PERSPECTIVES ON THROUGH-WALL RADAR IMAGING

Echoic Engineering LLC

Release Date: October 2020, WP-1 Rev. 1710

Author: Kelvin Yuk, PhD

CONTACT INFORMATION

Email: ksyuk@echoicrf.com | **Web:** https://echoicrf.com

THE MODERN SOLDIER

Soldiers are often tasked to perform reconnaissance and surveillance in unknown, hostile environments. Missions may require an operative to search for specific assets. However, these assets may be placed out of visual range and in a zone with insufficient mapping of the area, building or structure. Assets including people, money, electronics, weapons, chemicals and documents may be stored in purpose-built hidden compartments that are visually undetectable. Retrieving these items becomes nearly impossible in a fully enclosed space.

Ideally, a soldier would have an alternate, superior means to scan and detect hidden chambers electronically as shown in the concept art of Fig. 1a with a handheld device like the one shown in Fig. 1b [1, 2]. There are a number of sensing technologies for through wall interrogation which range from electromagnetic- (EM) to acoustic- to thermal-based techniques [3]-[5]. Of these technologies, radar waves are the leading technology because they can penetrate walls effectively and image an area under any conditions of light, temperature and weather.

(a) (b)

Fig. 1. (a) Through-wall detection during a military operation [1] and (b) a handheld through wall radar device [2]

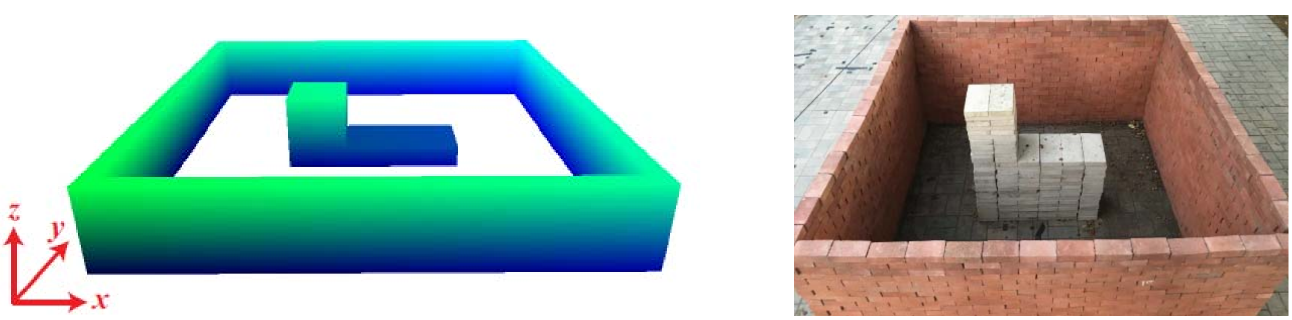
These through-wall-radar imaging (TWRI) techniques have recently received growing research interest as circuit technology scales in size, allowing the development of compact mobile devices [2]-[4]. It has been repeatedly demonstrated that TWRI can detect an area, chamber, walls, people and artifacts from behind walls [6]-[15]. Some of the performance metrics of TWRI systems are its ability to penetrate into a variety of standard building materials and thicknesses. These materials can include brick, cinder block, concrete, wood, and sheet rock.

Development of an easy-to-use, high-speed, handheld device is of prime importance especially in the field where mobility and universal operation is paramount. In this white paper, we investigate the challenges of developing a high performance, compact TWRI device. We will discuss a set of fundamental experiments to understand the propagation of radar through common building materials such as brick, cinder block, concrete, wood, and sheet rock. The optimal frequencies, power levels and modulations determined from these experiments will enable the design of the TWRI system. Special attention will be paid to stepped-frequency continuous-wave radar and ultra-wideband signals. The subsequent design process includes system level simulations of the transmit and receive sub-blocks, the selection of the signal generation technique, the design of a broadband, high directivity antenna and the application of imaging algorithms in the appropriate electronic control and processing scheme.

THROUGH WALL RADAR IMAGING CHALLENGES

A Through-Wall Scenario

This white paper illustrates the challenges in developing a high performance, handheld, automated hidden chamber detection device. In the simplest case, a hidden chamber is a compartment or room which is bound by four or more orthogonal walls, the ceiling and the ground. Its general shape is that of a rectangular prism and is completely enclosed. Furthermore, the room is constructed using standard building materials: brick, wood, drywall (plaster), concrete or cinder block. As an initial consideration, we will assume square rooms in which the wall material is the same for all four walls (walls are not different materials). An example scenario of the walled structure is illustrated in Fig. 2.



