REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 16 April 2003

3. REPORT TYPE AND DATES COVERED
Technical Report, 1 Aug 2002- 31 Jan 2003

4. TITLE AND SUBTITLE
Personnel Detection Technology Assessment: Final Report

5. FUNDING NUMBERS
[redacted]
DAAD19-02-1-0340

6. AUTHOR(S)
Brian Baertlein
Randolph Moses

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Ohio State University, Department of Electrical Engineering
Columbus, OH 43212

8. PERFORMING ORGANIZATION
REPORT NUMBER 743391-2

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING
AGENCY REPORT NUMBER

44372.1-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The sensor and processing technologies relevant to detection of dismounted personnel (hereafter, simply "personnel detection") were investigated. The need to detect personnel arises in a variety of military and civilian situations. To provide a basis on which to compare sensor and processing technologies, we defined five baseline military scenarios in which personnel detection would be necessary. The distinctive characteristics of personnel were enumerated, and sensors with the potential to detect those characteristics were studied. The sensor study suggests that while many sensors are very mature, restrictions exist on each of the sensors that prevent any one technology from meeting the requirements defined by the scenarios. In particular, few of the sensors have adequate range for perimeter control and covert detection/tracking scenarios. It was concluded that, in general, fusion of data from distributed sensor networks will be required to meet the scenario requirements. Recommendations are provided for specific sensor development, data collection, and processing algorithm development.

14. SUBJECT TERMS
Personnel detection, sensors, fusion, distributed sensor networks

15. NUMBER OF PAGES
50

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Personnel Detection Technology Assessment

Final Report

Prepared for:

Dr. William Clark
Associate Director, Electronics Division
US Army Research Office
ClarkWW@aro.arl.army.mil
(919) 549-4314

Prepared by:

Dr. Brian Baertlein, baertlein.1@osu.edu (614) 292-0076
Prof. Randy Moses, moses.2@osu.edu (614) 292-1325
Department of Electrical Engineering
The Ohio State University
Columbus, OH 43212

Contract Number DAAD19-02-1-0349
Project Number E-44372-EL-000-02204-1
OSU Project No. 743391

OSU ESL Report 743391-2

16 April 2003

Table of Contents

Executive Summary

The Ohio State University (OSU) investigated sensor and processing technologies relevant to detection of dismounted personnel (hereafter, simply "personnel detection" or PD). This document comprises the final report of that effort.

The need to detect personnel arises in a variety of military and civilian situations. To provide a basis on which to compare sensor and processing technologies, we defined five baseline military scenarios in which PD would be necessary. These include (1) perimeter control, (2) covert detection and tracking of personnel over a (possibly moving) region, (3) detection in urban environments, (4) interrogation of tunnels and bunkers, and (5) smart monitors of portals and perimeters that can distinguish between authorized and unauthorized personnel.

The distinctive characteristics of personnel were enumerated, and sensors with the potential to detect those characteristics were reviewed. These sensors ncluded (1) passive EO sensors in both visible and IR bands; (2) passive acoustics (microphones); (3) passive chemical sensors of molecular vapors (olfactory sensors) and bioaerosols; (4) passive low frequency electromagnetic (EM) sensors of both bioelectromagnetic signals (cardiac and neural functions) and passive sensors of ferrous metal; (5) passive imaging EM sensors at microwave, millimeter wave, and THz bands; (6) active ranging sensors including radar, sonar, and lidar; (7) active low-frequency EM sensors (metal detectors); (8) x-ray backscatter imagers; and (9) remote EO sensing of atmospheric composition and bioaerosols. Summaries of the only fielded PD sensors, the REMBASS II system and the AN/PPS-5D radar, are also included.

The aforementioned study suggests that several sensors have a possible role in PD. Many of those sensors are quite mature, and inexpensive COTS products are available in some cases. There are, however, restrictions on each of the sensors that prevent any one technology from meeting the requirements defined by the scenarios. In particular, few of the sensors have adequate range for perimeter control and covert detection/tracking scenarios. It was concluded that, in general, distributed sensor networks will be required to meet the scenario requirements.

Motivated by the sensor study findings, reviews of information fusion and sensor networking were performed. Although these topics will be essential to successful PD, they are relatively immature. Both topics are currently areas of active research. Although these topics have traditionally been considered independently, recent approaches to distributed sensor networks tends to integrate the functions of sensor control, resource allocation, information fusion and networking. Some key concepts and recent relevant work were reviewed.

Based on the findings reported here, the following recommendations were offered: First, a basic research study of personnel signatures is required. Although the signatures of military vehicles, aircraft, and even terrain have been studied in some detail, there is relatively little information on the signatures of personnel.

Second, a modest effort in sensor development is suggested. In general, further sensor research is unlikely to produce significant gains in PD performance, but a few sensor concepts bear further investigation. Among these are (1) sensors of olfaction, (2) compact, low-power bistatic radar receivers, and (3) EO sensors of remote atmospheric composition.

Third, research should be performed in the areas of information fusion and distributed sensor networks. A multi-sensor data set with thorough ground truth should be collected and seeded to interested research groups around the country. To explore promising concepts, a sensor network testbed should be constructed from modular components that will permit novel algorithms and sensor suites to be tested.

1.0 Introduction

The detection of human presence has always been critical to success in warfare, law enforcement, and search and rescue operations. The detection of dismounted personnel (hereafter, simply personnel detection or PD), has become particularly urgent as a result of the global war on terrorism and recent military operations by the US and other nations.

The need to advance US capabilities in personnel detection was recognized by the US Army Research Office (ARO). The Ohio State University was tasked to assess the status of sensors and signal processing technologies relevant to PD, and to identify areas where further research would benefit the US military. Significant benefits to civilian applications of PD will also accrue from this research, but needs specific to civilian applications were not explicitly considered in this work.

The study presented here has a broad scope. Personnel generate a variety of phenomena that are potentially detectable. In addition, processing technologies, specifically, fusion and distributed networking, will be essential in reaching adequate levels of performance. A vigorous attempt was made to be as complete and as inclusive as possible given the inescapable restrictions of finite resources. The authors will be pleased to accept any information regarding errors and omissions.

The work is organized as follows: Some PD scenarios of military importance are defined in Section 2. Potentially detectable characteristics of personnel are enumerated in Section 3. Sensors capable of detecting those characteristics are reviewed in Section 4. Processing issues that arise in PD are discussed in Section 5. Summary remarks appear in Section 6. Section 7 presents recommendations for future research.

In addition to this report, ARO also sponsored a two-day workshop on PD. During the workshop experts from academia, the Government, and industry were invited to speak on PD-related issues and to participate in group discussions. A portion of the information in this report and some of its major conclusions were drawn from the workshop discussions. The workshop proceedings are documented separately,[1] and may be consulted for additional information.

[1] B. Baertlein and R. Moses, Proceedings of the Workshop on Military and Civilian Applications of Personnel Detection, November 7-8, 2002, Columbus, OH, OSU ElectroScience Lab Report 743391-1.

2.0 Detection Scenarios

The conditions under which detection must occur determine (to a large extent) the sensors that should be brought to bear. In the course of this study the authors defined a number of general detection scenarios, which were later refined during the PD workshop. In this section we list and describe those scenarios. We provide for each scenario an indication of the sensor range and field of view required.

1) **Title:** *Temporary Perimeter Control*
Objective: Detect ingress of personnel along a user-defined perimeter.
Requirements: The system must be readily deployed, with the intention of later removing it or replacing it with a more substantial structure (e.g., a fence). The adversary personnel may be using the natural terrain and acoustic stealth to approach the perimeter. Ranges of interest extend from 100 meters to 1 km, although the concept could be expanded to include the continental U.S. (for Homeland Security). Airborne deployments are possible, as are deployments in lakes and rivers.

2) **Title:** *Covert Volume Monitoring*
Objective: Detect and track all personnel within a user-specified volume.
Requirements: The sensors may be deployed on a moving platform, in which case the volume of interest changes with vehicle location. The target personnel may or may not be aware of the sensors. Detection of ambush situations is necessary. (A scenario of special concern is the ambush of lightly armored FCS vehicles by personnel with shoulder-fired anti-tank weapons.) Ranges of interest extend to 2 km. Airborne deployments are possible.

3) **Title:** *Urban Environments*
Objective: Detect personnel within buildings.
Requirements: The buildings of interest are at most a few stories tall and less than 100 meters in horizontal dimensions. Building materials may include wood frame construction, brick, concrete blocks, or other local materials. Windows may or may not be present. The targets may be actively using the infrastructure for concealment. Covert detection may be required.

4) **Title:** *Tunnel/Bunker Interrogation*
Objective: Detect personnel within a tunnel or bunker structure.
Requirements: The sensor may have access to the entrance of the structure, or it may be mounted on mobile platforms that can enter the facility. (Detection of the tunnel or bunker is a separate task, not included here.)

5) **Title:** *Smart Perimeter Monitors*:
Description: Detect and classify (as friend or foe) personnel in high traffic environments.
Requirements: The relevant sensors may have very-short ranges (a few meters) and should be designed for indoor or urban environments, in which they (1) distinguish between authorized and unauthorized personnel in restricted areas, or (2) detect possible adversaries in unrestricted areas with high pedestrian traffic. A possible use for the sensors is to guarantee that a building remains secure after it has been cleared by friendly forces, or to protect the rear and flank of mobile troops. These sensors should be easily deployed.

3.0 Detectable Characteristics of Personnel

Humans directly or indirectly give rise to a number of phenomena that are potentially detectable. The goal of this section is to provide an exhaustive list of phenomena that might be detected by either passive or active sensors.[2] In Section 4 we describe sensors that address essentially all of the phenomena listed here.

3.1 Passive Sensors

Humans produce a number of phenomena that are detectable by passive sensors. Passive sensors are of particular interest in sensor networks, because of their low power requirements and their lower probability of interdiction. Many passive personnel signatures are quite weak.

3.1.1 Motility

Personnel move and, in doing so, affect their environment. Motion is a necessary component of most hostile activities, but it can also be suppressed for short durations. Motion produces a diverse range of detectable phenomena including acoustic and seismic signatures. More generally, however, motion is detectable by any sensor capable of change detection including, for example, differencing successive frames of an imaging sensor.

3.1.2 Metabolic Processes

Normal metabolic processes generate a large number of potentially detectable phenomena, which include the following:

3.1.2.1 Bioelectric Activity

Nerve impulses generate very weak bioelectric signals that can be detected by external probes at short ranges. The sources of these signals include the brain, heart, and skeletal muscles.

3.1.2.2 Internal Motion of Organs

Both respiration and cardiac action produce internal motion that are detectable by external sensors.

3.1.2.3 Chemical Releases to the Environment

Personnel cause material to be released to the environment through a variety of processes:

- Respiration results in a release of CO_2 and water vapor.
- The natural sloughing of dead skin cells releases particulate matter.
- Skin contact transfers natural oils and perspiration
- Skin secretions can produce aerosols and (by evaporation) airborne gases.

Some animals exploit these natural processes. The respiration-related increase in CO_2 is reportedly a cue for insects. Dogs are adept at detecting human chemical signatures. These cues are short range, but they persist over a "trail" that aids in tracking.

3.1.2.4 Temperature

Mammals sustain a relatively high body temperature. This signature is exploited by some snakes in their search for prey.

[2] In this work an "active" sensor is one for which the energy received by the sensor was produced by the sensor. A "passive" sensor receives energy produced by another source, possibly the target or the environment. In most cases, the difference between active and passive sensors is clear. For example, a monostatic radar is an active sensor, while a thermal imager is a passive sensor. For other sensors, however, the distinction is less clear. For example, the source for a bistatic radar may reside on a different platform, while the receiver is completely passive.

3.1.3 Communication

Personnel typically communicate verbally, often using artificial channels (e.g., radio propagation). All such signals are by definition detectable by passive sensors. Communication can also be suppressed for short durations.

3.1.4 Shape

The human form is readily identified by humans, with special emphasis on faces. Detection of this shape is possible using imaging sensors.

3.1.5 Presence of Tools

Personnel often require the use of tools or weapons to accomplish their mission. In some cases (especially when metallic tools are used), the tools may be more detectable than their user.

3.2 Active Sensors

Humans differ from their surroundings in several ways, and this difference can be detected by active sensors. A number of the passive phenomena listed above, most notably, motion, are also detectable by active sensors. The presence of metal tools is also commonly sensed using an active sensor (the electromagnetic induction sensor).

3.2.1 Physical Properties of Tissue

Human tissue has a number of properties that can be detected.

3.2.1.1 Chemical Composition

Biological tissues have a high water content and a high concentration of certain organic compounds. These properties can be used to distinguish tissue from most rocks and building materials. Short range sensors exist (for example, x-ray backscatter) that exploit chemical composition.

3.2.1.2 Electrical Conductivity and Permittivity

Human tissue approximates an aqueous saline solution. Over the frequency range from 10 Hz to 10 GHz the electrical conductivity[3] of tissue ranges from 0.5 to 9 Siemens/meter and the relative permittivity ranges from 35 to 10^6. In contrast, the properties of most natural and man-made materials, though also highly variable, are generally much different.[4] These diferences can be exploited by electrical sensors and radar.

3.2.1.3 Reflectivity and Emissivity

The optical reflectivity and emissivity of skin are clearly key parameters in the performance of EO sensors. Although the spectral reflectivity of skin varies with race and environmental exposure in the visible band, skin is a much more stable material at longer wavelengths. Steketee[5] measured the emissivity of living skin (white, black and burned) over the spectral regime from 1-14 μm. It was found that skin is well approximated by a black body, having a wavelength-independent response over that band, and an emissivity of $\varepsilon=0.98\pm0.01$.

---

[3] K. R. Foster and H. P. Schwan, "Dielectric Properties of Tissues," in *Handbook of Biological Effects of Electromagnetic Waves*, C.Polk and E. Postow, eds., CRC Press, pp. 27-96, Boca Raton, FL, 1986

[4] A. von Hippel, *Dielectric Materials and Applications*, Artech House, Boston, MA, 1995.

[5] J. Steketee, "Spectral emissivity of skin and pericardium," *Phys. Med. Biol.*, Vol. 18, pp. 686-694, 1973.

3.2.2 Clothing.

Covertly operating personnel tend to select clothing or artificial skin colorings that reduce observables in the visual band. Information on the reflectivity of such materials is not evident in the literature.

3.2.3 Response to Stimuli

Personnel respond strongly to certain stimuli (e.g., a sudden noise). Some of these responses are involuntary and not easily suppressed. Appropriate combinations of stimuli and sensors could be developed to exploit these responses.

4.0 Relevant Sensor Technologies

In this section we review sensors that can exploit the phenomena identified in Section 3. The discussion is organized by sensor type. For each type we provide a discussion of the detectable phenomena, the relevant physics, some potential countermeasures, and the current state of the art. At this time the US military has only two systems in the field that are designed explicitly for PD: the REMBASS system, and the AN/FPS-5D radar. Both of those systems and their capabilities appear in this section (see Sections 4.6.2 and 4.10).

An important class of sensor not considered here is passive detection of electronic communications. Those sensors and the supporting technologies are already mature, and they are currently used for other applications including ELINT and EW. Although such sensors are not discussed here, their products will be useful inputs to a multi-sensor PD system.

4.1 Passive Electro-Optical (EO) Sensors

Sensors that mimic the human visual system (and its extension to other wavelengths) are valuable information sources, particularly when aided by human (or machine) interpretation.

4.1.1 Sensor Concept

4.1.1.1 Detectable Phenomena

The phenomena detectable by a passive EO sensor include

- shape (for imaging sensors),
- thermal emission (for imaging and non-imaging thermal IR sensors), and
- movement.

