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An Analysis of Through- and In-the-Wall UWB Impulse Radar

System design considerations

Greg Barrie and Jake Tunaley

Defence R&D Canada – Ottawa
TECHNICAL MEMORANDUM
DRDC Ottawa TM 2003-134
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Abstract

Military application of through-wall radar requires the ability to detect targets through relatively high-density materials such as concrete, stone and brick. These materials can result in considerable attenuation of electromagnetic waves, increasing requirements for both radar power and signal processing.

Wall attenuation becomes a prominent limitation in the ensuing power budget. For the preliminary investigation undertaken here, conflicting physical requirements for high resolution and signal penetrating power are matched against the hardware and data processing limitations of large dynamic range, sampling rate and interference.

If the radar signal must penetrate concrete block, a practical *operational* frequency is about 3 GHz, and the usable frequency range is no greater than approximately 10 GHz. On the other hand, for common wall materials other than concrete block, and assuming that the material is dry, dynamic range does not constrain the resolution. Much higher resolutions in the millimeter range are possible.

The assumptions that the two-way attenuation can be up to 30 dB (at 10 GHz, say) and that the ratio of the RCSs can range over 20 dB imply that the dynamic range at the radar front-end must be *at least* 50 dB. This does not, however, address the multipath effects, which are statistical in nature, nor does it address the increased attenuation due to moisture in the blocks. An additional fade margin needs to be built into the power budget to maintain an acceptable detection probability.

The analysis presented here can be applied equally to radar-based detection of objects, such as pipes and wires buried *within* a wall. The RCS of these objects will be an order of magnitude less than that of human targets so that the SNR margin will typically be 10 dB less. Nevertheless they should still be detectable at the low end of the microwave range.

Résumé

Les applications militaires de surveillance radar « à travers les murs » doivent être en mesure de détecter des cibles à travers des matériaux de densité relativement élevée comme le béton, la roche et la brique. Ces matériaux peuvent atténuer de façon significative les ondes électromagnétiques. Par conséquent, les exigences relatives à la puissance du radar et à l'efficacité du traitement des signaux se trouvent accrues.

L'atténuation des signaux par les murs a un impact très limitatif sur le budget de puissance. Dans le cadre des travaux préliminaires de ce rapport, les exigences matérielles contradictoires de haute résolution et de pouvoir de pénétration du signal sont analysées en fonction des limites du matériel et du traitement des données associées à une dynamique étendue, à la fréquence d'échantillonnage et au brouillage.

En pratique, pour que le signal émis par le radar traverse un bloc de béton, la fréquence opérationnelle est d'environ 3 GHz, et la plage de fréquences utilisable ne peut pas dépasser environ 10 GHz. D'autre part, dans le cas de murs en matériaux courants autres que le béton, et en supposant que le matériau soit sec, la dynamique ne limite pas la résolution. En fait, des résolutions nettement plus élevées, de l'ordre de quelques millimètres, sont possibles.

Si on émet comme hypothèse que l'atténuation dans les deux sens peut atteindre 30 dB (à 10 GHz, par exemple) et que le rapport des surfaces équivalentes de la cible radar (SER) peut s'étendre sur 20 dB, cela sous-entend que la dynamique doit être d'au moins 50 dB dans la partie frontale du radar. Cela ne tient toutefois pas compte des effets de la propagation par trajets multiples, qui sont de nature statistique, ni de l'atténuation accrue en raison de l'humidité interne des blocs. Le budget de puissance devrait donc intégrer une marge supplémentaire de protection contre les évanouissements afin de conserver une probabilité de détection acceptable.

La méthode d'analyse présentée dans ce rapport peut également être appliquée à la détection par radar d'objets, tels des tuyaux et des fils électriques, qui se trouvent à l'intérieur même d'un mur. La surface équivalente de la cible radar (SER) de ces objets sera d'un ordre de grandeur inférieur à celle des cibles humaines, ce qui veut dire que la marge du rapport S/B aura 10 dB de moins. Cependant, il devrait quand même être possible de les détecter dans la partie inférieure de la plage des micro-ondes.

Executive summary

A challenging but nonetheless necessary requirement for military application of through-wall radar is the ability to detect targets through relatively high-density materials such as concrete, stone and brick. These materials can result in considerable attenuation of electromagnetic waves, increasing requirements for both radar power and signal processing.

