended, so that both the range-moment and "ghost solution" ambiguities have been addressed and resolved.

TECHNICAL BACKGROUND

As stated previously, almost all firearms (aside from improvised devices) contain ferrous metals. The firing pin and firing chamber of all guns are made using ferrous steel alloys, because they have the requisite strength and toughness to withstand the stress of repeated explosive discharges. Many guns, even most so-called "low metal content" and "titanium" guns, also use steel to line the barrel. These ferrous alloys are magnetic, and thus distort the Earth's magnetic field in their vicinity.

The field distortion takes one (or both) of two forms. The magnetic permeability of ferrous steel alloys means that the Earth's field induces a magnetization in the material. This magnetization can be described as a magnetic dipole induced in the body. The expression for magnetic fields produced by a magnetic dipole is given by the following equation:

$$\boldsymbol{B}(\boldsymbol{r}) = (\mu_0/4\pi r^3)[\boldsymbol{M} - 3(\boldsymbol{M}\cdot\boldsymbol{r})\,\boldsymbol{r}/r^2]\,, \tag{1}$$

where boldface indicates a vector quantity, and $\mathbf{B}$ is the magnetic field produced at location $\mathbf{r}$ by a magnetic dipole of moment $\mathbf{M}$. Note that the moment is also a vector, denoting a magnitude and an orientation.

The second type of field distortion occurs if the material has acquired a permanent magnetic moment, like a small bar magnet's. This moment, technically called the "remanent moment", also produces a field expressed by equation (1). However, the value of $\mathbf{M}$ expresses not the magnetization induced by the Earth's field, but its own remanent magnetization. This remanent moment depends on the history of a given weapon: the conditions of its manufacture, and the history of its use. For example, the mechanical shock of discharging the weapon causes minute changes in the crystal structure of the steel, and these changes accumulate with repeated use. The remanent moment is, in effect, a record of the structural changes in the alloy from the weapon's use.

In general, the distortion from a given weapon can be expressed by a single equation, with the total magnetic moment given by the vector sum of the induced and permanent moments. The induced moment is often parallel to the Earth's field, while the permanent moment is fixed with respect to the object. Its orientation thus depends on the object's orientation.

Detection and Sensitivity

Equation (1) tells us that the field from a magnetic moment decays as the inverse cube power of the distance to that object. The longest range at which the magnetic distortion of the object can be detected depends on the size of the object's magnetic moment and on the amount of noise in the measurement:

$$r_{\max} \propto (M/B_{\text{noise}})^{1/3} \,. \tag{2}$$

Sources of noise in the magnetic field measurement that contribute to B_{noise} are twofold: sensor noise and environmental noise. The former provides the absolute limit on detection range under ideal conditions. The latter often provides the real limit under operational conditions. Sources of environmental noise include moving magnetic objects (other than the target sought), geomagnetic fluctuations (caused by solar, ionospheric and atmospheric activity), and magnetic fields from the electric power grid, among others.

Many of the environmental sources of noise, such as geomagnetic fluctuations, arise from distant sources. One way to suppress these sources of interference is to measure not the magnetic *field*, $\mathbf{B}$, but rather the spatial *field differences*, also known as *gradients*. This method is called magnetic field gradiometry.

Advantages of Magnetic Field Gradiometry

As mentioned above, one key advantage of gradiometry is the suppression of many sources of noise. The gradient is obtained by spatial differentiation of the field. Thus, while the field from a dipole decays as r^{-3}, its gradient decays as r^{-4}. This extra power of r makes the effect of distant noise sources diminish rapidly. Of course, the signal from the target decays with the same functional form, but gradiometry can provide a net increase in signal to noise ratio, and hence a net increase in detection range.

However, this is not the most important advantage provided by gradiometry. That advantage is *the ability to locate targets.*

Locating Targets Using Magnetic Field Gradiometry

In general, the problem of locating a concealed weapon is that of finding a magnetic dipole of unknown strength and orientation, $\boldsymbol{M}$, at an unknown location, $\boldsymbol{r}$. The problem involves solving for a total of six unknown quantities: three describing the target's moment, and three describing its location. A magnetometer, measuring the three components of magnetic field at a location, provides only three parameters, which are manifestly insufficient for locating the target.

One can measure spatial differences of the magnetic field along three orthogonal directions: $\{x, y, z\}$. Each component of the field $\boldsymbol{B} = \{B_x, B_y, B_z\}$ can be differentiated along the three directions. This yields a nine-component matrix, with elements of the form

$$g_{ij} \equiv \partial B_i / \partial x_j \tag{3}$$

called the *gradient tensor*. At first glance, measuring all nine components of the tensor should give more than enough information to be able to determine the six unknowns $\boldsymbol{M}$ and $\boldsymbol{r}$. However, Maxwell's Equation

$$\nabla \cdot \boldsymbol{B} = 0 \tag{4}$$

says that the trace of the gradient tensor is zero, so that

$$g_{11} + g_{22} = -g_{33} \tag{5}$$

and only two of the diagonal elements add information. Another Maxwell's Equation says that, in space free of electric currents (in air, for example)

$$\nabla \times \boldsymbol{B} = 0 \, . \tag{6}$$

This says that the gradient tensor is symmetric, so that

$$g_{ij} = g_{ji} \, , \text{ for } i \neq j \, . \tag{7}$$

The upshot is that only five of the nine tensor components are independent; any measurement of the gradient tensor yields five data to solve for the six unknowns. However, this is substantially more than the three provided by a magnetometer, and it helps locate the object. In practice, one solves for four quantities that give the bearing to the target – which direction one must look in – and the orientation of the target's dipole moment. The fifth solution is the quantity M/r^4, which combines the information about target size (moment magnitude) and target distance into a single quantity. This is called the "range-moment ambiguity".