4.1.1.2 Sensor Physics

In this section we describe the physics that determine the signal-to-noise ratio (SNR) obtained by an EO sensor. For many imaging EO sensors, detection is not so much constrained by signal-to-noise ratio as by signal-to-clutter ratio. In those cases the sensor‘s ability to perform detection is largely determined by the performance of the image processing algorithms involved. Estimating the performance of such algorithms is beyond the scope of this document.

The SNR of an EO sensor can be expressed as:

$$\frac{S}{N} = \frac{P_r}{NEP}$$

in which P_r is the target power received by the sensor, and NEP is the noise equivalent power at the receiver. If the sensor has a receiving aperture with diameter D, and the irradiance falling on it is E_t, then P_r is given by

$$P_r = E_t\left(\frac{\pi D^2}{4}\right)$$

in which we have assumed that the irradiance arrives normal to the aperture. The target radiance is generally a combination of reflected ambient light and emission. Here we consider only the case of emission. A reflecting target oriented normal to the sensor can be analyzed using a similar approach if we make the substitution

$$E_t \to E_s \frac{A_t}{4\pi R^2} B$$

in which E_s is the irradiance of the source (e.g., the sun), A_t is the target surface area, R is the distance between the source and the receiver, and B is the bi-directional reflectance distribution function (BRDF) of the surface.

An emitting surface at temperature T_t will emit an irradiance E_t in accordance with Planck's law. We find

$$E_t = \frac{A_t \int_{\lambda_1}^{\lambda_2} M(\lambda, T_t)\varepsilon(\lambda)\tau(\lambda)d\lambda}{\pi R^2}$$

in which $\tau(\lambda)$ is the transmission of the atmosphere between the source and receiver, λ_1 and λ_2 are the wavelengths [in μm] that define the sensor passband, $\varepsilon(\lambda)$ is the emissivity of the target, and M is the spectral exitance predicted by Planck's law

$$M(\lambda, T) = \frac{c_1}{\lambda^5}\left(\frac{1}{e^{c_2/\lambda T} - 1}\right) \quad \left[\mathrm{Wm^{-2}}\mu\mathrm{m^{-1}}\right]$$

where

$$\begin{aligned} c_1 &= 2\pi c^2 h = 3.7413\times 10^8 \quad \left[\mathrm{W\ m^{-2}}\mu\mathrm{m^4}\right] \\ c_2 &= hc/k = 1.4388\times 10^4 \quad \left[\mu\mathrm{m\ K}\right] \end{aligned}$$

Approximating the emissivity and path transmittance as wavelength independent, we find

$$\begin{aligned} E_s &\approx \frac{A_t \tau\varepsilon \Delta M(\lambda_1, \lambda_2)}{\pi R^2} \\ \Delta M(\lambda_1, \lambda_2) &= \int_{\lambda_1}^{\lambda_2} M(\lambda, T_t)d\lambda \end{aligned}$$

which leads to

$$\frac{S}{N} = \frac{A_t \tau\varepsilon \Delta M(\lambda_1, \lambda_2) D^2}{4R^2 NEP}$$

The noise equivalent power (*NEP*) can be expressed in terms of the sensor's specific detectivity *D**, the detector area A_d, and the receiver noise bandwidth Δf. We find[6]

$$\frac{S}{N} = \frac{A_t \tau\varepsilon \Delta M(\lambda_1, \lambda_2) D^2 D^*}{4R^2 \sqrt{A_d \Delta f}} \tag{1}$$

[6] L. J. Pinson, *Electro-Optics*, Wiley, p. 145, 1985.

Scan rates are also an important issue in target detection. The noise bandwidth Δf is ultimately bounded by the reciprocal of the dwell time on target, which implies that increasing the scan rate will reduce target detectability. The dependence on $(D/R)^2$ is also important and is a limiting factor in many applications.

4.1.2 Technology Status

Weatherproof non-imaging passive IR sensors for perimeter monitoring are currently available as COTS systems. Cameras operating in the visible band are both compact and inexpensive. A COTS monochrome camera with 550x557 pixels having a 6 mm micro lens (26°x34° FOV, f/2.5) is available for less than $300.[7] The device has a maximum power consumption of 1 Watt, a volume of 9.4 cm^3 (excluding lens) and a mass of 19 grams (excluding lens).

COTS non-imaging IR sensors are also available but are typically much larger. Southwest Microwave[8] offers a narrow-field of view non-imaging sensor operating in the 8-14 µm LWIR band. The sensor weight is 1.8 kg (4 pounds). Power requirements are listed as 10-28 V and 30 mA maximum (0.3 to 0.84 mW maximum). The vendor claims a range of 107 meters (350 feet).

The most compact imaging IR camera currently available is the Omega LWIR camera from Indigo.[9] This uncooled micro-bolometer detector has a 160x120 pixel focal plane and a spectral response from 7.5-13.5 microns. The noise equivalent temperature difference (NEΔT) is <85 mK. The device volume is approximately 61 cm^3 (without lens), and its mass is < 120 g. The power consumption is quoted as <1.5 Watts nominal.

4.1.3 Countermeasures, Outlook and Net Assessment

Passive EO sensors are highly susceptible to countermeasures, since those sensors require a line of sight. Any opaque surface can provide temporary concealment, and humans are adept at conforming their bodies to the shapes of nearby obstacles when necessary. Concealing coloration is used in military uniforms world-wide, which reduces the effectiveness of sensors in the visible band. The need for an unobstructed line of sight has important consideration for sensor deployment. EO sensors are unlikely to be useful in ground-laid scatterable sensors because of the poor field of view, but they can be profitably deployed in trees, on the sides of buildings, and on airborne platforms.

In spite of their shortcomings, we believe passive, imaging EO sensors will play a major role PD technology. The intuitive data products, compact size, low power requirements, and low cost of such sensors make them very attractive. A final consideration is the processing power required to interpret image data. The size and power requirements of that processing can easily exceed the sensor's requirements. The device may be forced to uplink the data to a central location for analysis.

4.2 Passive Acoustic Sensors

As analogs of the human auditory system, passive acoustic sensors are both intuitive and capable of generating considerable information. In this section we review issues with these sensors.

4.2.1 Sensor Concept

---

[7] Such sensors are widely available. As an example, see Edmund Scientific, model E55-702.
[8] See http://www.southwestmicrowave.com/products.html
[9] See http://www.indigosystems.com/omega_specs.html

4.2.1.1 Detectable Phenomena

Personnel generate acoustic signatures via several phenomena including

- footfalls;
- vocalization;
- the use of tools, including weapon fire or explosions; and
- noises produced by vehicles or other activities (e.g., door openings, glass breaking).

4.2.1.2 Sensor Physics

The physical basis for acoustic sensors is well understood. Pressure variations produced by a localized source propagate to a receiver as spherical waves. At 20º C and standard atmospheric pressure, the speed of sound propagation is 343 m/s. For the range of frequencies audible to humans (roughly 20 Hz to 20 kHz) this corresponds to wavelengths of 17 m to 17 mm.

SNR calculations for acoustics sensors are traditionally done using dB referenced to a pressure level of 20 micro-Pascals (20 μPa). A detection threshold (DT) expressed in dB is given by

$$DT=RSL-DNL$$

in which RSL is the received signal level at the receiver and DNL is the detected noise level. The received signal level is the source level (SL) reduced by transmission losses (TL). We write

$$RSL=SL-TL$$

The source level depends on the sound produced by the source and on its directivity. The sound pressure levels produced by some events of interest (both signal and noise) in PD span an extremely wide range. Some sound levels for personnel-generated events and for background noise are presented in Table 1.

Table 1. Some Acoustic Phenomena Relevant to PD[10,11]

Source	Pressure [dB ref. 20 μPa]
Passenger car at 100 km/hr at 7.6 m (25 ft)	80
Shouting at 1 meter	80
Normal conversation at 1 meter	60
Whisper at 1 meter	20
Background traffic noises [light traffic at 30 m (100 ft]	50-60
Wilderness area	20-30

[10] E. Boeker and R. van Grondelle, *Environmental Physics*, p. 300, Wiley, New York, 1995.
[11] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics,* 4th ed., p. 361, Wiley, New York, NY, 2000.

The transmission losses depend on the local environment. In the absence of interfering reflections from the earth or other nearby surfaces, these signals attenuate as the inverse square of distance from the source. We have

$$TL = 10\log_{10}(4\pi R^2)$$

in which absorption by the medium (assumed to be dry air) has been neglected.

Reflections from the environment can modify transmission losses significantly. Those reflections may enhance or attenuate the signals with respect to normal free-space attenuation, and they also tend to disperse the waveform in time (i.e., to introduce echoes).

Infrasonics, the study of sound at frequencies below the range of human hearing (i.e., below about 20 Hz), is another area of active research. Infrasound sensors have been used in such applications as earthquake and avalanche prediction, atmospheric sounding, and meteorology.[12] Infrasound is also used for long-range communication by large mammals. Elephants have been found to emit sounds at frequencies of 5 Hz and up for locating other animals over large distances. The favorable propagation properties of infrasound make it attractive for detection of vehicles over long distances. Infrasonics have been explored as a basis for anti-personnel weapon systems, but there is little information on the production of infrasound by personnel.

4.2.2 Technology Status

Acoustic microphones are a very mature technology. COTS microphones have been widely used both singly and as arrays (for detection and direction finding) in a variety of military systems.

As an example of the sensor technology, we note the Emkay[13] model BL-1994 (Itsaca, IL), which has a volume of 1.2 cm (0.5 in) by 1.2 cm (0.5 in) by 2.5 cm (1 in.) and a power consumption of 0.5 mW (including the integrated FET amplifier). The spectral response is flat from below 20 Hz to 10 kHz.

4.2.3 Countermeasures, Outlook and Net Assessment

Passive acoustic sensors are currently used in fielded PD systems (see the REMBASS discussion in Section 4.10 below), and because of their low cost, low power requirements, mature status, and relative effectiveness, they will probably continue to be used.

Nonetheless, acoustic sensors are readily susceptible to countermeasures and, as a result, the adversary must be unaware of their presence for them to be effective. Humans find it easy to avoid many common sources of acoustic noise, and trained personnel can operate in an acoustically stealthy manner. Any of the detectable phenomena identified above can be suspended for an indefinite period if necessary.

4.3 Passive Chemical Sensors

Sensors of olfaction and other methods for assay of personnel chemical signatures are promising (as evidenced by the well known effectiveness of dogs in detecting and tracking personnel), but still under development. A number of important research issues remain unsolved. Some active EO sensors are also suitable for this task and are discussed in Section 4.9 below.

[12] Geophysical uses of infrasonics are discussed at http://www.etl.noaa.gov/et1/infrasound/
[13] See http://www.emkayproducts.com/

4.3.1 Sensor Concept

4.3.1.1 Detectable Phenomena

The phenomena detectable by an olfactory sensor are personnel-generated molecular gases (for example, CO_2 generated by respiration) and bioaerosols, i.e, the particles and airborne liquid droplets generated by personnel.

4.3.1.2 Sensor Physics

Consider first the chemical signature available for detection. Generation of bioaerosols by personnel is a topic of considerable interest in microelectronics clean-rooms. Estimates of the rate of generation are presented in Table 2, which indicates that the rate depends strongly on the subject's level of activity. The majority of personnel-generated particles are dead skin flakes, which range in size from a few microns to 50 microns with a median diameter of 20 microns. After release, such particles rapidly disintegrate, which increases the particle density. Particles larger than about 30 microns tend to settle out of the air rapidly.

Respiration can have a significant effect on the local atmospheric chemistry. The chemical composition of the standard atmosphere in the absence of personnel is given in Table 3. Exhalations contain a higher concentration of CO_2.and a lower concentration of O_2. Johnson and Dooly[14] indicate that during light exercise, personnel exhale roughly 1.5 liters of CO_2 per minute while consuming 0.6 liters of O_2. Using an average value of 1.6 liters per exhalation and 26 exhalations per minute, the total volume of gas expired is 41.6 liters. Thus, the volume fraction of CO_2 in exhalations is roughly 0.036, which is more than 100 times the background concentration noted in Table 3. Oxygen consumption produces a small decrement in the local oxygen concentration, but because of the higher ambient concentration of oxygen the effect is much less dramatic than that of CO_2.

Table 2. Particle emission from personnel for various activity levels[15]

Activity	**Emission rate (particles of size >0.3 μm)**
Sitting or standing	0.1×10^6
Walking at 2 mph	5×10^6
Walking at 3.5 mps	7×10^6
Walking at 5 mph	10^7
Intense physical activity	10^8

Table 3. Chemical composition of the standard atmosphere[16]

Constituent	**Volume fraction**
N_2	0.78084
O_2	0.20946
Ar	0.00934

[14] A. T. Johnson, C. R. Dooly, "Exercise Physiology," *The Biomedical Engineering Handbook*, 2nd ed., J. D. Bronzino, ed., Vol. 1, Ch. 26, CRC Press, 2000.
[15] C. W. Berndt, E. S. Burnett, Ph.D. and Robert Spector, *Cleanroom Garment System Application and Use*, http://www.s2c2.co.uk/monitor/tcm39/garment_system.html. Also see http://www.coastwidelabs.com/Technical%20Articles/Cleaning%20the%20Cleanroom.htm.
[16] R. C. Weast, ed., *CRC Handbook of Chemistry and Physics*, 62nd edition, p. F-172, CRC Press, Boca Raton, FL, 1981.

CO_2	0.00033
Trace gases	0.00003

Successful PD using passive chemical methods is dependent upon both bioaerosol transport and sensor effectiveness. Sensor issues are discussed in Section 4.3.2 below. Bioaerosol transport is a complex problem that depends on the particle size and composition, as well as the local topography, wind speed, and atmospheric turbulence. The dispersion of a particle stream by diffusion or wind can easily render a chemical sensor ineffective. Below we present an approximate result based on the following assumptions: (1) a constant wind speed U is blowing in direction x, (2) bioaerosols are emitted at a constant rate q by a point source located h meters above the earth, and (3) bioaerosols are bounced back into the air when they contact the earth. Under these conditions, the solution of the diffusion equation predicts a Gaussian particle concentration C at position (x,y,z) given by[17]

$$C(x,y,z)=\frac{q}{2\pi U\sigma_y(x)\sigma_z(x)}\left[\exp\left(-\frac{y^2}{2\sigma_Y^2(x)}-\frac{(z-h)^2}{2\sigma_z^2(x)}\right)+\exp\left(-\frac{y^2}{2\sigma_Y^2(x)}-\frac{(z+h)^2}{2\sigma_z^2(x)}\right)\right]$$

where the dependence on the down-stream position is implied in the standard deviations $\sigma_y(x)$ and $\sigma_z(x)$. The highest particle concentrations are found on the surface, downstream under the plume (y=0,z=0), where we have.

$$C(x,y=0,z=0)=\frac{q}{2\pi U\sigma_y(x)\sigma_z(x)}\exp\left(-\frac{h^2}{2\sigma_z^2(x)}\right)$$

Relations for $\sigma_y(x)$ and $\sigma_z(x)$ have been derived for a range of atmospheric stabilities.[18] For slightly unstable atmospheric conditions we have

$$\sigma_y(x)\approx 10(x/100)^{1.25}$$
$$\sigma_y(x)\approx 7(x/100)^{0.84}$$

As an example, a very gentle breeze with U=1 m/s (roughly 2.2 mph) blowing past a source at height h=1 meter produces a maximum concentration at 100 meters that is only 1.3% of the maximum encountered at 10 meters. At 1 km, the maximum concentration decreases to 0.01%. It should be emphasized that these are *maximum* values. For most locations, particularly those upwind, the concentration is essentially zero.