For the purposes of this report, baseline performance is chosen to be penetration of concrete blocks with sufficient Signal-to-Noise Ratio (SNR) to reliably detect targets. The basis of the present study is the radar equation, which relates received power to various parameters associated with electromagnetic propagation and detection. The analysis uses a parameter set representing realistic situations—many values are obtained from experiments carried out here at DRDC Ottawa.

Wall attenuation becomes a prominent limitation in the ensuing power budget. For the preliminary investigation undertaken here, conflicting physical requirements for high resolution and signal penetrating power are matched against the hardware and data processing limitations of large dynamic range, sampling rate and interference. UWB systems typically experience interference in the form of thermal noise, clutter and multipath, as well as surrounding RF systems.

Increasing the center frequency of the radar permits a higher bandwidth to be used. A benefit of this is improved resolution, but several effects that are detrimental accompany it. The most serious effect is associated with increased attenuation, at least for concrete block walls.

If the radar signal must penetrate concrete block, a practical *operational* frequency is about 3 GHz, and the usable frequency range is no greater than approximately 10 GHz. On the other hand, for common wall materials other than concrete block, and assuming that the material is dry, dynamic range does not constrain the resolution. Much higher resolutions in the millimeter range are possible.

This does not, however, address the multipath effects, which are statistical in nature, nor does it address the increased attenuation due to moisture in the blocks. An additional fade margin needs to be built into the power budget to maintain an acceptable detection probability.

The analysis presented here can be applied equally to radar-based detection of objects, such as pipes and wires buried *within* a wall. The RCS of these objects will be an order of magnitude less than that of human targets so that the SNR margin will typically be 10 dB less. Nevertheless they should still be detectable at the low end of the microwave range.

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Sommaire

La capacité de détecter des cibles à travers des matériaux de densité relativement élevée comme le béton, la roche et la brique constitue un défi important, et les applications militaires de surveillance radar « à travers les murs » doivent être en mesure de le relever. Ces matériaux peuvent atténuer de façon significative les ondes électromagnétiques. Par conséquent, les exigences relatives à la puissance du radar et à l'efficacité du traitement des signaux se trouvent accrues.

Aux fins du présent rapport, la performance de base consiste à pénétrer des blocs de béton avec un rapport signal/bruit (S/B) suffisamment élevé pour détecter les cibles de façon sûre. La présente étude est basée sur l'équation du radar, qui établit un rapport entre la puissance du signal reçu et divers paramètres associés à la propagation et à la détection électromagnétiques. L'analyse utilise un ensemble de paramètres qui représentent des situations réalistes – un grand nombre des valeurs proviennent d'expériences menées par RDDC-Ottawa.

L'atténuation des signaux par les murs a un impact très limitatif sur le budget de puissance. Dans le cadre des travaux préliminaires de ce rapport, les exigences matérielles contradictoires de haute résolution et de pouvoir de pénétration du signal sont analysées en fonction des limites du matériel et du traitement des données associées à une dynamique étendue, à la fréquence d'échantillonnage et au brouillage. Les systèmes à bande ultra-large (UWB) subissent en général du brouillage dû au bruit thermique, au clutter et à la propagation par trajets multiples, ainsi que du brouillage provenant de systèmes RF voisins.

Le fait d'augmenter la fréquence centrale du radar permet l'utilisation d'une largeur de bande supérieure, ce qui a comme effet d'améliorer la résolution. Toutefois, cela cause également plusieurs effets adverses, le plus sérieux d'entre eux étant une plus grande atténuation, du moins dans le cas des murs en blocs de béton.

En pratique, pour que le signal émis par le radar traverse un bloc de béton, la fréquence *opérationnelle* est d'environ 3 GHz, et la plage de fréquences utilisable ne peut pas dépasser environ 10 GHz. D'autre part, dans le cas de murs en matériaux courants autres que le béton, et en supposant que le matériau soit sec, la dynamique ne limite pas la résolution. En fait, des résolutions nettement plus élevées, de l'ordre de quelques millimètres, sont possibles.

Cela ne tient toutefois pas compte des effets de la propagation par trajets multiples, qui sont de nature statistique, ni de l'atténuation accrue en raison de l'humidité interne des blocs. Le budget de puissance devrait donc intégrer une marge supplémentaire de protection contre les évanouissements afin de conserver une probabilité de détection acceptable.