A further complication arises from the fact that the equations to be solved involve the fourth power of r. The quartic equations have four mathematical solutions for the bearing and orientation of the target dipole. Of course, only one of these is the actual solution, and the other three are so-called "ghost solutions", or simply ghosts.

The best source for a detailed mathematical introduction to the problem, along with one algorithm to solve it, is given by W.M. Wynn.[3] Despite the difficulties, magnetic gradiometry provides the best method not only to detect, but also locate (measure $\boldsymbol{r}$) and characterize (measure $\boldsymbol{M}$) an unknown magnetic object with a compact sensor system.

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[3] W.M. Wynn, "Detection, localization, and characterization of static magnetic dipole sources." *Detection and Identification of Visually Obscured Targets*, C.E. Baum, pp. 337-374, Taylor & Francis, Philadelphia, 1999.

A Very Useful Scalar Quantity

In addition to providing the gradient tensor components for localization, tensor gradiometry provides another quantity that proves to be most useful: the scalar magnitude of the gradient tensor. This quantity is obtained as the Pythagorean sum of the nine tensor components:

$$G = [g_{11}^2 + g_{12}^2 + g_{13}^2 + g_{21}^2 + g_{22}^2 + g_{23}^2 + g_{31}^2 + g_{32}^2 + g_{33}^2]^{1/2} \qquad (8)$$

This scalar has a particular property: it is *varies directly with the proximity of a magnetic object*. This property is unique. For example, the total field magnitude, another scalar:

$$B = |\mathbf{B}| = [B_x^2 + B_y^2 + B_z^2]^{1/2} \quad , \qquad (9)$$

can either grow or shrink with proximity, depending on the relative orientation of the target dipole, the Earth's field, and the measurement location. We often use the tensor magnitude G to determine detection thresholds and to assess performance of the system.

Resolution of the Range-Moment Ambiguity and Ghost Solutions

One way to resolve the problem of unambiguous localization of a target is to repeat the gradient tensor measurement at two different locations. Only one of the four possible target bearings from each location will intersect, and that represents the actual target location. Once the location is determined, the target's moment can be calculated trivially.

This method is highly suitable to gradiometer measurements from a moving platform. However, for measurements from a stationary platform, as envisaged in the application pursued here, the method is onerous. Either one requires two gradiometers per patrol car, or one requires the single gradiometer to somehow oscillate back and forth between two positions. Both increase the cost and complexity of the system, which is unacceptable in such a price-driven market as law enforcement technology.

QM was not able to develop its localization algorithms under the NIJ funding to the point where the ambiguities were resolved. However, under subsequent Army funding, we were able to solve the problem. We realized that in a stationary measurement, we can still use the magnetic field (despite the potentially higher noise levels involved). *If* the magnetic field measurement is usable, we obtain three additional measurements for a total of eight, allowing us to resolve both the range-moment ambiguity and the ghost problem.

KEY TECHNICAL ISSUES AND RESULTS

In order for the proposed effort to be a success, the following six technical questions had to be addressed.

1. Can weapons be detected and located magnetically?
2. Can detection and localization both work in the presence of distorting steel objects?
3. Is the achievable detection range sufficient to be operationally useful?
4. Does interference produced by police vehicles degrade detection performance excessively?
5. Can low-cost MR sensors be configured to operate as a Magnetic Tensor Gradiometer (MTG)?
6. Does the low-cost MR MTG operate well enough to be operationally useful?

The following subsections address each question in turn.

Can Weapons Be Detected and Located Magnetically?

The affirmative answer to this question was certain even at the start of the Phase I effort. Quantum Magnetics had demonstrated detection and localization of magnetic objects many times over, in the course of extensive work with the U.S. Navy.[4] INEEL, in the early course of its work on a weapons detection portal for NIJ, had shown that passive magnetic sensing provides superior weapons detection, even of low-metal-content weapons that present difficulties for traditional (metal detection) portals.[5] These two pieces of information together provide the needed information.

Can Detection and Localization Work in the Presence of Distorting Steel Objects?

This question is crucial in the patrol-car application, since the car itself is a large steel object. The presence of the car has several consequences. The most important are the following.

1. The steel in the car distorts the Earth's magnetic field, itself.
2. The steel in the car distorts the signal from the target object.

The first effect is easy to deal with. The nonzero background gradients from the car are simply measured and subtracted arithmetically from subsequent data. Procedurally, the system would measure the background as soon as the patrol car came to a stop, or when commanded (by a simply button) by the officer.

The second effect does not make detection more difficult, but it makes localization indeed more difficult. Since the car distorts the shape of the signal from the weapon, an algorithm based on localization using the undistorted signal shape will yield an erroneous result.

To address this problem, QM developed a training algorithm. A magnetic dipole of known strength and orientation (a calibrated bar magnet) is placed at an array of known positions within the field of view of the detector. The ordinary localization algorithm is allowed to operate on the resulting data. It yields an erroneous result for the position of the target, because of the interfering steel. Both the actual target position and the calculated position are entered into a database. A second algorithm calculates the transformation that maps the calculated positions to the actual positions. It is thereafter applied to actual data on actual weapons.