4.3.2 Technology Status

Because of health concerns related to airborne respiratory irritants, airborne pathogens, the hazards of toxins in food, and the potential for biochemical warfare, there has recently been considerable interest in sensors that can detect bioaerosols. Many such sensors are designed to detect specific molecules associated with chemical or conventional weapons (e.g., nerve agents or TNT). At this time, the discriminative constituents of human chemical signatures are not known. Hence, sensors that target specific molecules are (currently) inappropriate, and a more general class of sensors is required.

[17] E. Boeker and R. van Grondelle, *Environmental Physics*, pp. 254-258, Wiley, New York, NY, 1995.
[18] F.A. Gifford, *Nuclear Safety*, Vol. 2, No. 47, 1961.

One approach to a general chemical sensor is illustrated by the ORNL “CalSpec” device[19] which utilizes micro-electromechanical structures (MEMS). CalSpec is based on calorimetric spectroscopy and uses an array of micro-machined lever arms. This technique requires that the target material be in a gaseous state. (The skin flakes discussed earlier would not be detectable, but the presence of any volatile skin oils would be.) The end of each lever arm is coated with a substance that will absorb the target material. (The coating need not be highly selective, since classification is not based on the absorbed mass.) Next, each lever arm is illuminated with a different IR wavelength. The lever arms are bi-metallic and bend when heated via absorption of the IR energy. Light from a second laser (not at IR wavelengths) is reflected from the deflected lever arms and sensed in a manner that permits the deflection to be estimated. Since deflection can be related to absorption, an IR absorption spectrum is obtained in this manner. Classification of the absorption spectrum yields the identity of the chemical compound.

Another ORNL MEMS-based approach to general chemical sensing has been described by Datskos.[20] In that work an array of micro-cantilevers are created, each having a unique chemically selective coating. Molecules of the sample adhere to the cantilevers to a degree determined by the coating. The presence of the target molecule induces changes in the cantilever, including deflection and a shift in the cantilever’s resonant frequency. The changes may be enhanced by laser illumination, resulting in photo-induced bending. The changes induced by the target material are then sensed (typically using optical means), providing the response of each coating to the target material. Treating the response of each coating as a point in a multi-dimensional space, the resulting sensor output “vector” is classified using standard techniques, for example, selecting the known material whose vector is closest to the sample (the standard “nearest neighbor” classifier).

A somewhat different approach has been explored by Lewis et al.,[21] in which an array of electrically conducting elements is used. In that approach, thin carbon films, each impregnated with a different polymer, are exposed to the sample. The polymers absorb the sample to a degree determined by their chemical affinity. This absorption leads to swelling, which increases the resistance of the film. Measurement of the resistance provides (as above) a data “vector” which is used for classification.

Although the technology is still immature, a number of “electronic noses” have been commercially available in the US for several years.[22] COTS handheld devices can operate against mixtures of volatile compounds and are capable of detecting specific compounds in a complex environment. There is currently no evidence that these sensors have been used for PD. Similarly, there is no indication that the chemical constituents most suited for PD have been determined.

4.3.3 Countermeasures, Outlook and Net Assessment

The aforementioned chemical sensors, as well as biological olfaction sensors, are readily defeated by operating downwind of the sensor. This countermeasure, however, may be impractical in military situations, and there do not appear to be any other practical countermeasures to a passive chemical sensor. Limiting the production of bioaerosols is possible, but often impractical as evidenced by the “bunny suits” required in clean rooms.

---

[19] S. Rajic, P. G. Datskos, I. Datskou, and T. A. Marlar, “Ultra-responsive thermal sensors for the detection of explosives using calorimetric spectroscopy,” in *Detection and Remediation Technologies for Mines and Minelike Targets IV*, A. C. Dubey, J. F. Harvey, J. T. Broach, eds., Proc. SPIE, Vol. 3710, pp. 356-361, 1999.

[20] P. G. Datskos, Chemical detection based on adsorption-induced and photo-induced stresses in MEMS devices,” in *Detection and Remediation Technologies for Mines and Minelike Targets IV*, A. C. Dubey, J. F. Harvey, J. T. Broach, eds., Proc. SPIE, Vol. 3710, pp. 344-354, 1999.

[21] Mark C. Lonergan, Erik J. Severin, Brett J. Doleman, Sara A. Beaber, Robert H. Grubbs, and Nathan S. Lewis, "Array-Based Sensing Using Chemically Sensitive, Carbon Black-Polymer Resistors", *Chem. Mat.*, vol. *8*, 2298-2312, 1996.

[22] Examples include the Cyranose 320 (http://cyranosciences.com/products/cyranose.html), the FOX sensor (http://www.alpha-mos.com/), and the zNose from EST (http://www.estcal.com/Specs/4200Spec.pdf). See http://www.instruments.ru/manufacturers-suppliers/electronic-nose-instruments.htm for a list of additional sensors.

Passive chemical sensors may be particularly effective in closed areas, for example, as a probe slipped under the door of a room containing potential adversaries.

Since chemical agents are readily dispersed by wind and diffusion, perhaps the best deployment of these sensors is on mobile platforms, in particular, micro UAVs. Many existing chemical sensors are very small and light, making them good candidates for mobile platforms in general and UAVs in particular. Mobile platforms could move the sensors through air masses that were downwind of regions of concern. The platforms could also be used to track the chemical signature upstream back to its source.

4.4 Passive Low-Frequency Electric and Magnetic Sensors

As a result of nerve-related current flow, the human body generates a variety of bioelectromagnetic signals that may be detected externally. In this section we address the question of whether such signals could be detected by a remote observer, thereby revealing a human presence. Public interest (and concern) with this concept was heightened recently when the *Washington Times* reported a NASA intention to develop a non-contacting brain-wave sensor[23] using an unspecified technology.

Passive magnetic field sensors (magnetometers) can also detect perturbations in the earth's magnetic field caused by the presence of ferrous objects. In contrast to biologically generated fields, the fields produced by ferrous objects are well understood and readily predicted.

4.4.1 Sensor Concept

4.4.1.1 Detectable Phenomena

In principle, the phenomena that might be detected include electric and magnetic fields produced by

- cardiac action,
- brain functions, and
- skeletal muscle activity.

As noted above, one can also detect

- ferrous objects including vehicles, weapons and tools.

4.4.1.2 Sensor Physics

For many years now bioelectric signals have been exploited for medical purposes. The standard electrocardiogram (ECG), electroencephalogram (EEG), and electromyogram (EMG) all use electrodes in contact with the skin to record time varying electrical potentials caused by the current flow. More recently, biomagnetic signals have also been investigated. The challenge in PD is to sense these signals remotely. Interpretation of remotely sensed EEG data, which might reveal the intention of the subject, appears to pose a much more difficult problem and is not considered here.

[23] Frank Murray, "NASA plans to read terrorist's minds at airports", *Washington Post*, 17 August, 2002. (http://www.washtimes.com/national/20020817-704732.htm)

Biologically generated EM signals are extremely weak.[24] The heart generates the largest current flows and provides the strongest external signal. The ECG signal, an electrical potential difference produced by cardiac action, is on the order of 2 mV measured at the surface of the body.[25] Typical signal bandwidths are 0.05-150 Hz. The EEG signal is only on the order of 10 μV and occupies the frequency band below 40 Hz.[26] The strongest magnetic signal is the magnetocardiogram (MCG), which has an amplitude of 50 pT (roughly 10^6 times smaller than the earth's magnetic field). The magnetoencephalogram (MEG) signal is roughly 100 times weaker than the MCG, and measurements of it are typically performed in a magnetically shielded room.

A simple analysis will permit us to estimate the possibility of detecting these signals externally. Consider first the ECG signal, which is the strongest of the bioelectric phenomena. An analysis based on a spherical model of man suggests that this signal can be modeled by an equivalent current dipole of 3.7×10^{-5} Ampere-meters.[27] The frequency regime of interest is very low, and for observer distances of practical interest, the receiver will be in the near field of the dipole, for which $2\pi R/\lambda << 1$. Under these conditions, a quasi-static analysis is appropriate, which for a dipole source of moment $(I_0 l)$ would produce an electric field E that satisfies

$$|E| \approx \frac{3(I_0 l)}{4\pi\sigma R^3}\cos\theta$$

This expression holds for distances R much greater than the size of the human torso and much shorter than a wavelength. In this result σ=0.2 S/m is the mean conductivity of tissue and θ is the spherical angle measured with respect to the dipole axis (taken to be $\pi/2$ in what follows). Using the dipole moment stated above we find

$$|E| \approx \frac{44x10^{-6}}{R^3} \qquad [V/m]$$

At a distance of 10 meters, the expected field intensity is 44 nV/m and, hence, a 10 cm antenna will show an induced voltage on the order of 4 nV. It is interesting to compare this voltage to the root-mean square (RMS) Johnson noise voltage developed in a resistive load of Z Ohms at temperature T for a bandwidth of B Hz. We have

$$\sqrt{\langle V_n^2 \rangle} = \sqrt{kT_r BZ}$$

in which k=1.38×10^{-23} J/K is Boltzmann's constant. At T_r=300K with a bandwidth of 10 Hz and a standard 50 Ohm receiver, the RMS noise voltage will be roughly 3 nV. Evidently, standoff detection of ECG fields may be possible at short ranges, but it will be very challenging, particularly for a non-cooperative target. Detection of electrical brain wave signals (EEG) would be commensurately harder, because of the weaker fields involved.

As noted earlier, magnetometers are also used to sense perturbations in the earth's magnetic field caused by ferrous metal. The basis for detection is as follows: The field produced by any object can be described by a magnetic polarizability tensor **M**. As an example, for a ferrous sphere, the polarizability tensor has the simple form

---

[24] J. Malmivuo, "Biomagnetism," in *The Biomedical Engineering Handbook*, 2nd ed., J. D. Bronzino, ed., Vol. 1, Ch. 16, CRC Press, 2000.

[25] E. J. Berbari, "Principles of Electrocardiography," in *The Biomedical Engineering Handbook*, 2nd ed., J. D. Bronzino, ed., Vol. 1, Ch. 13, CRC Press, 2000.

[26] J. D. Bronzino, "Principles of Electroencephalography," in *The Biomedical Engineering Handbook*, 2nd ed., J. D. Bronzino, ed., Vol. 1, Ch. 15, CRC Press, 2000.

[27] H. A. Haus and J. R. Melcher, *Electromagnetic Fields and Energy*, p. 299, Prentice Hall, 1989.

$$\mathbf{M} = 3V\frac{\mu_r - 1}{\mu_r + 2}\mathbf{I}$$

in which $V=(4/3)\pi a^3$ is the volume of the sphere, μ_r is the relative permeability of the sphere, a is the radius, and $\mathbf{I}$ is the identity tensor. The earth's magnetic field $\mathbf{B}_0$ induces a magnetic moment $\mathbf{m}$ in a ferrous target given by

$$\mu_0\mathbf{m}=\mathbf{M}\cdot\mathbf{B}_0$$

in which $\mu_0=4\pi x10^{-7}$ H/m is the permeability of vacuum. The earth's magnetic field $\mathbf{B}_0$ varies across the earth, but it has a value of roughly 30-50 μT (0.3-0.5 Gauss) in the continental US.

The presence of this induced dipole moment creates a distortion $\mathbf{B}_1$ in the earth's magnetic field, given by

$$\mathbf{B}_1 = \frac{\mu_0}{4\pi R^3}\left[3\mathbf{a}_R(\mathbf{a}_R \cdot \mathbf{m}) - \mathbf{m}\right] = \frac{1}{4\pi R^3}3V\frac{\mu_r - 1}{\mu_r + 2}\left[3\mathbf{a}_R(\mathbf{a}_R \cdot \mathbf{B}_0) - \mathbf{B}_0\right]$$

in which $\mathbf{a}_r$ is a unit vector in the radial direction. For iron and steel objects (the materials used in most tools and weapons) the quantity $\mu_r \gg 1$ and, hence, $(\mu_r-1)/(\mu_r+2)\approx 1$. If we write $\mathbf{B}_0=B_0\mathbf{a}_0$, then we have

$$\mathbf{B}_1 \approx \frac{3B_0V}{4\pi R^3}\left[3\mathbf{a}_R(\mathbf{a}_R \cdot \mathbf{a}_0) - \mathbf{a}_0\right] = B_0\left(\frac{a}{R}\right)^3\left[3\mathbf{a}_R(\mathbf{a}_R \cdot \mathbf{a}_0) - \mathbf{a}_0\right]$$

The quantity in square brackets, the magnitude of which is on the order of unity, defines the vector sense of the field, and it is of secondary importance for detection. It is evident that the detection of a target is dominated by the ratio $(a/R)^3$, which makes magnetic field detection a short-range phenomenon.

4.4.2 Technology Status

The authors are not aware of any system that currently attempts to remotely detect bioelectric or biomagnetic signals at ranges larger than a few tens of centimeters. Given the distance scaling arguments advanced above, its does not seem prudent to pursue such a sensor. Very short range (i.e., less than 10 meter) sensing of the bioelectric cardiac signal may be possible, but our analysis suggests that the SNR will be on the order of unity.

Detection of low-frequency biomagnetic fields is somewhat easier because of the maturity of magnetometers, the sensors used to detect static magnetic fields.[28] The sensitivity of COTS high-temperature superconductor (HTS) Superconducting Quantum Interference Devices (SQUIDs) is on the order of 100 fT[29] over the frequency regime of interest in biomagnetics. Low-temperature superconducting (LTS) SQUIDs have sensitivities on the order of 10 fT. In contrast, the magnetocardiography signal (MCG) measured at a point adjacent to the heart (say, 0.1 meters from its source) has an amplitude of roughly $5x10^4$ fT, and the magnetoencephalography (MEG) signal is on the order of 10^3 fT. While these signals are significantly stronger than the sensor noise limits, they decay as R^{-3}. Hence, detection is unlikely at distances beyond roughly one meter.

In contrast to detection of biomagnetic fields, the presence of the ferrous objects can be reliably detected at short ranges using COTS sensors. As an example, we note the TFM100G2 produced by Billingsley

---

[28] See http://www.tristantech.com/prod_biomagnet.html

[29] One femtoTesla (fT)=10^{-15} Tesla. For reference, the earth's magnetic field is roughly 50 μT (0.5 Gauss)

Magnetics.[30] This sensor, which has the dimensions 3.51 cm x 3.23 cm x 8.26 cm and a mass of 100 grams, consumes less than 850 mW of power and has an RMS noise level (sensitivity) of 20 pT/(bandwidth)$^{1/2}$. Such a sensor, deployed singly or as an array, could readily detect the presence of nearby weapons sized metal masses.

4.4.3 Countermeasures, Outlook and Net Assessment

Countermeasures for bioelectric fields are readily devised, since low-frequency electric fields are shielded by thin dielectric coverings. In addition, when the sensor location is known, distance provides a simple countermeasure. The foregoing calculation indicates that detection of bioelectric fields is unlikely at ranges of more than a few meters.

In contrast, low frequency magnetic fields are extremely hard to shield against, because the skin depths are extremely large. Nonetheless, the R^{-3} decay with distance implies that only very short range detection will be practical. Environmental noise (particularly in urban areas) is a serious concern, because of the low frequencies involved.

In contrast to detection of bioelectric and biomagnetic signals, detection of ferrous metals in tools and weapons is extremely reliable (albeit limited to short ranges), and it has few practical countermeasures other than increasing the separation between target and sensor. Short range magnetic sensors are now used in PD. Although we do not anticipate major advances in the technology, we expect those sensors to continue to be used.

4.5 Passive Microwave and Millimeter-Wave Sensors

We showed in Section 4.1 that radiant emissions by personnel at IR wavelengths could be used in passive detection. By analogy, passive electromagnetic (EM) sensors can also be used at shorter wavelengths including microwaves (MW), millimeter waves (MMW), and TeraHertz (THz) frequencies.[31] Because the emissions under discussion tend to be weak, the relevant sensors tend to be imaging devices that achieve detection improvements through the use of shape information.