La méthode d'analyse présentée dans ce rapport peut également être appliquée à la détection par radar d'objets, tels des tuyaux et des fils électriques, qui se trouvent à l'intérieur même d'un mur. La surface équivalente de la cible radar (SER) de ces objets sera d'un ordre de grandeur inférieur à celle des cibles humaines, ce qui veut dire que la marge du rapport S/B aura 10 dB de moins. Cependant, il devrait quand même être possible de les détecter dans la partie inférieure de la plage des micro-ondes.

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Table of contents

List of figures

List of tables

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Introduction

The objective of this report is to establish the fundamental design requirements for short-range impulse radar employed for in-wall and through-wall detection. The radar must be portable, which places some restrictions on the transmitted power as well as the size of the antenna system. Additionally, the requirement of real-time operation requires fast and efficient processing.

Currently, personnel can be detected as a “blob” appearing on the radar screen, but there is little additional detail to identify a target as a combatant or a bystander. The resolution required to identify say, sidearms or other weaponry, is on the order of centimetres. Alternatively, detection of target motion is more easily perceptible, and resolution of approximately 10 cm should be sufficient for this purpose.

Three types of systems are of interest. The first is a simple fixed system, providing a range profile. The second type of system is a linear array of radar elements that provide a two-dimensional image. A representative example of this is the “Soldier Vision” system developed by Time Domain Corporation (TDC). The final system type is SAR-based, using various configurations to achieve two- and three-dimensional images (for example, see [1,2]). The simple fixed system is the building block for the remaining types and is the principal topic of this study. Aspects of these assorted systems have been investigated in previous reports [3-5].

Walls can introduce considerable attenuation of electromagnetic waves, increasing radar power requirements. In general, the attenuation due to building materials increases rapidly with frequency. Since resolution also increases with frequency, there is a trade-off between power and resolution. There are other effects that degrade radar performance at very high frequencies. These are the effects of phase errors caused by inhomogeneities in the wall, the effects of interference from transmitters within the radar bandwidth and the effects of large returns from the wall itself and from surrounding structures. The latter can tend to saturate the radar receiver due to the presence of strong, localized scatterers on the radar operator side of the wall. To mitigate this, the receiver should have a very large dynamic range.

The combined requirements for high resolution and wall penetration suggest radar with a large bandwidth in comparison with its center frequency. Short-range radar application implies that the average transmitter power can be small and this in turn suggests the employment of impulse radar.

Because the radar receiver introduces thermal noise, the signal from a target must be larger than some specified threshold to achieve reliable detection. The metric that is most readily identifiable as characterizing radar detection performance is the Signal to Noise Ratio (SNR). The SNR is improved by integrating multiple returns from pulses. If the target is stationary and the radar is both electrically and physically stable, there is no limitation to the number of pulses that can be integrated so that the SNR can be increased arbitrarily.

On the other hand, if the target is moving at a velocity that is not known a priori, there will be a limit to the number of pulses that can be integrated. Conventional radar processing employs Doppler shifts in frequency to characterize target velocity. For baseband signals such as that used for impulse radar, the lack of a sharply defined carrier frequency prohibits Doppler processing. An equivalent technique using a *velocity processor*, coherently integrates the target return over several pulses enhancing SNR. This method however, can increase the computational complexity as well as the monetary cost of the radar and its size.

Radar Equation

The basis of the present study is the radar equation, which relates the received power to various parameters related to EM propagation and detection. The following analysis uses a parameter set that is believed to represent realistic situations. The calculations should be interpreted carefully because, in specific scenarios, it may be possible to enhance the radar performance beyond the contemplated models.

The radar equation below provides the SNR for a single pulse of power, P, as a function of antenna gain, G, wavelength, λ (nominally at the center frequency), target RCS, σ, range, R, system losses, L, noise figure, F_n, and bandwidth, B.

Boltzmann's constant[1] is denoted by k and T_0 is the reference temperature, 290K.

With these parameters, the signal to noise ratio becomes

$$SNR = \frac{PG^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L F_n k T_0 B} \qquad (1)$$

The theoretical antenna gain is given by:

$$G = \frac{4\pi A_e}{\lambda^2}, \qquad (2)$$

where $A_e = \eta A$ is the effective antenna area. The antenna efficiency is characterized by the parameter η, such that $0 < \eta \leq 1$.

Table 1 provides two sets of parameters. The first one corresponds to an experimental system at DRDC Ottawa, while the second set corresponds to a practical system.