Figure 1 illustrates the correction algorithm operating on data from an actual gun being carried through the QM lobby. The sensor is hidden in the kiosk under the potted plant at the foreground of the image. As the project Principal Investigator (PI) enters the front door (passing close to a load-bearing wall with a great deal of steel reinforcement), the algorithms calculate the

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[4] G.I. Allen et al., "Initial evaluation and follow-on investigation of the Quantum Magnetics laboratory prototype, room-temperature gradiometer of unexploded ordnance location. *Proc. SPIE*, **3711** (Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions), 103-112, 1999, and

P.V. Czipott et al., "Development of a man-portable room-temperature gradiometer – phase II: portable and fieldable prototype." *Proc. SPIE*, **3711**, (Information Systems for Navy Divers and Autonomous Underwater Vehicles Operating in Very Shallow Water and Surf Zone Regions), 113-122, 1999.

[5] L.G. Roybal et al., "New approach for detecting and classifying concealed weapons." *Proc. SPIE*, **2935** (Surveillance and Assessment Technologies for Law Enforcement), 96-107, 1997.

position of the gun (under his coat, in his waistband, on his left hip) correctly, despite the proximity of the steel. In real time, the algorithm superimposes a red icon showing the weapon's location on a security camera image. From the door, the PI moves to the center of the lobby and displays the weapon. The icon correctly indicates the weapon, now in his hand.

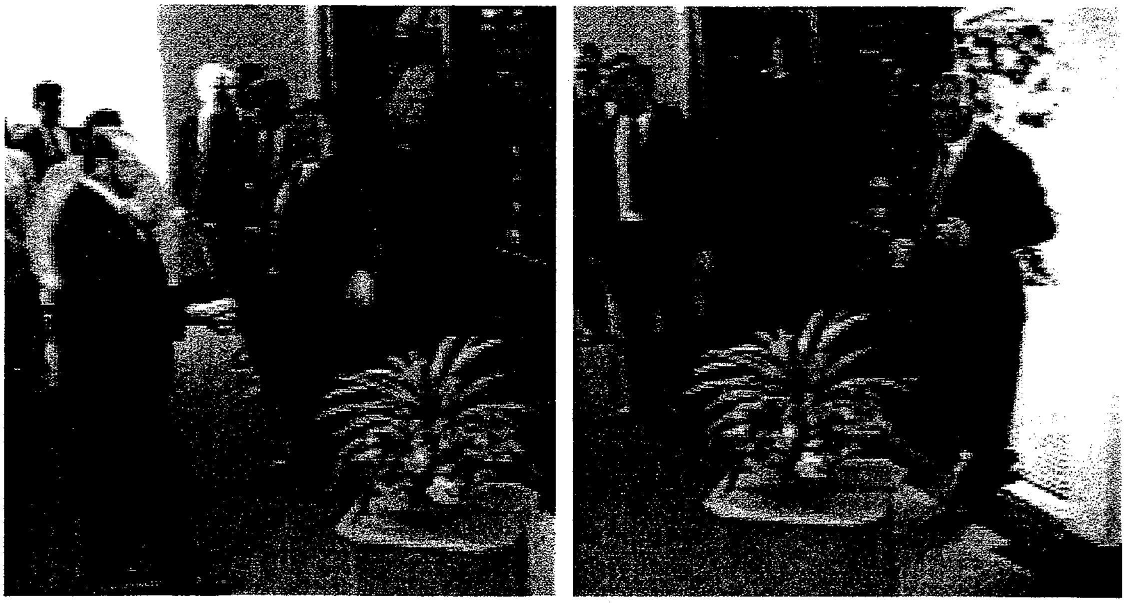

Figure 1. A person carrying a gun in the lobby of Quantum Magnetics. Entering (right) and displaying the weapon (left). The sensor (hidden under the plant in foreground) detects the weapon; computer algorithms display its location in real time as an icon superimposed on a security video camera image.

In the absence of the distortion-correcting algorithm, the icon would have been completely off the screen as the PI entered the lobby; it would have been approximately correct when the PI was in the center of the lobby area.

This demonstrates successful target localization, even in the presence of steel, as required for the success of the project.

Is the Detection Range to Weapons Sufficient for Operational Utility?

QM amassed a database of magnetic signatures from 39 different weapons and a larger number of potential clutter items, and analyzed their magnetic signatures. The histogram shown in Figure 2 presents the number of weapons detectable in one-foot range bins. The detection limit is based on the gradient signal from the weapon, compared to the noise level of the MR sensors used for the brassboard system. Maximum detection range is calculated where the signal equals the noise level as measured in the QM parking lot. The smallest weapons are detectable, on this measure, at a range of 8 feet from the sensor. Most weapons are detectable at ranges from 10 to 15 feet. Given that a bumper-mounted sensor is approximately 8 to 10 feet in front of an officer standing behind his/her door, the total separation between the weapon and the officer is adequate, giving him/her time to react.