4.5.1 Sensor Concept

4.5.1.1 Detectable Phenomena

The phenomena detectable by a passive EM sensor are identical to those of a passive EO sensor and include

- shape,
- thermal emission, and
- motility.

[30] Specifications are available at http://www.magnetometer.com/tfm100g2.htm

[31] TeraHertz waves are usually defined as electromagnetic waves oscillating at frequencies of 10^{11} to 10^{13} Hz (0.1 to 10 THz). The wavelengths of such waves range from 3 mm to 30 µm. By a somewhat arbitrary convention, the RF community often defines millimeter waves to be those at frequencies from 40 GHz to 100 GHz (.04 to 0.1 THz), which implies wavelengths of 7.5 mm to 3 mm. Although THz waves can penetrate a few millimeters of skin, the body is largely opaque in that band. Thus, in spite of some exaggerated claims that appear in the popular press, it is clear that THz imagers will not possess "X-ray like" penetration abilities or any other properties not already possessed by passive MMW sensors. THz imagers may have some advantages over MMW sensors, since some liquids exhibit rotational and translations molecular modes in this band, which makes spectroscopy a possibility. Unfortunately, atmospheric attenuation increases rapidly in the MMW and THz bands, so detection range is a concern.

4.5.1.2 Sensor Physics

Both IR and passive RF imagers detect thermal emission from a body. Similar to EO sensors, the SNR of a passive RF sensor is proportional to the size of the interrogated region and inversely proportional to the distance to the target. For passive RF sensors we will show that SNR is proportional to the ratio of the target and (equivalent) receiver temperatures. The principal advantage of the passive RF imager over a thermal IR imager is that longer wavelengths are better able to penetrate clothing and other light obscurants.

The expression for the SNR of a passive MW, MMW or THz imager is similar to that developed in Section 4.1 for EO sensors. There are, however, a few exceptions. At longer wavelengths, we can invoke the Rayleigh-Jeans approximation for Planck's law, which leads to

$$M_{\lambda}(\lambda,T) \approx \frac{2\pi ckT}{\lambda^4}$$

Hence, in this regime the emission is proportional to the apparent temperature, which is often referred to as the "brightness temperature." It is also conventional to describe the spectral dependence of RF systems per unit of frequency rather than per unit of wavelength. We have

$$M_f(f,T) = M_{\lambda}(\lambda,T)\left|\frac{d\lambda}{df}\right| = \frac{2\pi kT}{\lambda^2}$$

A second difference between passive RF and EO sensors deals with the receiver noise. Johnson noise is the dominant source of noise for the incoherent RF receivers used for passive RF systems. The noise power is given by

$$NEP = kT_r B$$

in which (as above) k is Boltzmann's constant, T_r is the receiver's noise temperature, and B is the receiver bandwidth. We have

$$\frac{S}{N} = \frac{A_t \tau \varepsilon \Delta M_f(f_1,f_2)\lambda^2 G}{4\pi^2 R^2 kT_r B}$$

Here,

$$\Delta M_f(f_1,f_2) = \int_{f_1}^{f_2} M_f(f,T)df$$

and we have used the gain G of the receiving antenna, given by

$$G = 4\pi\frac{(\pi D^2/4)}{\lambda^2}$$

in which D is the diameter of the (assumed circular) antenna aperture.

For sensors of modest bandwidth B and center frequency f_c, we can approximate the emission by

$$\Delta M_f(f_1, f_2) \approx M_f(f_c, T)B = \frac{2\pi k T_t B}{\lambda_c^2}$$

which leads to the simpler expression

$$\frac{S}{N} = \frac{A_t \tau \varepsilon G}{2\pi R^2}\frac{T_t}{T_r}$$

This result shows that the passive RF SNR is proportional to the antenna gain and the ratio of the target and receiver temperatures.

4.5.2 Technology Status

In a 1998 patent[32] Huguenin et al. described a passive MMW system operating in the band 91.5-96.5 GHz. The system used a polarization-switched twist reflector to illuminate a 16x16 "focal plane", comprised of Vivaldi antennas fabricated on a dielectric substrate. The antennas are mechanically scanned across the field of view to generate an image of 1024 pixels. More advanced versions of this system are now available from Millivision (Amherst, MA).[33] A resolution of 3 cm at 2 meters is quoted for the current version of the system.

A THz imager was recently developed and demonstrated as part of the EU "Star Tiger"[34] program, but the work does not seem to have been reported in the scientific literature (although press releases abound[35]). A novel aspect of the THz imager is the use of micro-machined components. As a result, it is reasonable to believe that THz systems will be compact and operate at low power.

4.5.3 Countermeasures, Outlook and Net Assessment

Obscurants are the most straightforward countermeasure to passive RF signatures. Passive MMW and THz RF signatures are not masked by light clothing, but they cannot penetrate building materials, foliage, or terrain features. Passive MW imagers at lower frequencies (from, say 1 GHz to a few GHz) have superior penetration capabilities.

The technology behind passive MMW sensors (up to 100 GHz) is relatively mature, and some impressive results have been demonstrated for airline passenger screening applications. Nonetheless, these sensors have a number of challenges. Because of the size and expense of a suitable two-dimensional array, the currently available systems use a scanned one-dimensional array to generate two-dimensional imagery. The time required for scanning is excessive for the large areas of interest in PD.

Passive THz imagers may offer some benefits because, as a result of micro-machined fabrication, such devices can be made very compact. That technology, however, is relatively new, and additional study is required to determine its limits. In addition, it is unlikely to penetrate obstacles more substantial than roughly 1 cm of low-moisture materials.

[32] US Patent #5,760,397. Also see G. R. Huguenin, "Millimeter-wave video rate imagers," Proc. SPIE, *Passive Millimeter-Wave Imaging Technology*, Vol. 3064, pp. 34-45, 1997.
[33] See http://www.millivision.com/
[34] Space Technology Advancements by Resourceful, Targeted and Innovative Groups of Experts and Researchers (STAR TIGER). See http://www.startiger.org/.
[35] See, for example, http://www.space.com/businesstechnology/technology/t-ray_camera_020613.html

4.6 Active Ranging Sensors (Radar, Sonar and Lidar)

Radar, sonar and lidar are each based on the concepts of wave propagation and scattering. All of these active sensors provide range information, and they are each capable and mature. A variety of PD sensors based on this concept have been developed.

4.6.1 Sensor Concept

4.6.1.1 Detectable Phenomena

Active ranging sensors permit sensing of two distinctly different phenomena:

- 2D and 3D shapes (for imaging sensors)
- Gross motion and motion of internal organs including cardiac motion and respiration (for Doppler sensors)

Sensors exist that are capable of capturing both types of information (albeit, typically in only one mode at a time).

4.6.1.2 Sensor Physics

As noted above, radar, sonar, and lidar are all based on similar physical principles. In this section we discuss the underlying concepts from the point of view of radar. Specializations to sonar and lidar are straightforward and are noted below.

The factors that affect a radar are readily illustrated using the so-called "radar-range equation," which relates the SNR to system design parameters. Assume that an electromagnetic power density W produced by a source of power P_t is transmitted by an antenna of gain G_t and illuminates a target at range R_t from the source. The signal to noise ratio is given by

$$W_{inc} = \frac{P_t G_t}{4\pi R_t^{\,2}}$$

The power density scattered by the target to a receiving antenna located at a distance R_r from the target is given by

$$W_{scat} = W_{inc} \frac{\sigma}{4\pi R_r^2}$$

in which σ is the target's bistatic radar cross section. The power received by a receiving antenna of effective area A_r is given by

$$P_{rec} = W_{scat} A_r$$

We can also state this result in terms of the receive antenna's gain G_r given above

$$P_{rec} = W_{scat} \frac{G_r \lambda^2}{4\pi}$$

Collecting these results and combining them with the relation for Johnson noise power given previously yields the bistatic radar range equation

$$\frac{S}{N} = \frac{P_{rec}}{P_{noise}} = P_t \frac{G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^{\,2} R_r^{\,2} k T_r B}$$

Most radars operate in a monostatic configuration, in which the transmitter and receiver are co-located and share the same antenna. In that case we have

$$\frac{S}{N} = P_t \frac{G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_r B}$$

Radar design involves numerous tradeoffs, some of which can be illustrated using this expression. We first re-express the gain in terms of the equivalent area of the transmitting/receiving antenna. We have

$$\frac{S}{N} = P_t \frac{A^2 \sigma}{4\pi \lambda^2 R^4 k T_r B}$$

The R^{-4} dependence of this expression is perhaps radar's most severe limitation. For example, we see that doubling the transmitted power will increase the detection range by a mere factor of $2^{1/4}$ or less than 20%. The other factors in the equation have a similarly limited ability to improve detection range. Since the target cross-section is fixed and only modest improvements are generally possible by reducing the noise product $T_r B$, performance can only be significantly improved by increasing the antenna area A, or by reducing the wavelength λ. Increasing the antenna area A is often unattractive, because it makes the system harder to transport and conceal. Since $\lambda = c/f$ (where $c = 3\text{x}10^8$ m/s is the speed of light), reducing the wavelength or, equivalently, increasing the frequency f, is a commonly employed approach, but it has limits, since propagation through the atmosphere and through many forms of concealment is degraded at higher frequencies.

There are a number of other tradeoffs. The range resolution ρ_r of a radar is determined from its bandwidth B via the relation

$$\rho_r = \frac{c}{2B}$$

Hence, the desire to reduce the noise bandwidth opposes the desire for improved range resolution. The cross-range resolution ρ_c for a uniformly illuminated rectangular antenna aperture of dimensions D_v (vertically) by D_h (horizontally) is given by

$$\rho_c = R \frac{0.56\pi\lambda}{2D_h} \approx R \frac{\lambda}{D_h}$$

which shows that better resolution is obtained from higher frequencies and larger antennas. Those features also yield better S/N, but they simultaneously reduce the radar's field of view and search rate.

The use of Doppler information to detect motion confers upon radar some attractive properties. In particular, it has long been known that Doppler radar was capable of detecting respiratory motion through walls and cardiac motion through the chest. The first mention of this capability in the open literature appears to be that of Chen et al. in 1986[36], but several earlier patents suggest that the concept was already well understood at the time of publication.[37]

The basis for Doppler radar is well known. If a sinusoidal waveform at frequency f illuminates a target moving with radial velocity v, then the backscattered waveform will be a sinusoid at the shifted frequency $f+f_d$, where

$$f_d = -f\frac{2v}{c}$$

In this result the sign of v is positive for receding targets. (Motion transverse to the line of sight produces no frequency shift.) Since the Doppler shift is proportional to (v/c) it represents an extremely small shift in frequency for all man-made targets. For a target moving at a moderate walk (3 miles/hr or 1.34 m/s), the ratio f_d/f is roughly 10^{-8}. Such small shifts, however, are readily detected by mixing the received signal with the transmitted signal. For a typical X-band radar at f=10 GHz, the frequency shift is approximately 90 Hz, comfortably within the audio frequency range. The smallest detectable frequency is inversely related to the duration of the illuminating pulse. Detecting motion at v=10 cm/s corresponds to a frequency shift of 6.6 Hz, which would require a pulse length of 150 ms. Such long pulse lengths are unattractive, since they limit the scan rate of the radar.

Sonar, an active acoustics sensor, functions in much the same manner as radar. The source emits a spherical acoustic wave that is scattered by the target producing a second spherical wave that propagates back to the receiver. The wavelength λ of the acoustic wave is again given by $\lambda=c_0/f$ where c_0=343 m/s in air.

The signal-to-noise ratio for sonar systems can be predicted using an analog of the radar range equation. To minimize the size of the antenna, short wavelengths are required, which usually leads one to ultrasonic frequencies (above the 20 kHz limit of human hearing.) Use of ultrasonic frequencies also avoids detection of the system by its adversaries.

An unfortunate problem with ultrasonic frequencies is their poor propagation characteristics. While microwaves and millimeter waves propagate through clear air with little attenuation (less than 10^{-5} dB/m at X band and less than 0.01 dB/m up to 150 GHz), ultrasonic waves suffer losses on the order of 1 dB/m at frequencies of 40 kHz or so. (This loss occurs in addition to the R^{-4} spherical wave spreading inherent in such systems.) As a result, ultrasonic sensors are limited to short range applications.

In addition, ultrasonic sensors have difficulty coupling from air to solid media. The transmission coefficient T for a planar acoustic (or electromagnetic) wave propagating through a layer of material with impedance Z is given by the following expression:

---

[36] K.-M. Chen, D. Misra, H. Wang, H.-R. Chuang, and E. Postow, "An X-band microwave life-detection system," *IEEE Trans. Biomed. Eng.*, Vol. BME-33, pp. 697-701, July 1986.

[37] Cf. N. S. Namerow, "Method for monitoring introsomatic circulatory function and organ movement," US Patent #3,483,860, Dec. 16, 1969; W. P. Allen, Jr., "Method for measuring physiological parameter," US Patent #4,085,740, April 25, 1978; G. S. Kaplan and A. S. Clorfeine, "Respiration Monitor," US Patent 3,993,995, Nov. 23, 1976.

$$T = \left(\frac{2Z_0}{Z+Z_0}\right)\left(\frac{2Z}{Z+Z_0}\right)\frac{e^{+i2\pi(D/\lambda_0 - D/\lambda)}}{1+\frac{Z_0 - Z}{Z_0 + Z}e^{-i2\pi(D/\lambda_0 + D/\lambda)}}$$

in which Z_0 is the impedance of air and λ and λ_0 are the (possibly complex) wavelengths in the material and in air. For many materials of practical interest, the material will have some loss and an appreciable thickness, and the exponential in the denominator is essentially zero. Furthermore, in a simple calculation of signal to noise ratio we are interested in the magnitude of this quantity. This leads us to consider

$$|T| \approx \frac{4|Z/Z_0|}{|1+(Z/Z_0)|^2}|e^{-i2\pi D/\lambda}|$$

For an electromagnetic wave, the ratio Z/Z_0 for most building materials is between 0.1 and 1, which implies that $|T|$ is on the order of unity. In contrast, for acoustic waves impinging on building materials[38] we have the impedance ratio $|Z/Z_0| \sim 10^{-3}$, which implies that T is also on the order of 10^{-3}. Finally, the received wave incurs this loss twice (once during illumination and once after reflection from the target) and, hence, the signal-to-noise ratio is proportional to $|T|^2$. For this reason, the presence of intervening solid materials makes ultrasonic sensors impractical.

4.6.2 Technology Status

Radar is a very mature technology, and a number of radar-based systems have been developed for PD. The only radar-based PD system currently fielded is the AN/PPS-5D Doppler-based ground surveillance radar (GSR). The system uses a parabolic dish antenna (37 dBi gain) mechanically scanned through a user-specified angular sector of up to 90°. The transmit power is 2 Watts at a frequency of 16 to 16.5 GHz. The stated capabilities of that radar are detection of moving personnel at ranges of 10 km and vehicle detection to 20 km. The minimum detectable radial velocity is 0.5 m/s (about 1.1 mph). The unit weighs 71 pounds, and prime power consumption is 40 Watts.

A much smaller (albeit less capable) COTS radar system useful for PD is the Outdoor Microwave Transceiver from Southwest Microwave model 385.[39] With a claimed detection range of up to 122 meters (400 feet) and an illuminated swath of width 6.1 meters or less, the device is intended for short-range perimeter monitoring (trip-wire like) functions. Operating at 24 GHz, the antenna is roughly 27 cm (10.6 inches) in size. The device's nominal power consumption is about 2 Watts.