[1] k = 1.38x10^{-23} J/K, or –228.6 dBw/Hz/K.

Table 1. Radar equation parameters

Parameter	Experimental configuration	Practical configuration
Transmit power [w]	10^4	100
Center frequency [GHz]	2	3
Wavelength [m]	0.15	0.10
Antenna gain [dBi]	7	1
Antenna efficiency	0.60	—
Antenna effective area [m^2]	0.115	0.01
RCS [m^2]	0.07	1
Range [m]	21	10
System losses [dB]	16	16
Bandwidth [GHz]	2	2
Range resolution [cm]	7.5	5.0
Receiver noise figure [dB]	10	10
SNR [dB]	**25.1**	**14.0**

The radar power is based on a pulse voltage of ~10^3V rms at the terminals of a line of characteristic impedance of between 50 and 100 Ω. The antenna gains are based on a dish diameter of about 0.5 m for the experimental system and a bowtie dipole antenna for the practical system. The estimated losses comprise 8 dB in the antenna feed and the wideband antenna itself and occur on both transmit and receive. The high bandwidth is obtained by heavy damping designed to broaden antenna response without generating ringing or phase dispersion. The noise figure includes the effect of noise introduced by the front-end amplifier. The RCS is that of a 0.15 m radius sphere ($\pi r^2 \approx 0.07 m^2$). In practice the returns may be distributed among many resolution cells; for example, if the return is spread over 10 cells, the effective RCS, σ_{eff}, for any one cell will be $\sigma_{eff} \approx 0.1\sigma$.

The single pulse SNRs predicted by the radar equation are given in the last row of the table. In the experimental system, a SNR of about 21 dB has been observed for a hollow metal sphere of diameter about 0.15 m. This compares well with the predicted value of 25 dB. It must be noted that a SNR above about 14 dB is required for reliable detection of a signal against thermal noise, so we observe that this provides a good margin.

To accommodate wall attenuation, the SNR can be enhanced by applying various techniques for processing gain. One method alluded to earlier integrates over multiple pulses to improve SNR. Another technique we are developing is called *Background Noise Conditioning* (BNC), which periodically samples the signal to dynamically suppress noise power spikes. Also, if there are several independent elements in the system, gains can be achieved by combining the outputs. For example, in the TDC radar, the output from 8 elements can be integrated coherently to yield a processing gain of 9 dB.

Material Penetration

The one-way attenuation of electromagnetic radiation through walls comprising various materials is shown below. It is probably reasonable to suppose that radar must be able to function through a concrete block wall or at least a brick wall. Extrapolating towards lower frequencies in Figure 1, the one-way attenuation for concrete blocks around 3 GHz appears to be less than 5 dB, resulting in a two-way path loss of approximately 10 dB [6]. Signal attenuation rises with frequency, so that at a frequency of 10 GHz, the concrete block will introduce a two-way attenuation of about 30 dB and for brick, about 6 dB. These estimates are based on concrete blocks of thickness 6".