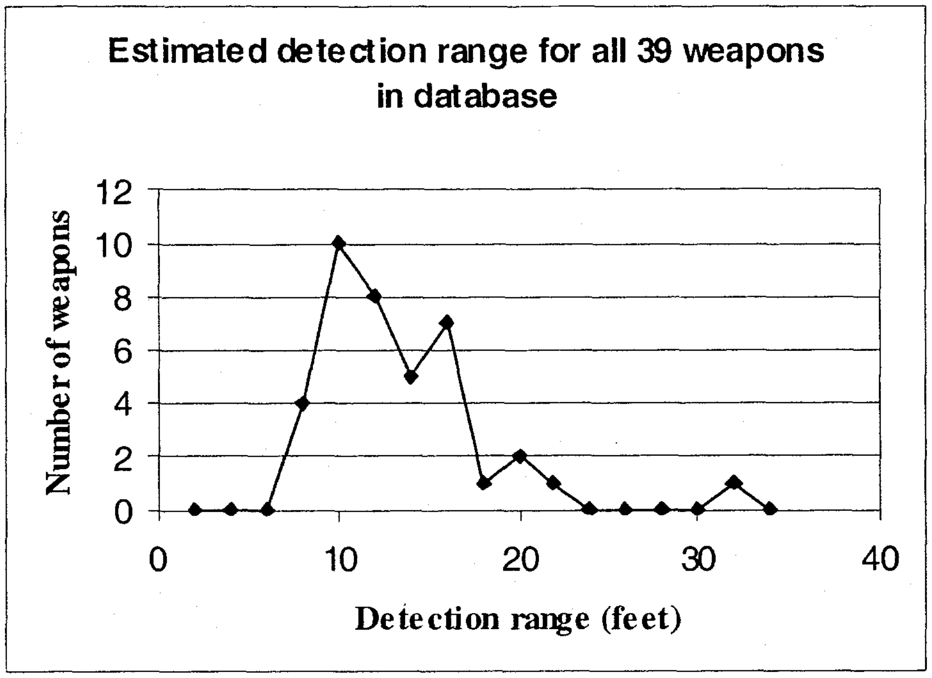

Figure 2. Histogram representing the number of weapons detectable at a given maximum range, for the 39-weapon QM database.

This data enabled an affirmative answer to this question.

Since completion of the NIJ effort and supported by internal funds, QM has investigated similar technology for use in portable, stand-alone weapons detectors. The effort has included collection of a much larger database of weapons signatures. Several local law enforcement agencies made their stores of confiscated weapons available for this purpose. The extended study has shown two things:

1. The magnetic signature of a given type of weapon (for instance, a given model of firearm) is variable over more than one order of magnitude. While considerable variation was expected, factors of 40 are surprisingly large. This means that knowing the magnetic moment of the potential threat is not as good at characterizing it, as originally thought.
2. The smallest signatures of the smallest weapons lead to shorter detection ranges than the histogram of Figure 2 had led us to believe. The least magnetic weapons can only be detected at ranges of approximately 2 feet from the sensor. This distance may still be operationally useful in the patrol car-mounted sensor application.

Does Interference Produced by Police Vehicles Degrade Performance Excessively?

The steel mass of a vehicle engine, chassis and body is only one form of vehicle interference. It causes a distortion of the Earth's static field, which is easily dealt with, as discussed above. It also distorts the signal from a weapon, for which we have developed a correction algorithm, also discussed above.

Other forms of interference occur at non-zero frequency and can lead to noise in the frequency band associated with magnetic objects moving at walking speeds. This band is roughly from 0.01 Hz up to no more than 3 Hz. These other forms of interference include the signal from engine operation. The engine includes steel or iron components (pistons, chains, and shafts) that reciprocate or rotate as the engine operates. The motion of these components then leads to periodic magnetic disturbances. Other sources of noise include electric currents flowing in the vehicle's systems, and time-variant gradients from opening and closing doors, among others. It is important to show that these sources of noise either do not interfere with the weapon detection measurement, or can be controlled.

Figure 3 shows noise spectra and time series of the quantity *G*, the gradient tensor magnitude, as a target is brought past the sensor. The pair of graphs on the left show the noise and signal with the engine of an employee's car turned off; the pair on the right show the same data with the engine idling. Noise levels are not appreciably different because the engine interference occurs at higher frequencies than those of interest.

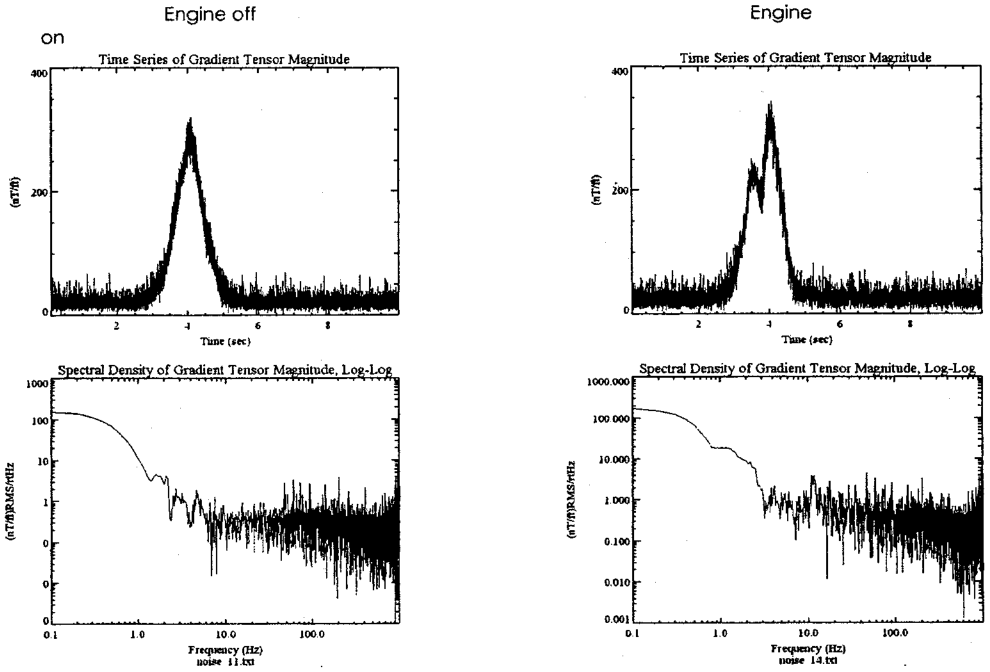

Figure 3. Time series (top) and spectral amplitude (bottom) of *G*, the gradient tensor magnitude, as a target is walked past the sensor mounted on a civilian vehicle. Left: engine off; right: engine on.