A handheld MMW Doppler radar developed by GTRI (the so-called "radar flashlight") performs through-wall detection of life signs.[40] The developers suggest that it is capable of detecting the respiration movements of a subject located 5 meters behind a hollow-core masonry wall with thickness of 8 inches or less. A prototype device weighs 7 pounds, and has a cylindrical shape with a pistol grip. The sensor has no imaging capability. Its output is a bar graph that rises and falls with target motion.

---

[38] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics,* 3rd ed., Wiley and Sons, New York, 1982.
[39] See http://www.southwestmicrowave.com/products.html
[40] G. Greneker, "Radar sensing of heartbeat and respiration at a distance with security applications," Proc. SPIE, *Radar Sensor Technology III*, vol.3066 1997. p. 22-27. Also see http://gtresearchnews.gatech.edu/newsrelease/RADARFLASH.html)

Time-Domain Corporation is developing a through-wall imaging radar, known as the "SoldierVision" system.[41] The goal of the effort is to develop a radar capable of providing a 2D bird's eye view of moving objects behind a wall. The system transmits a train of ultra-wideband pulses from a small antenna array. The prototype SV2000 system displays a 2D image covering an angular sector of 120°. The prototype unit's operating modes include ranges of 3 meters and 10 meters. The unit's weight is less than 10 pounds. Power is provided by standard military batteries.

An imaging MMW radar was developed by Sheen et al. at the DoE Pacific Northwest National Laboratory (PNNL) for detection of explosives concealed on personnel.[42] The radar comprises a horizontal linear array of 128 elements (64 transmitters and 64 receivers) that is scanned vertically. The 2D aperture and a wideband waveform (27-33 GHz) permit 3D images to be generated using holographic processing. The image resolution is approximately 0.5 cm laterally (cross-range) and 2.5 cm in range. Since the MMW signal penetrates clothing, but not tissue or other solid objects, the system is capable of detecting concealed objects. The system is designed for non-invasive search of personnel passing through a portal. The scan time is approximately one second.

A system with similar capabilities is described in an earlier 1991 patent by Huguenin et al.[43] That system was not scanned, and it exploited polarization to improve detection. It was found that weapons and other targets of interest tend to depolarize the incident field, while clothing did not. A later paper by Sinclair et al. in the UK described a similar sensor.[44]

There have been relatively few studies of ultrasonic sensors, which we attribute to the propagation and penetration problems noted above. Wild et al.[45] assert that the problem of transmitting through a layer of solid material can be reduced if the sensor can be coupled directly to the denser medium using, for example, a source in direct contact with the medium. That group described a through-wall ultrasonic sensor based on this concept.

Laser-based intruder detection systems are also available commercially. An example is the Laser Guard Sensor (LGS) produced by Laser Guard Ltd (Acco, Israel).[46] The manufacturer states that the system is capable of detecting intruders at ranges up to 300 meters, although the probability of detection decreases when the intruder maintains a low profile (e.g., crawling rather than walking).[47] The sensor weighs 16 kg, and its volume is approximately 30x30x43 cm^3.

---

[41] S. Nag, M. A. Barnes, T. Payment, and G. W. Holladay, "An ultra-wideband through-wall radar for detecting the motion of people in real time," Proc. SPIE, *Radar Sensor Technology VII*, Orlando, FL, 2002.
Barnes, M. A.; Nag, S.; Payment, T. "Covert situational awareness with handheld ultrawideband short-pulse radar," Proc. SPIE, *Radar Sensor Technology VI*, vol. 4374, 2001 p.66-77.
Also see http://www.time-domain.com/

[42] D.M. Sheen, D. L. McMakin, H. D. Collins, T. E. Hall and R. H Severtsen, "Concealed explosive detection on personnel using a wideband holographic millimeter-wave imaging system," *Proceedings of the SPIE - The International Society for Optical Engineering* Signal Processing, Sensor Fusion, and Target Recognition V v 2755 1996 p.503-13.
Sheen, D. M.; McMakin, D. L.; Hall, T. E., "Three-dimensional millimeter-wave imaging for concealed weapon detection," *IEEE Transactions on Microwave Theory and Techniques*. vol.49, no.9 Sept. 2001. p. 1581-92.

[43] G. R. Huguenin, P. F. Goldsmith, N. C. Deo, and D. K. Walker, "Contraband Detection System," US Patent 5,073,782. Dec. 17, 1991.

[44] G. N. Sinclair, R. N. Anderson and R. Appleby, "Passive millimeter-wave concealed weapon detection," in *Enabling Technologies for Law Enforcement and Security*, S. K. Bramble, E. M. Carapezza and L. I. Rudin, eds., Proc. SPIE, Vol. 4232, pp. 142-151, 2001.

[45] N. C. Wild, F. Felber, M. Treadaway, F. Doft, D. Breuner and S. Lutjens, "Ultrasonic through-the-wall surveillance system," in *Enabling Technologies for Law Enforcement and Security*, S. K. Bramble, E. M. Carapezza and L. I. Rudin, eds., Proc. SPIE, Vol. 4232, pp. 167-176, 2001.

[46] See http://www.laserguard.com/

[47] T. Yeager and P. J. Resca, " US Air Force law enforcement related requirements and programs," in *Enabling Technologies for Law Enforcement and Security*, S. K. Bramble, E. M. Carapezza and L. I. Rudin, eds., Proc. SPIE, Vol. 4232, pp. 1-10, 2001.

4.6.3 Countermeasures, Outlook and Net Assessment

Concealment is likely to be at least a partial countermeasure to PD radar. Although some radars can penetrate walls (see the discussion in Section 4.6.2), most systems are severely impaired by obscuring objects. To achieve reasonable ranges from antennas of modest size, it is necessary to use higher frequencies (X band and above). Those frequencies produce sensors that are limited to line of sight, with little ability to penetrate common natural obscurants such as foliage. In addition, scattering from the ground often poses a serious clutter problem. Hence, moving very close to the ground provides a measure of protection.

Doppler radars such as the AN/PPS-5D provide much needed clutter suppression, but they too have problems. They are readily defeated by seeking out areas with no line of sight for travel in the radial direction. Travel in directions transverse to the line of sight is not detected. Doppler radars can be used on moving platforms, but it is necessary to filter out the motion of the background terrain.

The most obvious radar countermeasure, radar absorbing material, is not practical as a PD countermeasure because of the bulky, fragile nature of that material.

Although radar can be effective in a number of PD scenarios, the sensors tend to be relatively large and to require high power levels. An example of this is the AN/PPS-5D, which requires a sizable, mechanically scanned dish antenna and 40 Watts of prime power. Such systems can be effective in open areas, but in hilly topography multiple systems would be required to eliminate blind spots.

Recently, bistatic radar systems have been discussed that overcome this problem. The bistatic radar approach uses a separate, high-power, externally located source to illuminate the region of interest. (In some implementations, the source may be cell phone base stations or TV transmitters.) The radar receiver, thus freed from the size and power requirements imposed by the transmitter and the transmitting antenna, can be a compact, passive device requiring minimal power. In general, a radar requires waveform timing information as well as a copy of the transmitted waveform. In a bistatic radar, the transmitted signal is typically acquired via the wide-angle sidelobes of the transmit antenna. Knowledge of the source location and the timing of the transmitted and scattered signals can then be used to infer the position of the target.

4.7 Active Low-Frequency EM Sensors

In most military scenarios personnel require metal tools or weapons to perform their mission. For this reason, detection of metallic objects is of interest. The relevant sensor technologies are well developed. Low-frequency electromagnetic induction (EMI) sensors, more commonly known as “metal detectors”, are in wide use for both civilian and military applications. In this section we review that technology and comment on its use in PD.

4.7.1 Sensor Concept

4.7.1.1 Detectable Phenomena

EMI sensors detect materials with high electrical conductivity by exploiting an inductive effect. Because the conductivities of both ferrous and non-ferrous metals are orders of magnitude higher than those of other materials, these sensors are particularly effective against metals. Some sensors may also have a limited ability to detect the presence a human body, but the effect in that case may be largely capacitive rather than inductive.

<u>**4.7.1.2 Sensor Physics**</u>

When a conducting material is subjected to a magnetic field, the field excites so-called "eddy" currents in the material. These currents produce a secondary field that tends to oppose the original (primary) field. EMI sensors detect the secondary magnetic field directly (in a pulsed system) or indirectly (via a change in the impedance of a tuned circuit in a CW system). Ferrous objects, even if poorly conducting, will produce a different secondary field through a distortion of the primary magnetic field. Sensors which exploit these phenomena have been used for many years in COTS metal detectors for treasure hunters and in airport security systems. Related techniques are used in geophysical exploration and in nondestructive testing of metal objects.

The theoretical basis for the calculation of currents induced by low-frequency magnetic fields (also known as magneto-quasi-static fields) is well known and can be developed as follows: We begin with a subset of Maxwell's equations, viz:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{dt}$$
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{dt} + \mathbf{J}$$
$$\nabla \cdot \mathbf{B} = 0$$

where **E** and **H** are the electric and magnetic fields, **D** and **B** are the electric and magnetic flux densities (or, more precisely, the electric displacement and the magnetic induction), and **J** is the electric current density. The fields and flux densities satisfy the constitutive relations, $\mathbf{D}=\varepsilon\mathbf{E}$ and $\mathbf{B}=\mu\mathbf{H}$, where ε and μ are respectively the permittivity and permeability of the medium.

When the time scale of interest is much larger than the time required to propagate a signal over a characteristic distance, then one can neglect the displacement current term $d\mathbf{D}/dt$ in Maxwell's equations, and we obtain Ampere's Law, viz:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

In a conducting medium the current **J** can be related to the electric field **E** via Ohm's law, $\mathbf{J}=\sigma\mathbf{E}$**,** where σ is the conductivity. Using the above results we obtain the diffusion equation

$$\sigma\mu \frac{\partial \mathbf{H}}{dt} = \nabla^2 \mathbf{H}$$

Propagation phenomena are not significant in EMI problems. Instead, the field evolves everywhere in space with the same temporal (often exponential) behavior.

Loops are frequently used both to generate the primary fields in induction sensors and to sense the secondary fields produced by eddy currents. The quasi-static magnetic field produced by a small transmitting loop of n_T turns with a z-directed axis is well known. We denote the magnetic field produced by this loop as $\mathbf{H}_p$, and we write

$$\mathbf{H}_p = \frac{I n_T dA_T}{4\pi R^3}\left[\mathbf{a}_r 2\cos\theta + \mathbf{a}_\theta \sin\theta\right] e^{-i\omega R/c}$$

where I is the driving current, dA_T is the area of the loop, and (r,θ) are the usual spherical coordinates. The time dependence $e^{+i\omega t}$ is assumed in this result and in the sequel.

It will be convenient to express this field in terms of the dipole moment of the loop, viz:

$$\mathbf{m}_{loop} = In_T dA_T \mathbf{n}_t$$

where $\mathbf{n}_t$ is a unit vector which defines the loop axis. The field produced by this dipole is

$$\mathbf{H}_p = \frac{1}{4\pi R^3}\left[3\mathbf{a}_r(\mathbf{a}_r \cdot \mathbf{m}_{loop}) - \mathbf{m}_{loop}\right]e^{-i\varpi R/c}$$

The voltage induced in a loop by a magneto-quasi-static field can be evaluated in a straightforward manner. Using the integral form of Faraday's law in the frequency domain and Stokes' theorem we find that the induced voltage V_{ind} is given by

$$V_{ind} = \oint \mathbf{E}\cdot d\mathbf{s} = i\omega\mu n_R \int_S \mathbf{H}_s \cdot d\mathbf{a}$$

where C is the circumference of the loop, S is the surface enclosed by C, n_R is the number of turns in the receiving loop, and $\mathbf{H}_s$ is the secondary field received by the loop.

For the electrically small receiving loop we can approximate the final integral by the product of the loop area and the received field. We have

$$V_{ind} \approx i\omega\mu n_R dA_R \mathbf{n}_R \cdot \mathbf{H}_s$$

where $\mathbf{n}_R$ is the unit vector that defines the receiving loop axis.

Several further simplifications of this result are useful. In the quasi-static frequency regime, the loops and the potential targets are electrically small and it is reasonable to express the fields generated by them in terms of equivalent dipole moments. We can express the magnetic dipole moment $\mathbf{m}_{targ}$ of an object in terms of its magnetic polarizability matrix $\mathbf{M}$ as follows:

$$\mathbf{m}_{targ} = \mathbf{M}_{targ} \cdot \mathbf{H}_p$$

where $\mathbf{H}_p$ is the primary magnetic field produced by the transmitting loop that would exist in the absence of the object. The induced voltage V_{ind} involves the unknown field $\mathbf{H}_s$. By using the reciprocity theorem,[48] we can eliminate this dependence in favor of the field transmitted to the object. We can show

$$V_{ind} = \frac{i\omega\mu}{I}\mathbf{m}_{targ} \cdot \mathbf{H}'_p$$

where $\mathbf{H}_p$' is the field that would be produced at the target when the receiving loop is driven by a current I. We note that because the location of the object and its dipole moments are unknown, the quantity $\mathbf{m}_{targ}\cdot\mathbf{H}_p$' is, like $\mathbf{H}_s$, unknown, but the above form is somewhat more convenient for the calculations that will follow.

[48] R. F. Harrington, *Time Harmonic Electromagnetic Fields*, McGraw-Hill, New York, NY,1961.

The key features of the EMI sensor are made clear by invoking a few simplifications. First, let the transmit and receiving loops be co-located. In that case $\mathbf{H}_p' = \mathbf{H}_p$, and we have

$$V_{ind} = \frac{i\omega\mu}{I}\left[\mathbf{M}_{t\arg} \cdot \mathbf{H}_p\right] \cdot \mathbf{H}_p'$$

Next, consider the response to a small metallic sphere. Let the radius of the sphere be a. In this case, the target polarizability tensor can be written in the form[49]

$$\mathbf{M}_{t\arg} = 2\pi D\mathbf{I}$$

in which $\mathbf{I}$ is the identity tensor, and D is a scalar that depends on the sphere's composition. For ferrous metals $2\pi D = V_{targ}$ where V_{targ} is the target volume.[50] Finally, if we let the loops be oriented in the z direction, we obtain the simple form

$$V_{ind} = i\omega\mu In^2 (dA)^2 V_{t\arg} \frac{1 + 3\cos^2\theta}{8\pi R^6}$$

Hence, the response of the EMI sensor is proportional to the volume of the target and inversely proportional to the sixth power of the range to the target. It is evident that EMI sensors are restricted to relatively short target ranges, particularly for small targets.

One can create a sensor of induced magneto-quasi-static fields that operates with either CW or pulsed fields. For CW operation the frequencies of interest are a few Hz to a few kHz. The target couples inductively to the receiving antenna, and the receiver detects the change in the effective inductance of the circuit. In practice, this detection may be done by either canceling the transmitted field or by detecting a change in the frequency of a resonant circuit.

For a pulsed system, the transmitter generates a pulsed magnetic field. After this primary field has decayed, the receiver attempts to detect the secondary field which arises from the eddy currents. One can show that these currents decay approximately exponentially with time. The response of a large target will decay slowly (on the order of milliseconds), which impact the maximum pulse rate. Conversely, the response of small metal objects decays very quickly (on the order of microseconds). In the latter case, careful engineering is required to minimize the sensor's self inductance so that the decay time of the target is not lost in the decay time of the transmitting loop.

4.7.2 Technology Status

In general, EMI and low-frequency electromagnetic sensors are mature technologies, widely available as COTS devices. The sensors are extensively used as portal monitors to protect retail sales locations from shoplifting (so-called "electronic article surveillance" systems) and to detect metal weapons in airports and other public

---

[49] W. R. Smythe, *Static and Dynamic Electricity*, 3rd ed., pp. 374-380, 408-409, Hemisphere Publishing (Taylor and Francis), Philadelphia, PA, 1989.