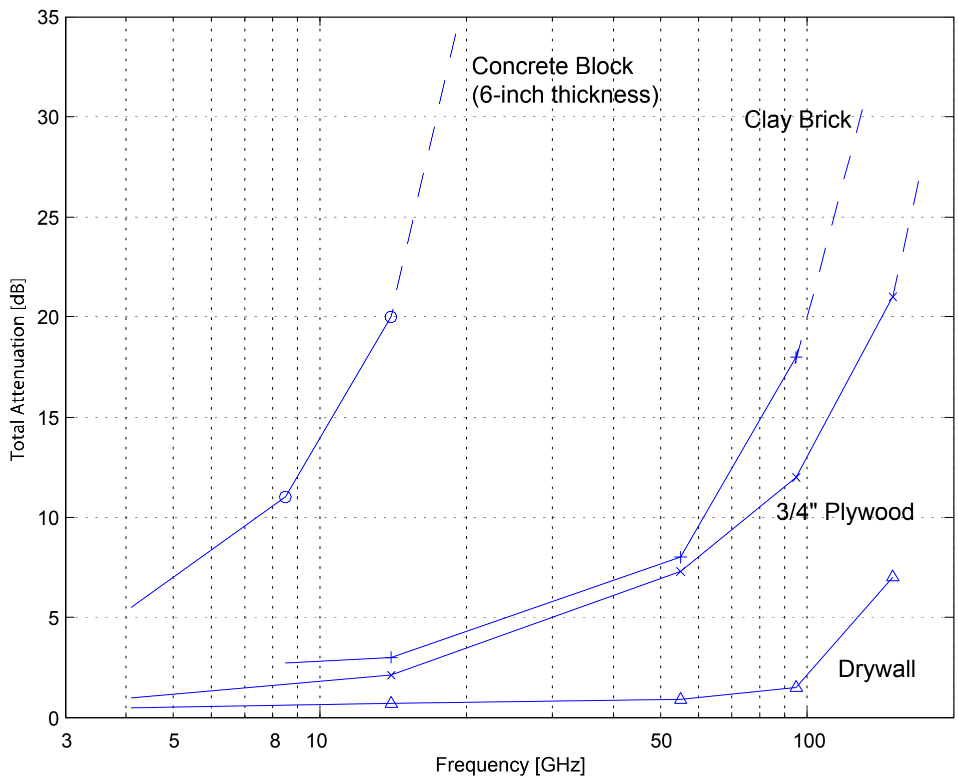

***Figure 1**. Total one-way attenuation of RF energy transmitted through various building materials. (Adapted from [6])*

A more demanding scenario involves concrete walls constructed of steel-rod reinforced concrete—the same report [6] contains data related to H-H and V-V polarized transmission through 8" thick walls (refer to Figure 2).

From the available published data, estimates for two-way propagation simply double the transmission losses. A more realistic approach considers changes to the angle of incidence. A recent study [7] focusing on lower frequency ranges (1-3GHz) measured transmission losses through concrete block walls. In this case, the results indicate that in order to keep <u>one-way</u> losses under 10 dB, the frequency of operation must be limited to frequencies below 1.5GHz and the incident angle kept to less than 60^{o}. For data referenced in this report, all of the values apply presumably to dry materials; when damp or wet, the attenuation is likely to be much greater.

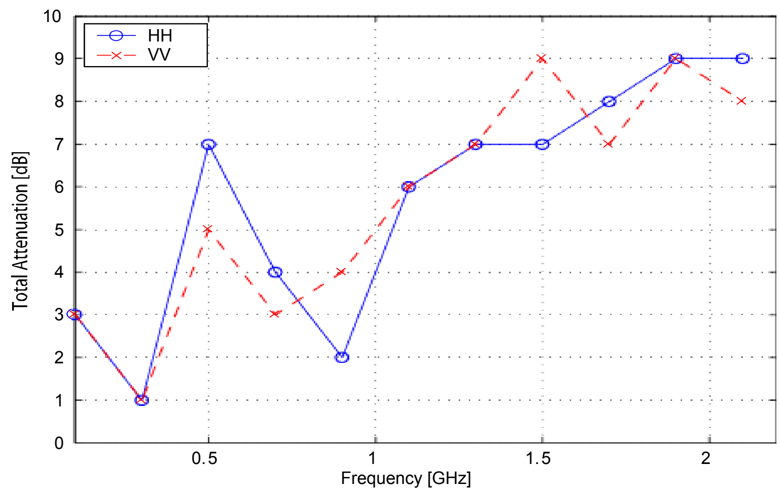

***Figure 2**. One-way loss of RF energy transmitted through 8" reinforced concrete. (Adapted from [6])*

In the simplest and most optimistic of models, the scattering geometry for the wall is similar to the scattering from the target except for the wall attenuation and the relative magnitude of the Radar Cross Sections (RCSs). Assuming that the two-way attenuation can be up to 30 dB (at 10 GHz, say) and that the ratio of the RCSs can range over 20 dB implies that in order to discern these returns, the dynamic range at the radar front-end must be *at least* 50 dB.

Dynamic Range

The impact of this on system performance can best be understood in terms of the A/D conversion of signal amplitude prior to processing. A standard result in communications theory is that uniform quantization requires approximately 6 dB per bit. Therefore, a dynamic range of 50dB requires about 8 bits. In contrast, if the attenuation is reduced to 10 dB, as is the case for concrete block at 3 GHz, the required dynamic range is reduced to 30 dB, equivalent to 5 bits. However, if the received signals must be digitized with this resolution, and the rate of digitization is twice the Nyquist frequency, there will be hardware implementation issues due to sampling limitations unless some form of *equivalent-time* sampling is used to enhance the bit resolution. (For a discussion of equivalent-time sampling, refer to [8, 9]).