(a) (b)

Fig. 2. Scenario with an L-shaped structure inside a square walled room (a) model and (b) actual setup using building materials [13]

In a typical use case:

- The operator uses the device from within an average sized room (< 200 square feet) and standing at a range of 1-2m from a wall that is suspected to enclose a hidden chamber behind it.
- The operator searches for a chamber that is adjacent to and on the same level ground plane as the operator's room. The device may be able to detect chambers beneath the floorboard but this case will be ignored for now.
- The hidden chamber may or may not contain various articles like electronics, weapons, chemicals, documents, money, people, etc. The presence of items may improve success rate of the chamber detection. However, one must also consider the case that the room is empty or that stored objects are have a low profile.

In order to detect a hidden chamber using TWRI

- the radar signal must penetrate the first incident wall
- the penetrating signal must be reflected by something behind the wall and returned at a detectable level

The target may be an artifact in the case of a populated room or another wall (and thus defining the boundary of the hidden compartment). By the principles of radar, the echo of the radar signal will provide information about the position, composition or shape of the walls and targets that interact with the illuminating signal. If a room contains stationary items, moving objects or people, the device should be able to distinguish these objects from the wall framework like studs on a gypsum-based drywall or rebar in a concrete wall.

Advances in compact, integrated RF systems on chip will enable the development of portable, short range radar applications. The vision for the final product is a handheld device that can be used in the field. This means that the device is lightweight (< 5 lbs), battery-operated and simple enough so that the user understands its operation and will have 40-50 min operating life. Existing devices have already proven that a portable TWRI device can be built using compact commercially-off-the-shelf (COTS) parts [15].

Through Wall Technology Already in Development

Many of the state of the art techniques and challenges of TWRI are conveniently summarized in [1]. Successful demonstrations of TWRI for stationary object detection [6, 7, 8], motion sensing [9, 10, 11], interior reconstruction [1, 12, 13], clutter mitigation [16, 17], and vital sign detection of humans [14] have been conducted. Through wall detection has been shown to be effective through a variety of wall materials including wood, drywall, plywood [6, 7, 8], concrete [9, 10], brick [12, 13] and multilayer combinations of those listed [14].

One of the most popular techniques is the use of synthetic aperture radar (SAR) which is ideal for spatial imaging. SAR gives excellent cross range and down range resolution and can be performed by physically moving the transmit (Tx) and receive (Rx) antennas or by multiplexing the Tx and Rx antenna combinations within a pre-arranged linear or grid formation. Since SAR requires the precise, controlled movement of antennas, innovative solutions to scanning have been introduced which involve the use of drones and UAVs [12, 13]. Synchronized movements of autonomous vehicles can produce accurate imaging profiles but require physically separated Tx and Rx units on opposing ends of the structure. This method can be used on a larger structure to define interior rooms or to scan the contents of a hidden room after it has been discovered. Other ways of scanning involve doing so by automated electronic means and by employing MIMO based techniques [17].

Because of the many parameters involved, a careful feasibility study will be conducted to find the most effective through wall methods. These include fundamental experiments on the wall itself, with the goal of determining how thickness and permittivity affect the fidelity of TWRI [18, 19, 20]. Wall characterization will be an important part of clutter mitigation and management [17]. Importantly, the efficacy of different signaling techniques such as pulsed radar, Doppler shift, ultra-wideband (UWB) chirps, stepped-frequency CW (SFCW) and the bandwidth (narrowband or UWB) will need to be investigated.

According to [4], a number of devices already exist which may have been part of a government research effort in another country. The website lists around 68 devices, many of which use radar-based techniques. If effective, these devices can be tailored for a variety of hidden chamber applications. However, their availability may be limited due to the sensitive nature of the technology. Also, acoustic or ultrasound based methods appears to be the most viable competitor to radar-based through-wall technology [21]. A list of acoustic-based surveillance methods is available [3].

Pathways to Improvement

Ultimately, the range, resolution and speed of operation will be universal benchmarks for TWRI technology. Some of the continuing challenges in TWRI radar are precision wall reconstruction in complex room environments, target differentiation, clutter mitigation and the effectiveness through thick, dense, high-moisture walls. The accuracy of TWRI is dependent on a number of factors including power, frequency, bandwidth, antenna design and overall complexity of the Tx/Rx system over the scope of wall materials, thicknesses, and chamber dimensions.