[50] The polarizability tensor of nonferrous metals, is also proportional to the target volume, but complications arise that require a more lengthy explanation. For more details, see K.F. Casey and B. A. Baertlein, "An Overview of Electromagnetic Methods in Subsurface Detection," in *Detection and Identification of Visually Obscured Targets*, pp. 24-27, C. E. Baum, ed., Taylor and Francis, 1999.

facilities. Detection of distant metallic objects or very small pieces of metal is more challenging, but very capable designs have been demonstrated by several research groups.

Because EMI sensors are severely range limited, perhaps the best use of such sensors in PD is the above-cited monitoring of portals and other public places where personnel must travel through a restricted area. An attractive concept has been proposed by Nelson,[51] in which an array of EMI sensors could be deployed in the floor of high traffic sites. The sensor array would permit individuals with significant metal contact to be detected and tracked as they moved through the area.

4.7.3 Countermeasures, Outlook and Net Assessment

The strong range dependence of the EMI phenomenon makes distance a reliable EMI countermeasure. Common obscurants (building materials, clothing and packaging) have little effect, but metal is obviously an effective shield and a common source of confusion. (An adversary might carry a metal cooking pot displayed openly to mask the signal from concealed small arms.) Another common tactic for defeating EMI sensors is to avoid metal articles. The widespread use of EMI sensors has, unfortunately, motivated the development of weapons made of ceramics and other nonmetallic materials. Although these sensors are now in wide use, the increasing availability of countermeasures suggests that this sensor may not be effective in the future.

4.8 X-Ray Backscatter Sensors

None of the technologies discussed previously are effective in detecting personnel behind metal walls. Inasmuch as a large number of buildings, containers, and essentially all vehicles are constructed of metal, this leaves a large capability void.

Recently, sensors of backscattered x-rays have been described that are capable of detecting personnel behind metallic barriers. In this section we review the technology that underlies those sensors.

4.8.1 Sensor Concept

4.8.1.1 Detectable Phenomena

The basis for PD using x-ray backscatter is the chemical composition of tissue. The sensor exploits differences in low-energy x-ray scattering by tissue versus other materials.

4.8.1.2 Sensor Physics

The atomic number Z – an element's number of protons – is of key importance in this discussion. Human tissue (and that of other animals and plants) is composed of low Z materials as indicated in Table 4. Plastics are composed of hydrocarbons, and also have a low effective Z. Natural stones tend to be rich in oxygen bearing compounds, as indicated by the composition of the earth's crust given in Table 5. As a result, natural terrain tends to be a relatively low Z material also. Metals have much high atomic numbers, the most common of which are aluminum (Z=13) and iron (Z=26).

[51] C. Nelson, "Wide Area Metal Detection," presented at the *Personnel Detection Technology Workshop*, Columbus, OH, 7 Nov. 2002.

Table 4. Chemical composition of the human body

Element	Mass fraction	Atomic number Z
Oxygen	0.650	8
Carbon	0.185	6
Hydrogen	0.095	1
Nitrogen	0.032	7
Trace elements	0.038	N/A

Table 5. Chemical composition of the earth's crust

Element	Mass fraction	Atomic number
Oxygen	0.4660	8
Silicon	0.2772	14
Aluminum	0.0813	13
Iron	0.0500	26
Calcium	0.0363	20
Sodium	0.0283	11
Potassium	0.0259	19
Magnesium	0.0209	12
Other elements	0.0141	N/A

Low energy x-rays (roughly 0.1 M eV and below) tend to undergo Compton scattering from low Z materials.[52] Conversely, the same photon energies will be absorbed (via the photo-electric effect) by high Z materials. Thus, if one radiates a scene with low-energy photons, the backscattered signal reveals the low-Z material. If an appropriate x-ray source is used for illumination and the backscattered signal is received by an array, a detailed image of the low Z material can be reconstructed using methods analogous to computer tomography.

It is important not to confuse x-ray backscatter sensors with well known x-ray sensors now used in other applications. Such systems are typically based on transmission, rather than backscatter, and different physical processes are involved. Medical x-ray systems use much lower energies and typically operate at 0.1-10 keV. The systems used in airport security scatters operate at roughly 100 keV. At much higher energies x-rays can be absorbed by explosives, producing an electron-positron pair. The annihilation of the pair produces a high-energy gamma ray at 0.511 MeV that is detected by a specialized detector. Another type of explosive detector, thermal neutron activation, also generates an electron-proton pair when low-energy neutrons are captured by nitrogen atoms in the explosive.

4.8.2 Technology Status

A COTS x-ray imaging systems with potential uses in PD has been developed. The "BodySearch" system is produced by American Science and Engineering, Inc. (Billerica, MA).[53] Using 60 keV x-rays, the BodySearch system images backscatter from materials with Z values of roughly 15 or less and absorption for higher Z values. The resulting images clearly indicate scattering from tissue and absorption by metals (primarily iron and steel). The technology is presently used in systems that scan airline baggage, cargo containers, and

[52] K. S. Krane, *Introduction to Nuclear Physics,* p. 202, Wiley, New York, NY, 2002.
[53] See http://www.as-e.com/

shipping palettes. It is also used to scan personnel for concealed weapons as an alternative to strip searches. The BodySearch sensor is large, occupying a volume 3.2 meters deep by 1.6 meters wide by 3 meters tall (127" deep x 46" wide x 120" tall). The acquisition time for a high-resolution body scan is reported to be approximately 10 seconds. The range of the system is very limited: the subject must stand immediately adjacent to the sensor. It remains to be seen if the x-ray beam can be made to propagate a sufficient distance and if the detector array can be modified to produce a system of interest in PD.

4.8.3 Countermeasures, Outlook and Net Assessment

The abundance of low Z materials in the natural environment (i.e., in foliage and rocks) suggests that a subject in the field will readily find concealment. It also suggests that natural backgrounds will produce strong clutter levels and that image processing will be an important part of any x-ray backscatter PD sensor.

The size of an x-ray backscatter system and its limited range pose tremendous challenges to PD. Nonetheless, the ability of this sensor to interrogate closed metal containers makes it unique among all of the system examined here. The system may find use in specialized applications, including inspection of vehicles for concealed personnel and drive-by surveys of buildings.

4.9 Remote Sensing of Airborne Chemical Signatures

As noted in Section 4.3, respiration and other bodily processes generate airborne particles and gases that may be useful for personnel detection. A problem with most of the passive sensors discussed in Section 4.3 is that they depend on diffusion or wind to move these chemical signals to the sensor. As a result, detection is limited by environmental conditions, which are typically unreliable.

In this section we discuss methods of remotely sensing chemical constituents using EO sensors. Many of these sensors were developed as remote monitors of airborne pollution. Their application to PD presents a number of opportunities and challenges, which we discuss herein.

4.9.1 Sensor Concept

4.9.1.1 Detectable Phenomena

The sensors under consideration here measure the chemical composition of a remote air mass. The personnel-generated phenomena to be sensed include local increases in airborne particle density, gases (including exhaled CO_2) and other bioaerosols produced by personnel. Estimates of personnel chemical emissions appeared previously in Section 4.3.

4.9.1.2 Sensor Physics

Remote detection of personnel-generated chemical signatures is complicated by several facts. First, as discussed in Section 4.3, diffusion and wind motion tend to disperse the target material, thereby weakening the signal. Second, the target material is biological in origin, and similar materials may be generated naturally (albeit in lower concentration). For example, respiration produces high local concentrations of CO_2, but small quantities are also present in the atmosphere. The total CO_2 mass integrated along a sensor viewing path of a few hundred meters can easily dwarf the more concentrated but more localized CO_2 increase produced by personnel.

Spatial localization can help to overcome both of these problems. The use of a directional sensor with high range resolution can mitigate clutter from extraneous sources. In addition, wind-driven plumes tend to be (roughly) linear features with a known orientation, and this fact can be exploited by the signal processing if a spatially resolved map of concentration is available.

Although a number of sensors have the potential to measure airborne chemical signatures of personnel, differential absorption lidar (DIAL) has a number of attractive properties for PD. The DIAL concept involves using a lidar to probe the region of interest. Spatial localization is possible if one appropriately chooses the range and cross-range resolution of the lidar. The concentration of a single molecular species is sensed by probing the region twice with two different but closely spaced wavelengths. The first wavelength (the so-called "off" wavelength) is chosen to lie in a spectral band where the molecular species of interest scatters but does not absorb. The second wavelength (the "on" wavelength) is chosen in a band where the species both scatters and absorbs. The spectra of many molecules contain a number of strong, narrowband absorption lines suitable for a DIAL sensor. For CO_2, absorption lines arise at MWIR wavelengths near 2.7 μm and 4.25 μm, but other potential lines are found in the MMW bands.

Backscattering from the two wavelengths can be used to determine the density of the target molecular species. To see this, note that the received signal *S* produced by the target species at range *R* and a pulse length Δ*R* is given by[54]

$$S(R,\lambda) = E(\lambda)\frac{A}{4\pi R^2}\xi(R)\eta(\lambda)\beta(R,\lambda)\Delta R \exp\left[-2\int_0^R dR\big(\alpha(R,\lambda)+\sigma(R,\lambda)N(R)\big)\right]$$

in which *E* is the laser's transmitted power, *A* is the receiver area, ξ is the fraction of the detection cone illuminated by the beam, η is the detector efficiency, β is the scattering phase function of the target species, α is the attenuation coefficient for all species other than the target species, σ is the attenuation coefficient for the target species and *N* is the density of the target species. The ratio of two such measurements at different wavelengths yields

$$\frac{S(R,\lambda_1)}{S(R,\lambda_2)} = \frac{E(\lambda_1)\eta(\lambda_1)\beta(R,\lambda_1)}{E(\lambda_2)\eta(\lambda_2)\beta(R,\lambda_2)}\exp\left[-2\int_0^R dR\big(\Delta\alpha(R,\lambda)+\Delta\sigma(R,\lambda)N(R)\big)\right]$$

in which Δα and Δσ are the change in the respective quantities with wavelength. If the two wavelengths are closely spaced, then the transmitter power, detector efficiency, and absorbance of non-target species will not be significantly different, and we can write

$$\ln\left[\frac{S(R,\lambda_1)}{S(R,\lambda_2)}\right] = \ln\left[\frac{\beta(R,\lambda_1)}{\beta(R,\lambda_2)}\right] - 2\int_0^R dR\big(\Delta\sigma(R,\lambda)N(R)\big)$$

The difference between the measured response at a range *R* and at range *R*+Δ*R* is proportional to the desired quantity *N*. It is appropriate to consider

$$\frac{d}{dR}\ln\left[\frac{S(R,\lambda_1)}{S(R,\lambda_2)}\right] = \frac{d}{dR}\ln\left[\frac{\beta(R,\lambda_1)}{\beta(R,\lambda_2)}\right] - 2\Delta\sigma(R,\lambda)N(R)$$

[54] E. Boeker and R. van Grondelle, *Environmental Physics*, p. 381, Wiley, New York, NY,1995.

in which the derivatives are to be approximated by numerical differences. If scattering by the target species is not strongly wavelength dependent, then since $\Delta\sigma$ can be measured a priori, this expression yields an estimate for *N*.

The DIAL approach appears to be attractive for detection of PD-generated CO_2: As noted in Section 4.3, respiration appears to produce a large increase in local CO_2 concentrations, the detection ranges of interest in PD can be relatively short (at most a few km), and there are a number of suitable absorption bands for CO_2. It remains to be seen if these advantages can overcome the problems of a relatively small path length for the target molecules and wind-induced dispersion of the signature.

Although the discussion here has focused on the DIAL sensor concept, in certain circumstances other approaches may be useful. Another interesting concept is open-path Fourier-transform IR (OP-FTIR) spectroscopy. The OP-FTIR approach involves spectral measurements of blackbody radiation from an air column. The presence of specific spectral emission lines is indicative of the target species. Unfortunately, simply pointing the FTIR sensor into an unbounded path would produce a signal that integrates all of the target species along the entire path and, as indicated above, the contribution generated by personnel may only be a small fraction of that present in the remainder of the path. An alternative to this, which is used in FTIR monitoring of limited areas, is to place a retro-reflector at the boundary of the region of interest. In this manner, emissions from areas beyond the region of interest are eliminated. A powerful extension of this technique involves multiple sensors and reflectors, each of which senses the response at multiple angles. The resulting data set can then be processed using CT algorithms to produce a spatially localized map of the area.[55] This concept may be attractive in PD applications when a sensor suite is being emplaced to detect personnel in a large fixed area or in indoor environments.

4.9.2 Technology Status

Although a number of DIAL sensors have been developed, they have been used almost exclusively for long-distance atmospheric monitoring, which require large lasers and large optics. Such systems are not useful indicators of DIAL effectiveness for PD.

One COTS lidar system suitable for PD and bioaerosols sampling is the WindTracer infrared Doppler lidar produced by Coherent Technologies (Boulder, CO).[56] This device remotely measures particle density rather than the concentration of a specific chemical species. The vendor claims detection ranges of up to 15 km for high concentrations (the typical range is stated as 8 km), and sensitivities of a few hundred to a few thousand particles per liter. The system's range resolution is 50-100 meters, and it has a minimum range of 400 meters. The system size is 3.3 cubic feet, and its mass is 285 pounds.

OP-FTIR sensors are also commercially available. An example is the Remote Air Monitor 2000 (RAM 2000) produced by AIL Systems.[57] The sensor has a range of up to 500 meters. A sensitivity of 0.1-15 parts per billion (ppb) is claimed for a 100 meter path. The nominal scan time is 1.7 seconds, and up to 32 scan directions may be programmed into the device.

[55] CT processing of FTIR data has been described by several groups. For a recent example, see A. R. Piper, L. A. Todd, and K. Mottus, "A field study using open-path FTIR spectroscopy to measure and map air emissions from volume sources," *Field Analytical Chemistry and Technology*, Vol. 3, No. 2, pp. 69-79, 1999.
[56] See http://www.ctilidar.com/products/product_catalog/homeland_security.htm
[57] See http://www.ail.com/page8b.htm.

4.9.3 Countermeasures, Outlook and Net Assessment

There appear to be few practical countermeasures to detection of bioaerosols and exhaled CO_2. Nonetheless, the ease with which these materials are dispersed by wind makes them challenging to detect.

Although the technology has not been explored in any detail, it appears that laser-based concepts like DIAL may be an attractive technique for monitoring personnel movement over large areas. One such scenario would put the sensor aboard an airborne sensor that flies over the region of interest. In another scenario, a fixed asset (possibly an indoor facility) could be protected by a single sensor with a scanned beam placed in a corner of the room. We suggest that these concepts merit further investigation.

4.10 Multi-Sensor Systems- REMBASS II

In addition to the individual sensors described above, there exist multi-sensor suites that can be used for PD. The Remotely-Monitored Battlefield Sensor System (REMBASS) is a passive multi-sensor system developed by the US Army for covert personnel detection. REMBASS-II is an improved version of the earlier REMBASS and I-REMBASS systems, originally developed from the Unattended Ground Sensor System (UGSS) of the Vietnam era.

The system is designed for unattended sensing of personnel and vehicles. To conserve battery power, the system normally operates in a low power mode. When an overseer sensor notes a change in the ambient signal level, the sensors are activated and a data stream is collected. The received signals may be transmitted to a remote observer via an RF link and a compact omni-directional antenna. The entire unit operates on 4 COTS 9V lithium batteries, and it has a normal lifetime (assuming 1000 activations per day) of 30-45 days depending on the ambient temperature.