Thus, the requirement to observe personnel through concrete block walls results in another trade off between the precision of the data and the number of samples required. For example, using real-time sampling, the Tektronix TDS 7404 oscilloscope can sample up to 20 GS/s with a precision of approximately 4.8 bits for an analog bandwidth of 4GHz [9]. To attain this performance Tektronix interleaves the four available A/D samplers to achieve a higher overall rate.

A more common approach is use equivalent-time sampling of the data to slow down the acquisition rate. Here, the number of pulses needed to acquire a range profile is equal to the number of range bins. Equivalent-time sampling incurs a loss of information, so that data that could be employed to enhance the SNR is lost. The use of multiple pulses in this method has an impact on the transmitted power requirement.

To summarize, if the radar must penetrate concrete block, an upper limit to the frequency is about 3 GHz; this implies that the minimum size of the resolution cell in range is about 5 cm. On the other hand, for common wall materials other than concrete block, and assuming that the material is dry, dynamic range does not constrain the resolution. Much higher resolutions in the millimeter range are possible.

Processing Gain

The processing gain that can be obtained depends on the Pulse Repetition Frequency (PRF). The maximum PRF is related to the minimum unambiguous range. This is given by:

$$PRF_{\max} = \frac{c}{2R_{\min}}, \qquad (3)$$

where c is the speed of light. Assuming that the minimum unambiguous range is 15 m, the maximum PRF is 10^7 pulses per second (10MHz).

For a person located behind a concrete block wall, they must be identified either by shape or by motion. The problem with identification by shape is the large return from the wall (and especially structures surrounding the radar but outside of the wall) and with artifacts associated with the processing. There is also the possibility of artifacts created randomly by thermal noise. Also, with a linear array of antennas, the coupling between the antennas can produce ghost targets. A better solution is to detect personnel moving with respect to the radar. In the case of drywall, this does not apply and shape detection is possible.

Coherent integration requires that the person move less than a distance of about $\lambda/8$ during the integration time. For example, with a center frequency of 3 GHz, the wavelength is 10 cm. If it is assumed that the maximum speed that a person will move is 2 m/s, this restricts the integration time to about (2m/s) / 1.25cm = 6.25 ms.

In principle about 62,500 pulses can be integrated but this must be reduced by the number of samples needed to obtain a range profile, namely the number of range bins. Using a bandwidth of 1 GHz, the resolution cell size is 15 cm, so that the number of range cells is about 100. The result is that the number of range profiles available for integration is about 625. The coherent gain is therefore about 28 dB.

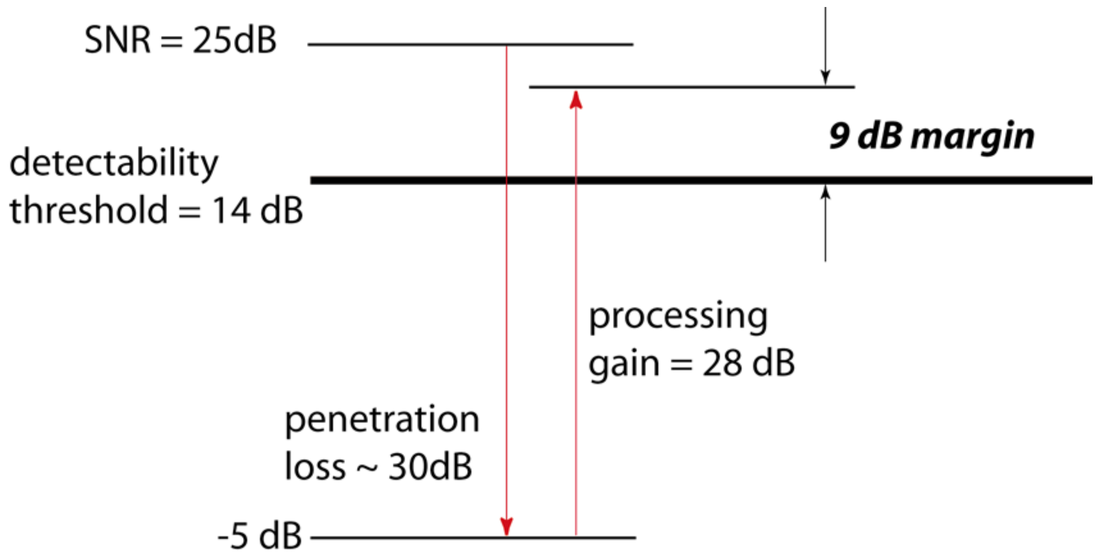

Figure 3. *Power budget as described in text.*

The SNR in Table 1 is about 25 dB without accounting for any attenuation. Even if the wall introduces up to 30 dB of attenuation, it is possible to recover most of this by coherent integration and the target will still be detectable with a margin of approximately 9 dB (refer to Figure 3).