In general, the best TWRI frequencies for penetrating dense materials reside below 1GHz, although most systems use signals < 3GHz to include the widely used 2.4GHz ISM band. For bandwidth, most TWRI systems use SFCW employing > 20% fractional BW (aka ultra-wideband) while the deployment of actual UWB pulse radars are limited [12, 18]. Investigations into modeling of power returns as a function of wall properties are important but limited as well [19]. Furthermore, strong reflections from thick or dense walls with high moisture content may desensitize the detection of the target echo [8] and will require increased Tx power.

As the imaging of 2D is improved, some studies are now focusing on the through-wall reconstruction of 3D structures [12, 13]. Higher complexity room configurations can be addressed using 3D EM simulations [16]. Simulations have also been conducted in detailed scenarios where weapons are placed close to a wall, which makes detection even more difficult due to limited radar resolution and wall-scattering [19].

Target differentiation also applies to the detection of people. Human sensing by Doppler-radar vital signs allow the differentiation of people from background clutter by extracting the modulating heart-rate and breathing-rate signals [14]. However, in examples where several people are present, as in a hostage situation, there no simple solution to identify the hostage from its captor.

Multipath is a major concern as radar waves ricochet from the side walls and within the hidden chamber before returning to the receiver. This issue can be addressed through time gating [18] to reject multipath signals entering outside of the measurement window. Another way to develop immunity against multipath is by designing antennas with small sidelobes and narrow beamwidths [22].

Processing speed is yet another challenge. Ideally, the radar image can be composed with correct proportions on a real-time portable device. However, due to the numerous algorithms necessary to improve resolution and mitigate clutter, few real-time devices with full image reconstruction are available. One of the fastest reports a frame rate of 10.8fps but is not handheld [10].

The Need for Advanced Detection

There is a critical need for a handheld TWRI technology in a wide range of applications where persons or high value targets are hidden from plain sight. Some of the main applications include military reconnaissance, surveillance, hostage and disaster situations. Other applications may be in disrupting illegal smuggling by scanning for compartments, tunnels and packages. Detection of valuable items hidden behind walls, in niches, and in packages are important to detect potential security threats. In the commercial sector, the technology can be used to detect wall studs and for discovering hidden chambers as part of archaeological discovery [23]. Ground penetrating radar is a regularly implemented tool in the search for artifacts located within the great pyramids and for the reportedly underground Nazi gold train [24, 25].

As criminals become more sophisticated in their techniques, we need to employ a rapid means of monitoring and threat detection. Newly developed methods to locate suspicious spaces will allow law enforcement and military to determine whether additional resources are needed for a given area. Portability is imperative for adopting this technology in the aforementioned scenarios.

A DEVELOPMENT APPROACH FOR TWRI

An initial study consists of determining the optimal architectures, frequencies, power levels needed to accurately perform TWRI in the most common scenarios. This study aims to assess the performance of available state of the art technologies and discuss the risks and payoffs of the various types of radar techniques. As a starting point for the scientific study, experimentation will be performed using laboratory grade equipment and techniques with the exception of a few components. An operational prototype which meets the requirements of a handheld, portable device will only be developed after establishing the device specifications from this experiments. However, we can discuss the practical concerns of the prototype as it pertains to the state of the art. Each part of the system and the level of sophistication will evolve as the device progresses over time.

A comprehensive study is needed to investigate the feasibility of a compact, TWRI system. This study is composed of several parts

- Investigation of wall and materials using free space methods
- Investigation of different modulation techniques, frequencies and antenna architectures
- Development of a TWRI radar system using laboratory instruments and evaluation boards

EM characteristics of walls

The first stage is to measure the propagation characteristics of walls constructed out of common building materials and over a variety thicknesses [18, 19, 20]. The properties of radar waves incident on a wall can be analyzed from electromagnetics as a classic case of reflection, refraction and transmission as shown in Fig. 2 [19]. It is critical to gain an understanding of the wall because the wall has finite thickness and creates internal EM reflections at the air-wall (front) and wall-air (rear) interfaces as well as amplitude loss and phase dispersion. The wall may have an inhomogeneous composition and high moisture content, further complicating the analysis [19]. This situation is different in that the predominant propagation medium is air, while for GPR it is the earth.