The only interference that proved intractable, during tests with QM employee vehicles, was the interference from repeatedly opening and closing a car door while a tracking measurement was in progress. This simply means that the officer must take care not to let the doors wobble while a suspect is being asked to walk past the sensor.

We then repeated similar measurements on a patrol car made available by the SDPD. We immediately noted much higher levels of interference under certain conditions. Police vehicles are equipped with many electronic systems not found on civilian cars, and these produce substantial magnetic interference. Even systems in common, such as air conditioning, produced much more interference on the SDPD vehicle. One of the largest interference sources proved to be the light bar, and even worse, the alternately flashing headlights of the police car. The fluctuating electric currents in these systems, with return paths allowed to flow through the car chassis, proved highly troublesome.

At first, the problem seemed daunting. However, we developed adaptive signal processing methods, using adaptive filtering techniques, that proved effective in removing most of the interference, so that we were able to achieve noise levels nearly as low as those obtained with the QM employee vehicles. Figure 4 shows the raw tensor magnitude (*G*) signal (in red) obtained for a weapon simulant (a screwdriver) being walked past the system adjacent to the police car. The target cannot be seen. The same signal after adaptive filtering (which is easily implemented in real-time operation) is shown in blue, on the same scale. The target signal is clearly seen, and the noise to either side is roughly equivalent to the noise from a QM employee's car.

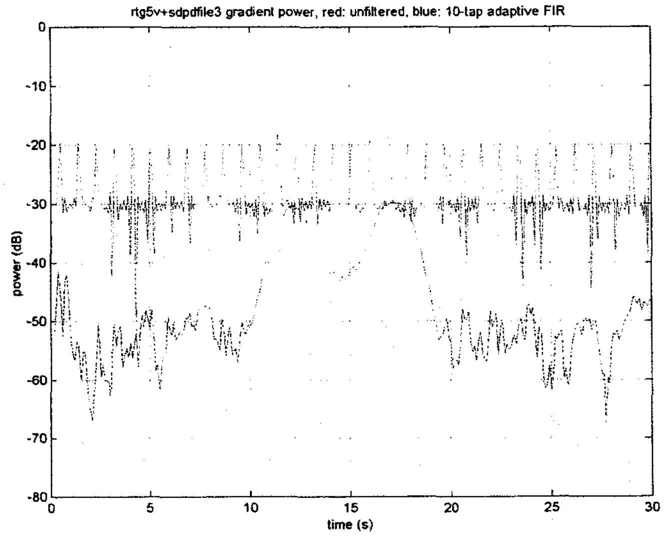

Figure 4. Time series of *G*, the gradient tensor magnitude, as a target is walked past the sensor mounted in front of a police cruiser with headlights flashing alternately. Red: raw time series. Blue: time series after application of an adaptive filter (using the first 2 seconds as the training data), revealing the target signal clearly.

One must note that adaptive filtering will not suppress interference that changes its spatiotemporal characteristic during a record. Interference of this kind includes the sudden start or stop of an air conditioning system, opening and closing doors, and the like. Tests showed that operating the officer's radio system does not produce detectable interference in the frequency band of interest.

Can MR Sensors Be Configured to Operate as a Magnetic Tensor Gradiometer?

Heretofore, magnetic tensor gradiometers (MTGs) had been fabricated using only either superconducting sensor systems or fluxgate magnetometers. The former, while exquisitely sensitive, are prohibitively expensive and require complex cryogenic refrigeration to operate. The latter, although less expensive and operating at ambient temperatures, remain beyond the budget of most law enforcement agencies. For example, the fluxgate magnetometers used in the Navy systems cost approximately $20,000; to this must be added the cost of the sensor structure, control electronics, and computer.

Magnetoresistive (MR) sensors are thin-film, mass-produced devices that are inherently inexpensive. While not as sensitive as fluxgate sensors, they offer sensitivity adequate for many applications. In the NIJ effort, QM sought to demonstrate that MR sensors could be configured into an MTG – a first for the technology. Figure 5 illustrates three MR sensors positioned on a sensor board developed by QM. The three MR chips fit in a volume the size of a penny spun on its axis.

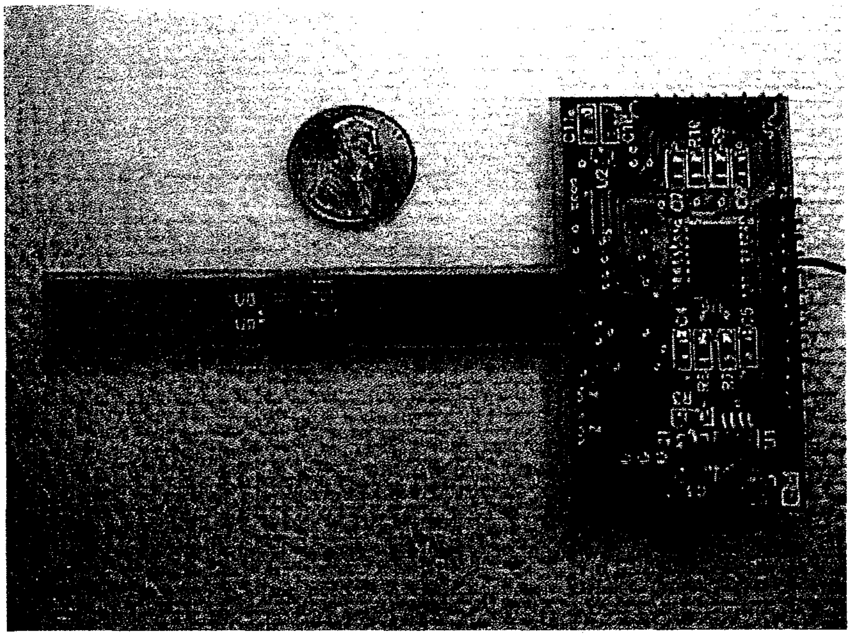

Figure 5. Three MR sensors mounted on the long stem of an electronics board that also contains the first-stage signal conditioning electronics (on the right-hand end). A penny provides scale.