This does not, however, address the multipath effects, which are statistical in nature, nor does it address the increased attenuation due to moisture in the blocks. An additional fade margin needs to be built into the power budget to maintain an acceptable detection probability.

Highest Useable Frequency

Increasing the center frequency of the radar permits a higher bandwidth to be used. The effect of increasing the frequency and bandwidth is shown in Table 2. The only advantage of this is an improvement in the resolution and several effects that are detrimental accompany it.

Table 2. *Effect of increased operating frequency*

Attribute	Effect
Resolution	• Resolution cell size decreases • Target ID enhanced
Attenuation	• Increases rapidly with frequency • Artifacts increased; target ID reduced
Dynamic range	• Requirement increases because of increased attenuation • A/D sampling becomes impractical
Coherent integration gain	• Decreases because number of range cells increases • Decreases because wavelength decreases and coherency is lost
Noise bandwidth	• Increases, resulting in an increase of transmit power to maintain SNR
Wall inhomogeneity	• Creates phase errors that lead to a loss of coherence in two- and three-dimensional image processing
Interference	• Interference at discrete frequencies can be notched out, but broadband interference is a problem. • Frequencies less than 700 MHz to 1 GHz should be avoided to minimize interference from commercial cellular, radio and TV systems.

The most serious effect is associated with increased attenuation, at least for concrete block walls. Consequently, a practical upper limit to the usable frequency is less than 10 GHz.

Two and Three Dimensional Processing

The fundamental noise and dynamic range considerations are not affected by processing an image in 2 dimensions when a linear array of radars is used and each radar is accompanied by a simple processor to recover a range profile. However, there will typically be an improvement in the SNR for each pixel because it results from a coherent integration process. If a synthetic array is employed, as in 3 dimensional image processing, the movement of the target must be considered, as this will tend to cause a loss of coherency. The detailed performance of 2- and 3-dimensional systems is a topic for further analysis.

In-The-Wall Radar

There is a requirement to establish wall composition to determine the difficulty of breaching a structure for forced entry, and to find out whether electric, water or gas services can be denied to the occupants of a building when the only available access is limited to the external portion of the wall.

Typical walls may range from drywall attached to a wooden or steel frame, through brick and concrete block to poured concrete with steel reinforcing rods. It should be possible to identify the method of construction using a variety of sensors. An exception for radar might occur if the wall is faced with a metallic cladding that cannot be removed.

To be useful, and for the purposes of detection, it is not necessary that the device should have a very high resolution of the order of a centimeter. On the other hand, a resolution of greater than 10 cm will tend to prevent classification of detected objects within the wall. The device should be remote in the sense that its use does not involve penetrating the wall mechanically, and personnel behind the wall should not be alerted in an obvious manner. The device should be reasonably covert.

The analysis presented in the main part of this report can be applied equally to radar-based detection of in-wall objects, such as pipes and wires. The RCS of these objects will be an order of magnitude less than that of a person so that the SNR margin will typically be 10 dB less. Nevertheless, returns should still be detectable at the low end of the microwave range.

A single sensor type might be of significant value for this requirement, but a combination of sensors and the fusion of data from the sensor suite combined in one device is probably the optimum strategy. A possible scenario is as follows.

Radar and acoustic waves penetrate solid material to detect objects such as metallic and plastic piping as well as electrical wiring. Penetrating radar detects conducting pipes and wires relatively easily compared to plastic pipes because their radar scattering cross section tends to be much higher. Plastic pipes are characterized based on acoustic returns. Electrical wires embedded in a wall or located in a conduit may have a signature similar to a water pipe. To distinguish these, an electromagnetic sensor detects the low frequency electromagnetic fields surrounding wiring and especially wiring that is carrying current. Water pipes are distinguished from gas pipes using temperature sensing, based on infrared (IR) signatures of the wall exterior.