The current version of the system features three types of sensor modules: (1) an acoustic-seismic sensor, (2) a non-imaging passive infrared detector, and (3) a magnetic sensor. The acoustic-seismic sensor is capable of detecting tracked vehicles at ranges of 750 meters, wheeled vehicles at 500 meters, and personnel at 75 meters. The IR detector senses temperature differentials caused by vehicles or personnel, and will provide both target direction and count. A range of 3-75 meters is stated for vehicles and 3-30 meters for personnel. The magnetic sensor detects the movement of ferrous metal. Detection ranges are quoted as 25 meters for tracked vehicles, 15 meters for wheeled vehicles, and 3 meters for personnel (carrying a weapon). Sensor module volumes range from 400-1600 cm^3, and module weights range from 0.6 to 1.2 kg each.

4.11 Summary of Sensor Capabilities

The foregoing sensor information is summarized in Table 6, which describes in qualitative terms the capabilities of sensor technologies relevant to PD. The legend provides an explanation of the column headings. When more than one implementation of the sensor is possible, a device is assumed that is sufficiently small and inexpensive to be practical for a PD sensor network.

It is evident from the table that a large number of sensors (both COTS devices and sensors currently under development) are capable of detecting personnel under some conditions. It is also true that the sensors are challenged by the scenarios defined in Section 2. In general, sensor range is a problem for the long range scenarios (Scenarios 1 and 2). Few of the sensors have the ability to detect personnel at those ranges without resorting to spatially distributed arrays. Those sensors that may have adequate range (EO and radar) typically require a line of sight, which may not be available and certainly will not be dependable for moving sensors.

The existing sensors for PD, described in Section 4.6.2 and 4.10 above, have a number of shortcomings. The AN/PPS-5D radar has a very large detection range, but it is limited to line-of-sight environments. Proliferating the sensor to cover blind-spots caused by the terrain or buildings is not practical, because the sensor is relatively large and heavy. In addition, its high power requirements make it unacceptable for long-term unattended operation. The REMBASS-II system is based on the attractive concept of small, low-power sensors, but the acoustic, non-imaging IR, and magnetometric sensors currently used in that system are not capable of satisfying the scenario requirements defined in Section 2. In general, all of those sensors have very limited range for dismounted personnel and they are susceptible to countermeasures. Nonetheless, the extension of REMBASS to include more capable sensors, more sophisticated networking, and in-network data fusion is an attractive goal.

Another finding from the preceding sections is that with few exceptions, improvements in sensor technologies are unlikely to yield quantum improvements in PD capabilities. The potential exceptions to this situation are olfactory sensors, EO-based chemical sensors, and bistatic radars. Recommendations for some further sensor work appear in Section 6.

Table 7 reviews the usefulness of these sensors in each of the scenarios of Section 2. In completing that table some simplifications were made to the scenarios. First, it was assumed that the region of interest did not move in Scenario 2. Second, it was assumed that only a single room was to be interrogated in Scenario 3, and that access to the walls of the building was available. Finally, in Scenario 4 it was assumed that a robotic platform was available to transport the sensors beyond the line of sight if required.

A significant feature of Table 7 is the large number of caveats supplied as notes. Several of the sensors have limited range, and their ability to monitor a wide area requires that an array of sensors be emplaced. When the distance to be monitored was greater than 100 m, sensors that had an effective range of less than 10 meters were not considered because of the large number of sensors that would be required. It is notable that none of the sensors suitable for Scenarios 1 and 2 can fulfill all of the requirements of those scenarios without restrictions.

The restrictions in Table 7 suggest that no single sensor is likely to yield acceptable performance. This conclusion is due in part to the diverse conditions that are likely to be encountered in the field, and it is particularly true for the long-range scenarios (1 and 2). For those scenarios it is also likely that networks of sensors will be required. As indicated by Table 6, the sensor detection ranges are far less than the ranges of typical organic direct fire weapons. Only by networking these sensors, can the required detection range be achieved. Even when sufficient range is present, reliable detection by a single sensor is questionable. Human sensor signatures can be weak and extremely varied. Moreover, the environments in which personnel are found are highly variable. This state of affairs suggests that fusion of data from multiple sensors and from ancillary sources will be required to achieve acceptable performance.

Table 6. Capabilities of sensor candidates

Technology	Maximum Range	Size	Power	Weather Dependence	Counter-measures?	Cost	Maturity	Notes
Passive EO and IR	0.1-1 km	Small-medium	Low	High	Y	Low-High	High	A wide variety of EO/IR sensors are in use with various capabilities. Fielded in REMBASS
Acoustic	10-100 m	Small	Low	Low	Y	Low	High	Currently fielded in REMBASS
Point Chemical Sensor	1-10 m	Small	Low	High	N	Low	Low	Very dependent on weather. Additional research required.
Bio-EM	0.1-1 m	Small – medium	Low	Low	N	Med	Very low	Substantial research required. Very short ranges likely
Magnetometers	1-10 m	Small	Low	Low	N	Low	High	Only detects ferrous metal tools and weapons. Fielded in REMBASS
PMW-PMMW-THz	10-100 m	Medium	Low	High	Y	High	Med	PMW and PMMW sensors are maturing but bulky. THz sensors are smaller but require development.
Radar	0.1-1 km	Medium	High-Low	Low	N	Low-High	High	Existing monostatic system fielded. Bistatic system would require lower power.
Sonar	1-10 m	Medium	Med	Low	N	Med	Med	Very limited range, poor penetration of walls, obscurants.
Lidar	0.1-1 km	Large	High	High	N	High	High	Laser efficiency an issue
EM induction	1-10 m	Small	Low	Low	N	Low	High	Detects metal tools and weapons
X-ray backscatter	1-10 m	XLarge	High	Low	N	High	Med	Only sensor capable of penetrating metal. Additional development probably required for greater range.
EO Chemical Monitor	0.1-1 km	XLarge	High	High	N	High	Low	Promising but unproven technology for PD. Extensive use in pollution monitoring.

Legend

Size legend: “Small”=pocket sized, “Medium”=shoe-box sized, “Large”=backpack sized, “Xlarge” = vehicle required.

Power legend: ratings are in hours of continuous operation for a 100 cm^3 battery (about 50 Wh). “high”=less than 10, “med”=more than 10 but less than 100, “low”=more than 100

Weather legend: Magnitude of impairment as a result of change in temperature, or presence of wind, fog, or rain

Cost legend: Low=$3-$30, Med=$30-$300, High=$300-$3000

Countermeasures legend: The expected performance of the sensor when the target is employing common methods of stealth, including maintaining a low profile, avoiding vocalization, and walking quietly.

Maturity legend: Very low=sensor is in conceptual stage only. Basic research is required. Low=Sensor concept is well understood, but no suitable sensor exists. Development is required. Med=Suitable prototype sensor has been demonstrated or used in a controlled environment. High=Suitable COTS sensor exists.

Table 7. Sensor suitability to PD scenarios

Technology	Scenario 1: Perimeter Control	Scenario 2: Covert Volume Monitor	Scenario 3: Urban Environ.	Scenario 4: Tunnel/Bunker Interrogation	Scenario 5: Short Range Monitoring	Remarks
EO/IR	Yes (b)	Yes (b)	Yes(b)	Yes(b)	Yes (b)	Line of sight required. Some sensors require silar illumination
Acoustic	Yes (a)	Yes (a,c,e)	Yes (e)	Yes (e)	Yes (e)	Target must be speaking or otherwise generating noise
Point Chemical Sensor	No (m)	No (m)	Yes (a)	Yes	Yes	Dependent on wind direction. Limited use in tracking
Bio-EM	No	No	Yes (a)	Yes	Yes	Sensor provides information on physiological state of personnel.
Magnetometers	No	No	Yes (a,o)	Yes (o)	Yes (o)	Well suited for vehicles
PMW-PMMW-THz	Yes (l)	Yes (a,l)	Yes (l)	Yes (l)	Yes (l)	Compact THz sensor assumed
Radar	Yes (h)	Yes (h)	Yes (i)	Yes (h)	Yes	MMW radar assumed. (compact size)
Sonar	No	No	Yes	Yes	Yes	Short range applications only
Lidar	Yes (b)	Yes (b)	Yes (b)	Yes (b)	Yes (b)	Exposed targets only
EM induction	No	No	Yes (a,f)	Yes (a,f)	Yes (f)	Personnel must possess metal tools or weapons
X-ray backscatter	No	No	Yes (k)	Yes (k)	Yes (k)	Possible use for interrogating metal containers, rooms
EO Chemical Monitor	Yes (n)	Yes (n)	Yes (n)	Yes	Yes	Signature persists after personnel depart.

Legend

An affirmative entry indicates that the sensor may satisfy some (but not necessarily all) sensing needs for the scenario.

When multiple implementations of the sensor exist, the entries apply to sensors that are sufficiently small and inexpensive for widespread use.

Notes:

(a) Requires a network of sensors
(b) Requires a line of sight to target (well suited to airborne platforms)
(c) Not for moving ROI
(d) Requires moving target and change detector
(e) Requires speaking target
(f) Target must be carrying metal objects (e.g. weapon)
(g) Requires a robotic platform
(h) Needs line of sight, and UWB sensor if foliage is present
(i) Requires specialized radar to penetrate walls
(j) Requires extensive clutter mitigation
(k) Large size of sensor limits it to specialized applications
(l) Sensor has limited ability to penetrate obscurants
(m) Wide area coverage might be possible from a mobile platform, e.g., mini-UAV
(n) High winds can render sensor inoperative or unreliable.
(o) Target must have ferrous metal tool or weapon.

5.0 Data Exploitation Technologies

Although processing is often viewed as a supporting task with respect to sensor development, this is not the case in PD. As noted in Section 4.11, information fusion and sensor networking are key enabling technologies, without which reliable PD may well be impossible. In this section we review those processing technologies.

Another key technology that is not covered here is classification of friendly and enemy forces. Noncombatants are present at the site of many conflicts, and they must be distinguished from the (often less numerous) adversaries. Non-cooperative discrimination of personnel using voice, gait, and other observables is a challenging research problem, as is the determination of intent based on sensor cues. These problems are still beyond the current state of the art, and for this reason, discussion of the topic has been omitted.

5.1 Information Fusion

In this section we discuss fusion, which comprises methods for synergistic combination of information from multiple sources. The fusion of sensor data (so-called "sensor fusion") is a useful subset of this technology, but unnecessarily restrictive because of the diverse information sources available for PD (ELINT, order-of-battle information, databases, etc.)

5.1.1 Background

There exist numerous objectives for and approaches to fusion. Fusion can be used for parameter (e.g., state vector) estimation or for detection and classification. The algorithms used in parameter estimation and detection/classification are typically different. In this work we consider only the latter problem, because of its relevance to PD. We briefly review a fusion approach based on classical techniques from statistical decision theory augmented by some specialized concepts.

The process of personnel detection begins with the acquisition of sensor data and other information. Restrictions related to legacy sensors or limited communication bandwidth may cause the collecting sensors to present different types of data. The sensors may reduce their raw data to "features" (parameters that contain essential information about the data), to probabilities that a given target is present, or to binary decisions regarding target presence.

The optimal approach to fusion depends strongly on the type of information being fused. A useful fusion taxonomy has been presented by Hall,[58] who categorizes the fusion processes in accordance with the level (data/feature/decision) at which the data are combined. The fusion of raw (or minimally processed) data is referred to as "data-level fusion." "Feature-level fusion" is obviously used for feature data. For probabilities we employ "soft decision-level fusion" and for binary decisions we have "hard decision-level fusion." Because of the high dimensionality of most raw sensor data, the reduction to features is often an intermediate step in all of the approaches.

It is noted below that data-level and feature-level fusion are mathematically equivalent, although their implementations are typically much different. The techniques used for decision-level fusion algorithms are generally distinct from those used for data-level and feature-level fusion. Finally, the concept of performing fusion at only one level is often unnecessarily restrictive. An alternative characterization of the process is

[58] Hall, D.L., *Mathematical Techniques in Multisensor Data Fusion*, Artech House, Boston, 1992.

offered by Dasarathy,[59] who argues that fusion can be done at multiple points in the classification or estimation process.

In the remainder of this section we discuss practical issues that arise in implementing fusion algorithms.

5.1.1.1 Data-Level and Feature-Level Fusion

One can define algorithms for data-level or feature level fusion that are similar to those used in conventional multi-variate statistical decision theory. We represent the random samples from the i-th sensor by the symbol $\mathbf{d}_i$ for i=1,2,…,N_s, with N_s the number of sensors. As noted above, it may be desirable to reduce these data to features $\boldsymbol{f}_i$, and we use the symbol $\boldsymbol{x}_i$ to represent either the data $\boldsymbol{d}_i$ or the feature vector $\boldsymbol{f}_i$ for sensor i. We then combine or "fuse" the quantities $\boldsymbol{x}_i$ into a single datum $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N\}$. Data-level fusion may result in fused data $\mathbf{X}$ with very high dimensions.

Fusion algorithms can be awkward if the sensors produce data that are not "commensurate", i.e., do not have the same form. When the data have the same form, then $\mathbf{X}$ is just a higher-dimensional form of the $\mathbf{x}_i$, and fusion is conceptually the same as single-sensor detection. Fusion of non-commensurate data can be challenging. In some cases the problem can be corrected by simply interpolating all data sets to a common coordinate system. In other cases, it may be necessary to eschew data-level fusion for feature-level fusion, since feature extraction reduces all data sets to feature vectors (i.e., lists of numerical parameters). In feature-level fusion one simply concatenates the component feature vectors. In that case $\mathbf{X}$ is a single long vector, which is then treated using conventional statistical decision theory. In addition to statistical decision theory, other approaches to the detection process (e.g., neural networks, fuzzy logic, clustering, and other classifiers) can also be used with good (and sometimes superior) results.

5.1.1.2 Decision-Level Fusion

As noted above, decision-level fusion algorithms are typically different from data-level and feature-level algorithms. In this approach data or features from each sensor are used to compute individual detection probabilities or binary decisions, and these probabilities/decisions are combined via a process described in this section.

Decision-level fusion is very convenient when diverse sensors are involved, because decision outputs are sensor independent and trivially commensurate. Many existing sensors already have algorithms for performing detection, and those detection outputs can be used directly in a decision-level fusion system. Furthermore, because the operations performed in fusion involve manipulation of simple binary variables or scalar probabilities, they are often tractable analytically, which has led to a marked preference for decision-level fusion algorithms among the academic community. But while they have a number of attractive properties, decision-level fusion approaches are generally not optimal. The action of reducing the raw data to decisions (or even to features) discards a great deal of information, which may be essential in the decision process. One can show that when the sensor data are independent, the decision-level fusion process is optimal, but in practice one seldom encounters truly independent sensors.

Decision level fusion has been investigated extensively, and a variety of techniques have been proposed.[60] When probabilities ("soft decisions") are being combined, Bayesian methods (including Bayes nets) are applicable. Dempster-Schafer techniques have also been used. When a finite number of binary decisions are

---

[59] B. Dasarathy, *Decision Fusion*, IEEE Press, Piscataway, NJ, 1994.
[60] P. K. Varshney, *Distributed Detection and Data Fusion*, Springer, New York, NY, 1997.

being combined, one can enumerate all of the possible fusion algorithms. Among these are the common "OR" algorithm (in which a detection is declared if *any* of the individual sensors detected a target) and the complementary "AND" algorithm (which requires that *all* sensors declare a detection). Among the most widely used algorithms is the simple majority voting approach, in which the plurality decision is used. One can show that if independent sensor "votes" (binary decisions) are weighted by the reliability of the sensor, then the resulting weighted voting algorithm is optimal.[61]

5.1.1.3 The Fusion Process

The act of "fusion", i.e., combining information from different sources into a single entity, inherently implies a reduction in the dimension of the data. The manner in which this combination is performed determines the effectiveness and the practicality of fusion.