Because funding for the effort was sparse, we used a sensor platform being developed for the U.S. Air Force. In order to achieve low-noise performance, the MR sensors must be operated in a region nearly free of ambient magnetic fields. This region is provided by three orthogonal coils carrying current to produce fields canceling the ambient field. The assembly is called a "flux cube". Figure 6 illustrates such a flux cube. The MR sensors lie at the center of the cube; the signal conditioning portion of the board (seen in its entirety in Figure 5) here can be seen protruding from the cube.

Feedback electronics use the MR sensors as null detectors and continually adjust the current in the flux cube coils to maintain null. The time variation in the current required to maintain null gives the time-varying magnetic field signal used to detect targets.

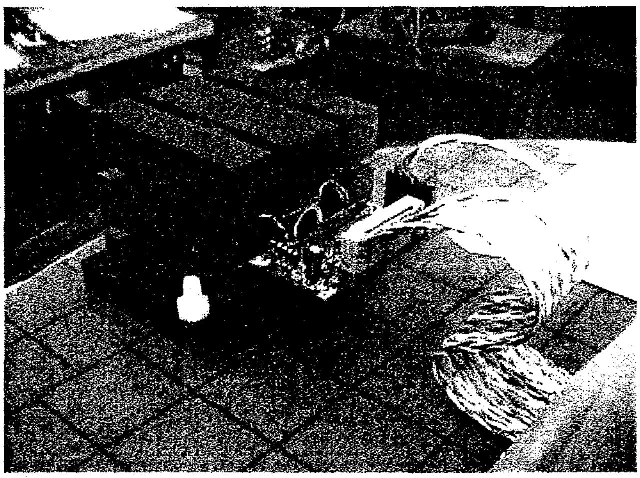

Figure 6. The MR sensor board installed in a flux cube. Current in three orthogonal coils cancels ambient fields for low-noise operation.

Figure 7 is a photograph comparing the Navy fluxgate and Air Force MR MTG platforms. Despite the small inherent size of the MR sensor, performance considerations led to an overall sensor size larger than the Navy MTG. Ongoing work, supported by the U.S. Army, is leading to more and more compact overall configurations.

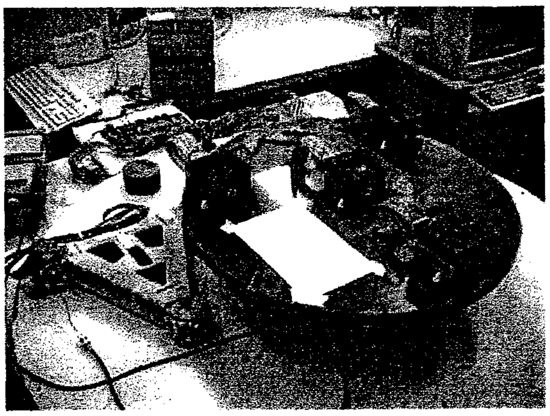

Figure 7. Photo showing the U.S. Navy fluxgate gradiometer (triangular structure to the left) and the first MR gradiometer, built with U.S. Air Force support (four flux cubes on a circular platform).

The gradiometer uses four flux cubes to enable low-noise measurements of all independent components of the gradient tensor. The central flux cube houses the "reference sensor", which measures the ambient fields and generates the current in all the flux cube coils. The other three flux cubes house the "primary sensors" that measure the spatial difference signals. Since they already operate in low field, the spatial difference signals can be measured with high gain and low noise. The common-mode signal represented by the Earth's field has been pre-canceled, thanks to the reference sensor.

This sensor configuration, crucial to attaining the dynamic range required for low-noise gradiometry, was invented by workers at IBM Research[6] and named the "Three-Sensor Gradiometer". QM has licensed the invention and helped to develop it further.

The electronics to operate the MR sensors, flux cubes and Three-Sensor Gradiometer are custom electronics developed by QM under direct NIJ support on this program. Figure 8 illustrates the main electronics board that operates the 12 MR sensor elements, four flux cubes, and the interface to a personal computer (PC), all under digital signal processor (DSP) control.

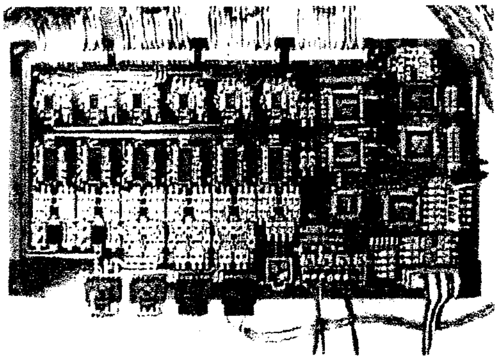

Figure 8. The main MR gradiometer electronics board, developed by QM under this NIJ program.

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[6] R. H. Koch et al., "Three Squid Gradiometer." *Applied Physics Letters*, Vol. 63, p. 403, 1993.