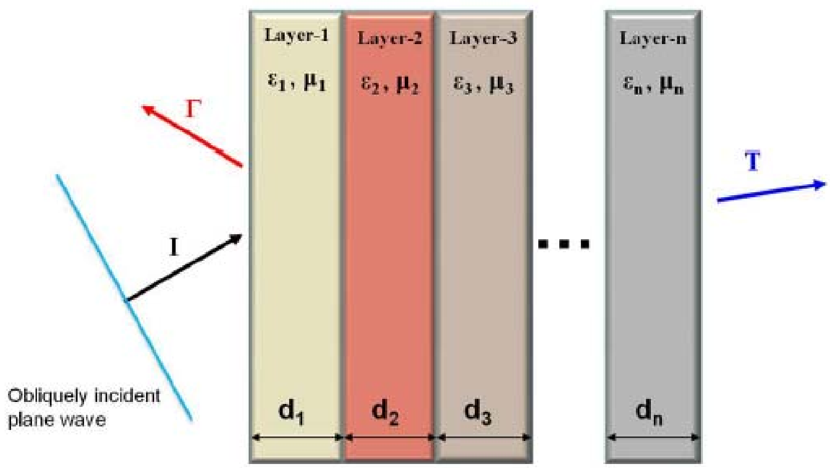
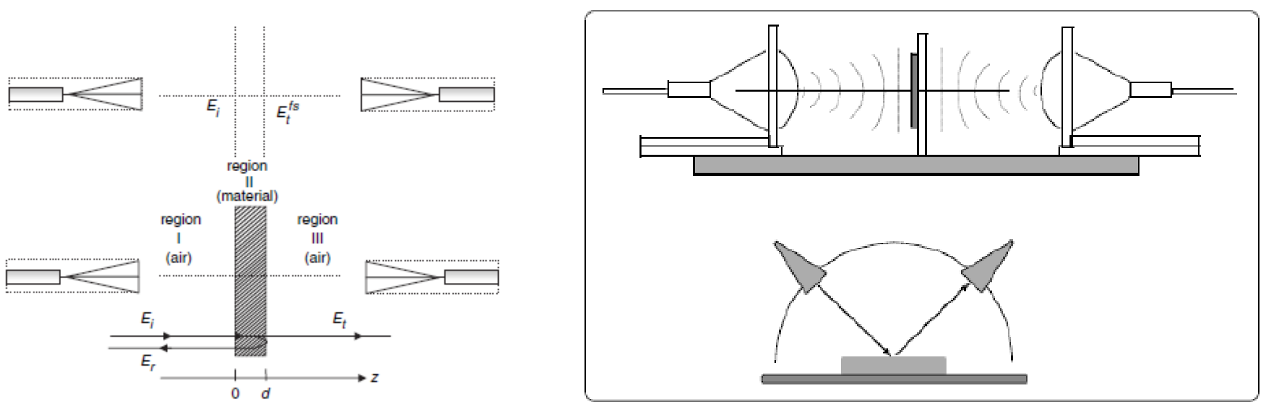


Fig. 2. Multilayer transmission and reflection of EM waves on wall [19]

The first step in the feasibility study is to construct walls consisting of common building materials like wood, gypsum, cinder block and brick based on standard construction techniques as shown in Fig. 4. If possible, wood and gypsum walls will be built on moving platforms as this will help in calibration and repeatability [18]. The walls will be characterized using the free space technique as illustrated in Fig. 5 to extract its frequency dependent complex permittivity [18, 19, 20, 21, 26].

(a) (b) (c)

Fig. 4. Wall construction for through-wall signal testing (a) wood frame (b) plywood (c) gypsum [6,7]



(a) (b)

Fig. 5. Free space method of characterizing wall (a) (top) calibrating in the absence of a wall and (bottom) in the presence of the wall [18] and (b) transmission and reflection based methods [26]

We will follow the methods outlined in [18] for the wall characterization using standard gain horn antennas, a network analyzer, time-domain techniques and gating over a wide range of frequencies and at the necessary power levels. This will result in a transfer function indicative of the wall's dielectric properties [18]. A precise calibration method will be investigated and chosen among the three possible methods: TRL (Thru-Reflect-Line), TRM (Thru-Reflect-Match), Gate Reflect Line (GRL) [26]. We can see that the dielectric constant and loss tangent of different wall materials are frequency dependent as shown in Figs. 6a and 6b.