As noted above for data-level and feature-level fusion, the simplest method of performing fusion is to simply enlarge the data vector by concatenation. This approach, unfortunately, does not reduce the size of the input data space, but it has the advantage of simplicity. All the machinery of classical statistical decision and estimation theory can be brought to bear. In fact, much work referred to in the literature as feature-level fusion is indistinguishable from ordinary pattern classification applied to concatenated feature vectors. The process of reducing the dimensionality of the input space to that of the decision space is done implicitly by the pattern classifier. The disadvantage of this "concatenation" method of fusion is that the dimensions of the problem may be enlarged beyond the limits of the training data.

Alternatively, we can merge information acquired from different sensors into a single piece of information using a transformation of the form $\{\mathbf{x}_1\, \mathbf{x}_2 \ldots \mathbf{x}_{N_s}\} \rightarrow \mathbf{x}$ in which $\mathbf{x}$ has a smaller dimension than the concatenated vector $\mathbf{X}$. A simplistic example of this process is averaging of data or features acquired by commensurate sensors. Averaging and other simple approaches to fusion typically require that all of the sensors produce compatible information and, hence, they may not be suitable (or even possible) for sensor suites involving diverse sensors. The development of more sophisticated methods for fusion is an open research topic.

5.1.2 State of the Art and Research Needs

Sensor fusion has been investigated for more than 20 years. The vast majority of fusion studies involve one of two approaches: (1) minor variations on decision level fusion, or (2) the concatenation of feature (or data) vectors into a larger feature vector and subsequent classification of the enlarged vector. It was argued above that studies of the latter type are equivalent to standard multi-variate classification problems, since the "fusion" operation is actually done by the classifier. In doing so, however, we do not wish to deprecate the considerable work that must be done on such mundane matters as registration of diverse data sets (also known as "association"), accounting for differences in sensor reliability, and obtaining reliable training and performance estimates for classifiers that use small data sets. In real-world applications of fusion, these problems arise in addition to the significant hardware problems of keeping a large number of sensors functioning simultaneously.

Some aspects of decision-level and feature-level fusion are well addressed by the extant mathematical machinery but, in general, fusion is an area with numerous unsolved research problems. We noted above the need to develop new methods for fusion of non-commensurate data sets. Another problem common to all fusion applications is that of sensor suite selection: Given limited platform resources (e.g., power, space, and viewing aperture), and a target that exhibits diverse signatures for different sensor modalities, what sensors should be used for fusion? In several previous applications of sensor fusion, trial data sets were collected and

[61] P. K. Varshney, *Distributed Detection and Data Fusion*, Section 3.3, Springer, 1997.

processed in an attempt to answer this question, but seldom can one afford to acquire a sufficiently large data set to reach a defensible conclusion. Furthermore, the available sensors are often experimental prototypes that are undergoing continuous "improvement." The sensors actually fielded may bear little resemblance to the sensor suite used in testing. Research should be devoted to developing a reliable method of predicting sensor performance, showing how each sensor contributes to the fused suite. Some preliminary studies along these lines have been conducted using statistical[62] and fuzzy approaches,[63] but there is ample room for improvement.

Some of the greatest challenges in sensor fusion arise in optimally exploiting very diverse types of information. For example, how can one optimally combine olfactory sensor data with imagery of the same region? The olfactory data is not specific to location, and because of the delay involved in transport it may be collected some time after the personnel have departed. If multiple personnel were detected in the imagery, one has the problem of associating the two signatures. An interesting approach to this data association problem has been presented by Fisher[64] who used information theory to associate events in imagery with events in an audio track that were recorded asynchronously.

Issues also arise in combining sensor data with auxiliary data. For example, if one obtained intelligence reports that an adversary was approaching a sensor suite, that information might be used to adjust certain a priori probabilities in a classifier. The information might also be used to cue specific sensors directed at the adversary's most likely path. The use of sensor data both in detection and in resource allocation is a largely unexplored research problem.

5.2 Sensor Networking

Distributed sensor networks (DSNs) are a relatively new topic and are currently an area of active research. To a large degree, the underlying technology is in its infancy. In this section we present some key concepts and a discussion of areas where research will be of greatest benefit to the PD mission.

The network required for PD involves sensors and wireless communication equipment packaged in small modules (network nodes) and distributed over a region of interest. GPS sensors may also be included in the nodes to provide spatial awareness. The network is likely to be heterogeneous, comprising nodes with different sensor suites selected by the user to address local environmental or tactical needs. The nodes may also be capable of semi-autonomous operation, and may have internal control and processing capability.

The primary functions of the sensor networking software are (1) to configure these nodes for effective communication, and (2) to task sensor nodes to acquire the most useful data while minimizing resource consumption. The software may also have a third objective, namely, to process and fuse sensor data to obtain information of interest to a user. That function may be performed at a central site rather than within the network nodes. In general, the network configuration, control paradigm and subsequent processing (which includes fusion) are interrelated and should be considered as a unit.[65]

---

[62] B. A. Baertlein, W. J. Liao and D.-H. Chen, "Predicting sensor fusion performance using theoretical models," in *Detection and Remediation Technologies for Mines and Minelike Targets VI,* A. C. Dubey, J. F. Harvey, J. T. Broach, V. George, eds., Proc SPIE, Vol. 4394, pp. 1035-1046, 2001.

[63] J. M. Keller, S. Auephanwiriyakul and P. D. Gader, "Experiments in predictive sensor fusion," in *Detection and Remediation Technologies for Mines and Minelike Targets VI,* A. C. Dubey, J. F. Harvey, J. T. Broach, V. George, eds., Proc SPIE, Vol. 4394, pp. 1047-1058, 2001..

[64] J. W. Fisher III, M. Wainwright, E. Sudderth and A. S. Willsky, "Statistical and Information-Theoretic Methods For Self-Organization And Fusion Of Multimodal, Networked Sensors," manuscript in review, 2001.

[65] H. Qi, S. Iyengar, and K. Chakrabarty, "Distributed sensor networks – a review of recent research," *Journal of the Franklin Institute*, vol. 338, pp. 655-668, 2001.

The network configuration process is normally done once when the network is emplaced, but it may be repeated in the event of node failures or movement. Configuration requires that each node establish a communication link with one or more neighboring nodes. Once the links are created, a routing protocol must be defined to identify which nodes will act as "hubs", relaying data toward the network's user. An optimization process is typically used to define the most desirable network topology. A typical constraint may be that the number of relay "hops" required by any node is minimized. An example network using RF sensors was described by Corr and Okino.[66] In that work a geographical addressing scheme was described, and a routing protocol for the network was defined. The concept was tested on six nodes, and network communication performance metrics were measured for GPS data.

DSN control and resource allocation have been investigated by several groups. Stoeter et al.[67] developed a distributed control architecture that was later used by Rbyski et al.[68] to operate a "team" of miniature robots for surveillance and reconnaissance. In their approach, sensors were tasked by resource controllers (RCs), and groups of one or more resources were controlled by aggregate resource controllers (ARCs). Control decisions and "behaviors" (general goal-oriented activities) interacted with the ARCs to achieve specific objectives.

Network bandwidth is a critical resource that is strongly affected by the fusion process. Performing data-level sensor fusion at a central node makes maximal use of the available information, but it requires that the sensors transmit their data through a significant portion of the network, which can consume a large amount of bandwidth. In addition, it does not exploit any distributed processing present in the nodes. A solution to this problem is the mobile agent concept.[69] In that approach the network control software recognizes that an event has occurred in a given spatial neighborhood. The sensor nodes in that neighborhood are formed into a local cluster and one node is designated the local hub for the cluster. The central control node dispatches autonomous software (the "agent") to the local hub. The agent performs fusion using the processing available within the cluster. In this manner, fusion-related data transfers are restricted to nodes within the cluster, thereby minimizing the communication burden in the remainder of the network.

---

[66] M. G. Corr and C. M Okino, "Networking Reconfigurable Smart Sensors," in *Enabling Technologies for Law Enforcement and Security*, S. K. Bramble, E. M. Carapezza and L. I. Rudin, eds., Proc. SPIE, Vol. 4232, pp. 341-351, 2001.

[67] S. A. Stoeter, P. E. Rybski, M. D. Erickson, M. Gini, D. F. Hougen, D. G. Krantz, N. P. Papanikolopoulos, and M Wyman, "A robotic team for exploration and surveillance: Design and architecture," in *Proc. Sixth Int. Conf. Intelligent Autonomous Systems,* Venice, Italy, 2000, pp. 767-744.

[68] P. E. Rybski, S. A. Stoeter, N. P. Papanikolopoulos, I. Burt, T. Dahlin, M. Gini, D. F. Hougen, D. G. Krantz, and F. Nageotte, "Sharing Control," *IEEE Robotics and Automation Magazine*, vol. 9, No. 4, pp. 41-48, Dec. 2002.

[69] H. Qi, S.S. Iyengar, and K. Chakrabarty, "Multi-resolution data integration using mobile agents in distributed sensor networks," *IEEE Trans. Syst., Man and Cybernetics: C,* Vol.31, No. 3, pp. 383-391, 2001.

6.0 Summary

Recent US and foreign military operations make it evident that an effective PD capability is urgently required. As discussed in Section 4.11, the existing fielded sensors (the AN/PPS-5D radar and the REMBASS multi-sensor system) are inadequate to fulfill this requirement. The need is particularly acute for MOUT scenarios, but another need is looming. Block 1 of Future Combat Systems (FCS) is scheduled to be deployed during 2008. The lighter armor on FCS vehicles makes them vulnerable to shoulder-launched rocket-propelled grenades (RPGs), which implies a need to detect personnel capable of using those weapons.

Detection of personnel has many issues in common with the general problem of detecting small targets in highly cluttered environments, but several PD-specific issues can be identified:

First, human signatures are generally difficult to sense. Humans have low SNR for many sensor modalities, since their physical properties are often not significantly different those of their surroundings. We note that humans may have no metal content (similar to natural terrain), they are composed of organic material (similar to foliage) and the surface temperatures of clothing are often similar to ambient air temperatures. The problem is exacerbated by the fact that trained personnel are adept at concealment. Personnel are relatively small compared to other features in the environment, and they are able to adapt to their surroundings. In addition, countermeasures to many sensors (e.g., walking softly and using concealment) are well known and easily used.

Second, the signatures of humans and environments containing humans (e.g., urban areas) are highly variable. For example, optical imagery of humans span the myriad poses that a human can assume and the variety of human clothing. Hence, it is often difficult to identify simple discriminative features of personnel.

Third, we found that the sensors capable of detecting personnel signatures have relatively short ranges. Many of the sensors capable of detecting personnel have ranges of less than 10 meters, and few of them have ranges much in excess of 100 m. In contrast, the ranges in excess of 1 km are required in some scenarios of interest.

The above facts suggest that PD will require multi-modal networks of sensors to achieve acceptable levels of performance. Hence, sensor networking and sensor fusion concepts will play crucial roles in any future development. Many PD sensors are light enough to be deployed on small airborne platforms (micro-UAVs). An airborne sensor network could be effective in the volume monitoring scenario identified in Section 2. Such a network would be particularly useful for defending a moving force.

Non-cooperative discrimination of friendly and enemy personnel is important in many situations, particularly in crowded urban environments. Unfortunately, that capability is currently beyond the state of the art. More capable sensors and higher level of reasoning will be required to infer intent from ID or behavior information.

7.0 Recommendations for Future Research

Based on the analysis presented herein and comments received during the PD Technology Workshop, a number of research needs have been identified and are presented below. In future studies of PD, it is important to keep in mind that PD is a relatively new technology. Innovations both in sensors and processing are likely to occur, and future research should strongly encourage new approaches and new concepts.

7.1 Personnel Signatures

A thorough, first-principles study of personnel signatures is suggested. Relatively little is known about personnel signatures for many of the sensors considered in Section 4. Some of the quantities that should be measured include but are not limited to

- The reflectivity and emissivity of skin and clothing at visible and IR wavelength.
- Odorants specific to personnel (for example, those that allow dogs to detect people)
- The radar cross section of personnel at frequencies from a few GHz to MMW.
- The spatial distribution of bioaerosols and respiration-generated CO_2 produced by personnel in typically clothing.

The study should include signatures of humans in isolation (i.e., with an unrestricted sensor field of view) and in the field (i.e., with full or partial concealment provided by foliage and terrain features).

7.2 Sensor Development

Table 6 shows that many of the sensors of interest are mature, but we believe that three sensor concepts bear additional exploration.

The first of these are local sensors of air chemistry (olfaction analogs) discussed in Section 4.3. We suggest investigation of technologies based on detection of molecular vapors and bioaerosols. Some key areas of future research include optimizing the sensors for odorants produced by personnel and developing strategies for dealing with vapor/particle transport via sensor arrays or concentrators. The potential for putting an olfaction sensor on a micro-UAV or micro-UGV should be examined.

A second sensor topic that bears further exploration is bistatic radar. Long-range monostatic radar is infeasible for a battery-powered PD sensor, because of the power required to transmit a signal that attenuates as the inverse fourth power of range. In contrast, a bistatic radar uses transmissions from an external source (e.g., a transmitter on a remote airborne platform, or even local TV and cell phone transmitters) to illuminate the target. The PD sensor then needs only a simple receiver – a low-power, passive device. Target range information can still be obtained from knowledge of the transmitter location and a comparison of waves that emanate directly from the transmitter and those scattered from the target.

Finally, we suggest that an EO sensor of remote air chemistry be developed. A preliminary assessment, presented in Section 4.9, suggests that personnel respiration can raise local atmospheric CO_2 levels by as much as two orders of magnitude. It appears that differential absorbance laser (DIAL) technology could measure and localize this increase from considerable distances. Such a sensor would exhibit the novel capabilities of olfaction sensors while achieving longer detection ranges. The ability of a DIAL sensor to spatially localize the signatures and to map out signature evolution with time (for example, to track a plume) should also be explored.

Table 6 also identifies some immature sensors that may ultimately contribute to the PD mission. Specifically, we note that bioelectromagnetic sensors may be able to detect personnel signatures at close ranges. X-ray backscatter sensors are able to detect personnel behind metal barriers, but the existing systems are not well suited to PD. Further development of those sensors is discouraged at this time. Although they may prove attractive in the future, we believe that the Army's resources are better spent in other areas.

7.3 Development of Fusion and Networking Hardware and Software

We noted above that a distributed sensor network (DSN) will probably be necessary for reliable PD. To support that effort, a DSN testbed should be developed to evaluate promising concepts. A flexible set of modules with wireless RF links should be assembled, and a robust communication network with self-routing protocols should be developed. The sensor modules should be equipped initially with a set of inexpensive COTS sensors (e.g., similar to those used in REMBASS II). Although a terrestrial testbed should be explored first, many of the sensors identified here are compatible with small airborne platforms, and an airborne testbed using a "swarm" of micro-UAVs should also be considered in the future.

Software for information fusion should be developed. To support that effort, we suggest that the Army immediately acquire a high-quality multi-sensor data set. The acquisition of this data set is a prerequisite for fusion work, and it can help to scope the network size and bandwidth required for PD. A suite of readily available sensors should be used to collect signatures from humans and background clutter in a wide variety of conditions. The conditions should include both rural and urban environments. To support subsequent fusion studies, the sensors should be operated concurrently and oriented to view the same events. Extensive supporting ground truth information should be acquired. The resulting data set should be seeded to interested research groups nationwide. Studies should be done to identify the best sensor configurations and combinations. Where possible, performance bounds (e.g., Cramer-Rao bounds), should be developed from the data. Close coordination of the fusion and network control software are required, and opportunities for synergy between fusion and control should be sought out.