Does the Low-Cost MR MTG Operate Well Enough to be Operationally Useful?

QM designed the MR sensor electronics to provide the lowest noise possible. In consultation with the MR sensor element manufacturer, QM determined an optimal excitation and modulation scheme to suppress instrumental noise sources. Figure 9 shows noise spectra for all 12 MR sensor elements in the MTG. The noise levels, 100 $pT/Hz^{1/2}$ at 1 Hz at worst, represent well over an order of magnitude noise improvement over results obtained by the element manufacturer. The best reproducible results, around 20 $pT/Hz^{1/2}$ at 1 Hz, represent the absolute theoretical noise floor limit calculated by the manufacturer, but never before seen by anyone.[7]

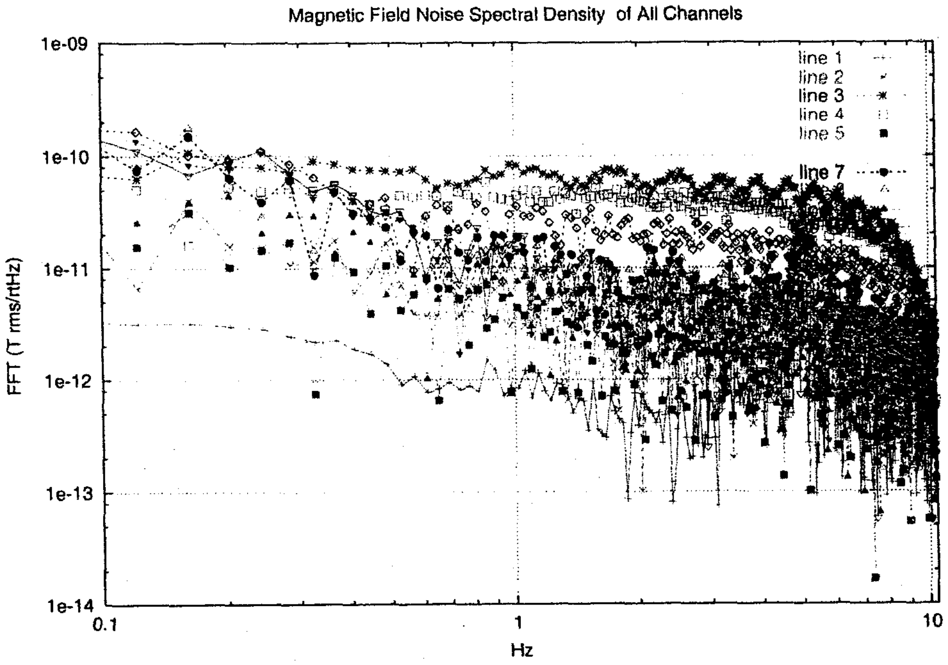

Figure 9. Noise spectra of each MR sensor element in the MTG. All sensors beat the noise target of 100 $pT/Hz^{1/2}$ at 1 Hz, which represents better than an order of magnitude improvement on previously achieved performance.

This sensor noise floor remains higher than the 5 to 10 $pT/Hz^{1/2}$ provided by the high-end fluxgates used for the Navy. However, direct comparison of MTG noise levels when operated in the QM parking lot shows that the two systems provide equivalent results. In other words, the system noise is dominated by environmental, not instrumental, effects for both systems. This is shown in Figures 10 and 11.

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[7] Y. Dalichaouch et al., "Development of a room-temperature gradiometer system for underground structure detection and characterization." *Proc. SPIE*, **4040** (Unattended Ground Sensor Technologies and Applications II), 74-82, 2000.

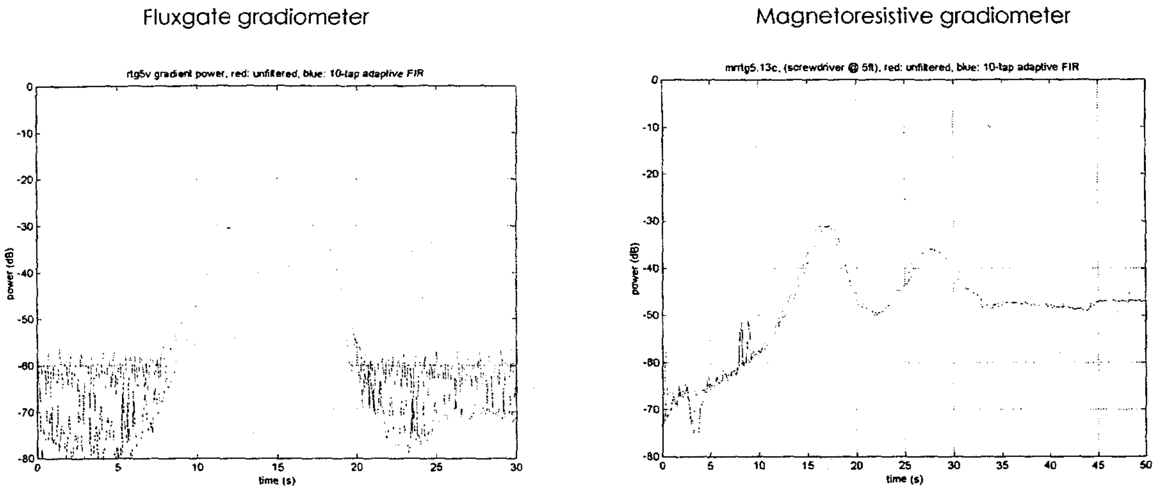

Figure 10. Direct comparison of time series of *G*, the gradient tensor magnitude, taken of the Navy's fluxgate MTG (left) and the Air Force/NIJ MR MTG (right) in the QM parking lot. Red traces indicate raw data; blue, adaptively filtered data. The feedback loop of the MR MTG had not yet stabilized when the data were acquired, accounting for the drift in background. However, the initial background noise level matches that of the fluxgate MTG.