Since water has an electrical permittivity of 80, the moisture content in the wall will have a large impact on signal penetration [19, 27]. One part of this study will be to re-characterize the walls under various levels of hydration. The hydrated dielectric constant and permittivity of solid concrete at different hydration levels is shown in Fig. 7. Moisture on concrete walls has been found to reduce signal levels as much as 20dB [19].

A following step would be to then build small enclosed rooms using the specific wall material. Fortunately, rooms are commonplace and these locations will be documented as field test sites for the portable system.

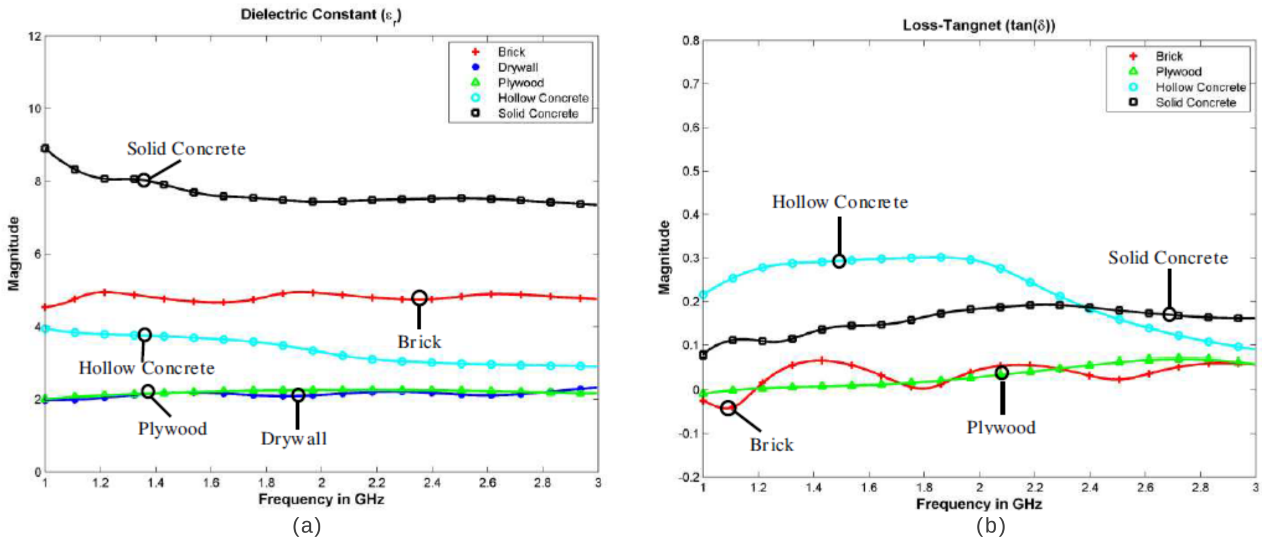


Fig. 6. Complex permittivity measured using the free space technique (a) dielectric constant (b) loss tangent [19]