As discussed previously, for significant penetration of solid walls, low frequency radar signals are desirable. High resolutions tend to require high frequency microwave signals. This suggests a radar sensor of the impulse type that combines both of these desirable attributes. In terms of availability, such impulse radars are typically employed for applications such as mine detection and can be purchased off the shelf: it may be possible to adapt them for wall structure analysis. Acoustic and IR sensors are also available as “stud-finders” and the technology of magnetic field sensing at 60 Hz is relatively trivial.

Conclusions

To be useful militarily, it has been assumed that radar must be able to penetrate concrete block walls. This tends to restrict the center frequency and the bandwidth to the low end of the microwave range, namely to a few gigahertz. Thus the resolution cell size will be a few centimeters at best and is more likely to be in the range 5 to 10 cm. In contrast, for other wall materials not constructed from masonry, it may be possible to achieve millimeter resolutions.

In summary, there are two main potential limitations in through-wall imaging. The first is related to the “competition” between processing gain and the need to overcome large penetration losses. Lacking a sufficient margin, it will be very difficult for an operator to discern legitimate targets from surrounding clutter. One approach to this has been to implement a tracking algorithm [1] that attaches an icon to each moving target so that its status is clear to the operator.

This relates directly to the second limitation, namely multipath interference arising from the reflection of RF energy from targets and then surrounding structures. While the initial direct reflection from the wall can quite possibly be time-gated out, the ensuing “smeared-out” returns cannot easily be separated. As a consequence, the processed image contains artifacts that degrade image quality. It is imperative that the system has sufficient dynamic range to correctly process this information.

For “In-wall radar”, the constraints are not so demanding; it should be technically feasible and inexpensive solutions should be possible.

In many cases, substantial performance gains can be achieved by accurately characterizing the RF operating environment, and paying close attention to the interplay between signal & data processing algorithms, and the hardware within which they are implemented. In quite general terms, this defines the direction of our current and future research effort.

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List of symbols/abbreviations/acronyms/initialisms

A/D	Analog-to-Digital conversion
BNC	Background Noise Conditioning
dB	decibel
dBi	dB referenced against isotropic radiator
DRDC	Defence Research & Development Canada
EM	Electromagnetic
H-H	Horizontal-to-Horizontal polarization
IR	Infrared (wavelengths between ~ 10^{-4} and 10^{-2} cm)
PRF	Pulse Repetition Frequency
RCS	Radar Cross Section
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SNR	Signal-to-Noise Ratio
TDC	Time Domain Corporation
Tx / Rx	Transmit / Receive
UWB	Ultra-Wideband
UWB-SP	Ultra-Wideband Short Pulse
V-V	Vertical-to-Vertical polarization
VHF / UHF	Very high frequency (0.03 – 0.3 GHz) / Ultra high frequency (0.3 – 1 GHz)

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Military application of through-wall radar requires the ability to detect targets through relatively high-density materials such as concrete, stone and brick. These materials can result in considerable attenuation of electromagnetic waves, increasing requirements for both radar power and signal processing.

Wall attenuation becomes a prominent limitation in the ensuing power budget. For the preliminary investigation undertaken here, conflicting physical requirements for high resolution and signal penetrating power are matched against the hardware and data processing limitations of large dynamic range, sampling rate and interference.

If the radar signal must penetrate concrete block, a practical operational frequency is about 3 GHz, and the usable frequency range is no greater than approximately 10 GHz. On the other hand, for common wall materials other than concrete block, and assuming that the material is dry, dynamic range does not constrain the resolution. Much higher resolutions in the millimeter range are possible.

The assumptions that the two-way attenuation can be up to 30 dB (at 10 GHz, say) and that the ratio of the RCSs can range over 20 dB imply that the dynamic range at the radar front-end must be at least 50 dB. This does not, however, address the multipath effects, which are statistical in nature, nor does it address the increased attenuation due to moisture in the blocks. An additional fade margin needs to be built into the power budget to maintain an acceptable detection probability.

The analysis presented here can be applied equally to radar-based detection of objects, such as pipes and wires buried within a wall. The RCS of these objects will be an order of magnitude less than that of human targets so that the SNR margin will typically be 10 dB less. Nevertheless they should still be detectable at the low end of the microwave range.

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Ultra-Wideband radar, Impulse radar, through-wall imaging, in-wall imaging, wall attenuation

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