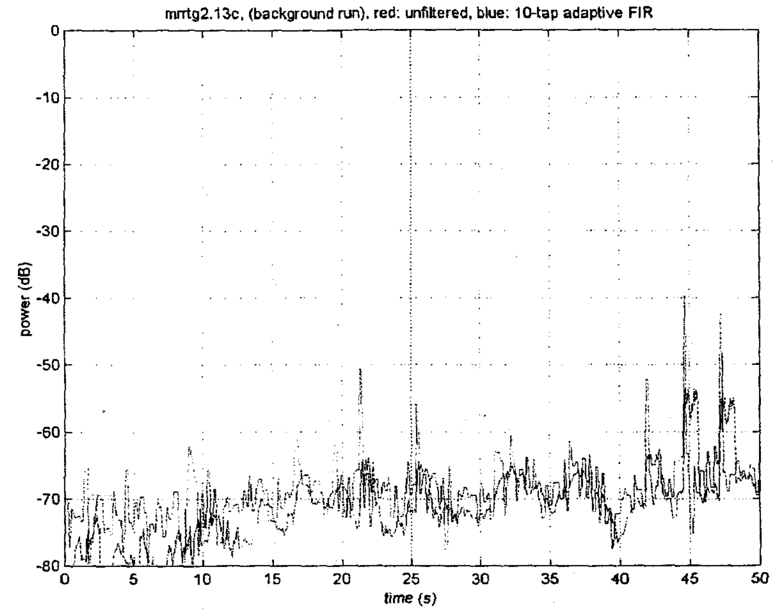

Figure 11. Background noise on the MR MTG after the feedback loop stabilized. Red trace: raw time series; blue: adaptively filtered data. The noise level remains comparable to the fluxgate gradiometer's (Figure 10) throughout the record.

These results demonstrate the operation of an MR tensor gradiometer in the open, yielding the operational performance required of the patrol car-mounted application scenario.

A Note on Data Collection

All data collected that show a target passing by the sensor were collected in the QM parking lot, in the configuration indicated by Figure 12. The configuration intends to replicate a typical roadside stop, with some gap between the patrol car and the suspect car ahead of it. A medium-sized screwdriver, with a magnetic moment corresponding to a medium-sized handgun, was used as the target. It was carried from the "suspect" vehicle back toward the "patrol car", then across the front of the "patrol car" where the sensor was mounted, and back. Data shown in previous figures represents the target at a five-foot closest approach to the sensor. Signals at 8 feet are approximately 10 times smaller.

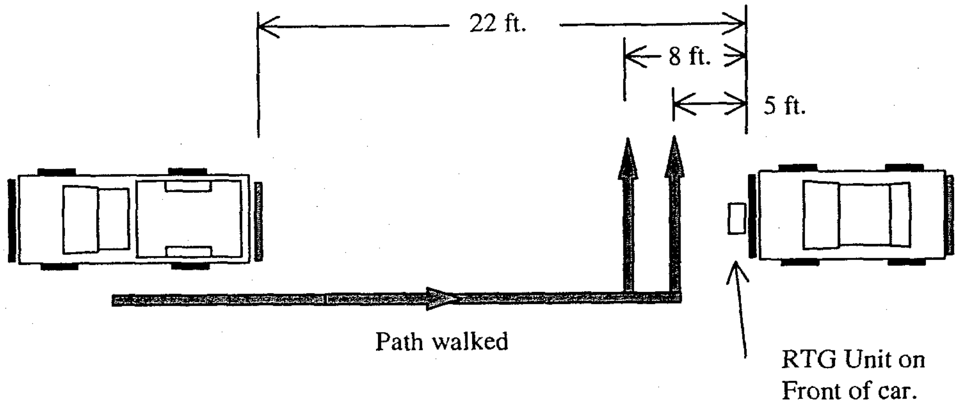

Figure 12. Schematic diagram of experiments on the MTG mounted to a vehicle.

MAJOR TECHNICAL ACCOMPLISHMENTS UNDER THE NIJ PROGRAM

- Fabrication and demonstration of a working magnetic tensor gradiometer (MTG) using magnetoresistive (MR) sensor elements – the first such in the world.
- Operation of MR sensors with noise floors below 1 $\mathrm{nT/Hz}^{1/2}$ at 1 Hz – a world record outside a magnetically shielded environment.
- Successful operation of MTGs mounted on vehicles to detect magnetic targets.
- Development of a robust algorithm to locate magnetic targets.
- Development of a robust algorithm to compensate for the distorting effect of nearby, stationary ferrous structures.
- Development of an adaptive filtering algorithm that suppressed patrol car interference by 20 dB.

CONCLUSIONS

The work performed under this cooperative research agreement was technically a great success. Several firsts were achieved. However, the basic application scenario identified by NIJ at the beginning of the program proved not to be feasible. The Fourth Amendment precludes an officer from requiring vehicle occupants to exit their vehicle without probable cause (such as attempts to evade arrest, hot pursuit, and the like). The entire purpose of the application scenario was to provide the officer with probable cause information, but the actions required are not allowed by law. Other potential uses for a patrol car-mounted system are either not high enough in priority to justify the acquisition cost, or too technically difficult to implement.

The work, however, finds ongoing application in other scenarios for law enforcement, building security, and military needs.