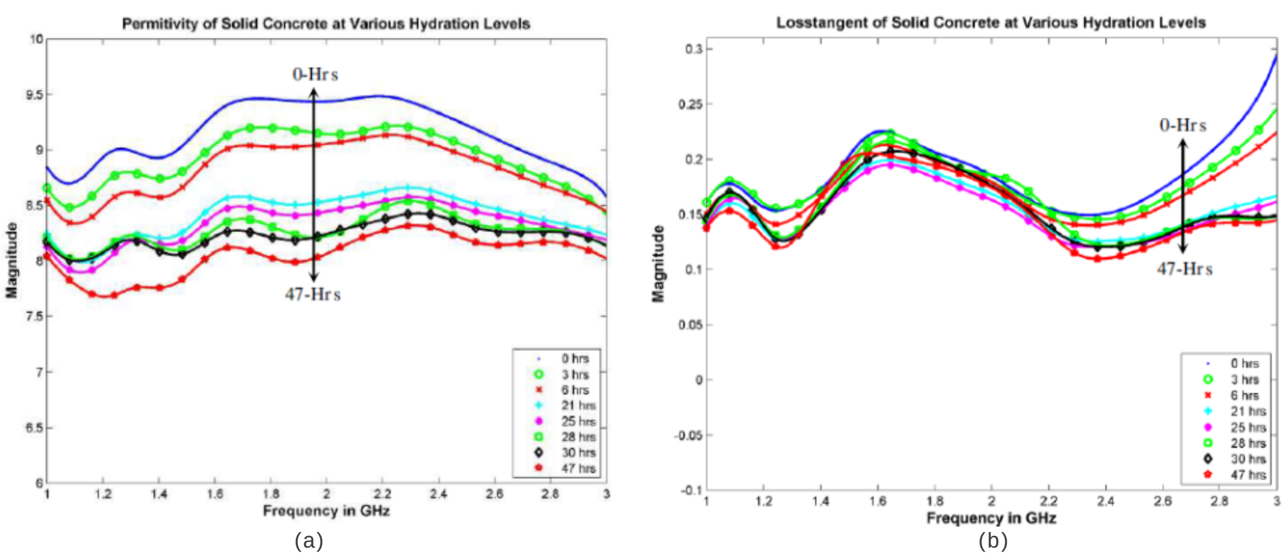


Fig. 7. Complex permittivity of solid concrete wall with different hydration levels (a) dielectric constant (b) loss tangent [19]

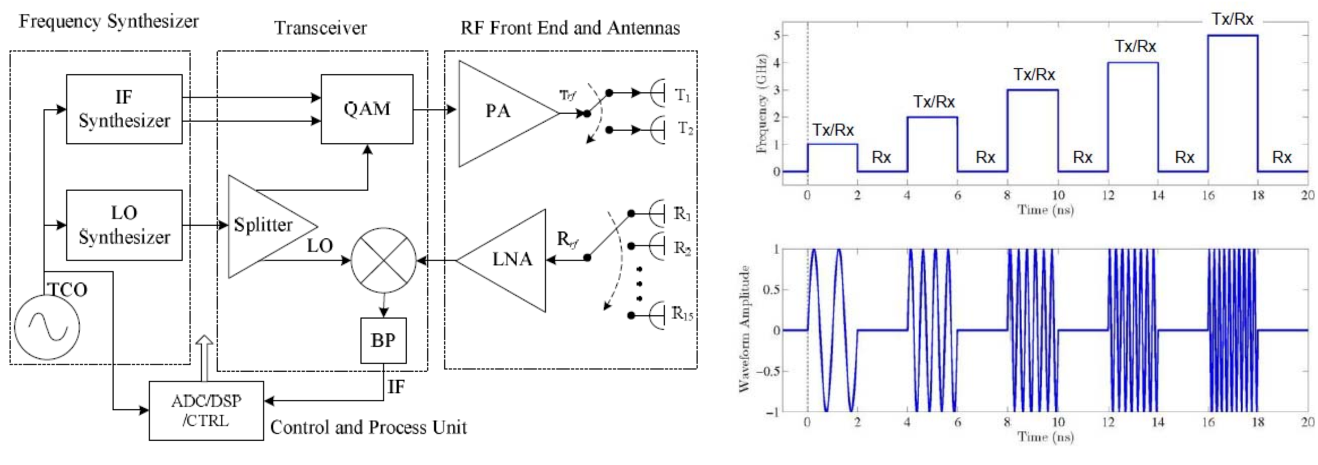
An RF system for TWRI

Investigation of wall properties will provide us with an understanding of the signaling requirements for wall characterization and penetration. From there, a developmental TWRI radar system can be built to investigate the maximum achievable imaging fidelity using a number of subsystems including:

- RF front end (signal generation, modulation and demodulation)
- Antenna system and configuration
- Electronic control, processing and visualization
- Clutter management (hardware or software)

RF front end

The merits of a variety of radar architectures for TWRI will be analyzed including pulsed, FMCW, SMCW, Doppler and UWB. For example, a block diagram of a SFCW TWRI system is shown in Fig. 8. The Tx path consists of a modulator (IF synthesizer and QAM block), a local oscillator (LO Synthesizer) and a power amplifier (PA). The Rx path consists of an low-noise amplifier (LNA), mixer-based downconverter and filter. Instead of sweeping the Tx and Rx across a large area, an array of fixed Tx and Rx antennas switched to different combinations is used to image a zone of interest [10, 11, 17].



(a) (b)

Fig. 8. SFCW radar for TWRI (a) block diagram [11] and (b) waveform [28]

For the first stage of radar development, the signal generation, mixing, amplification, reception and baseband processing will be performed using laboratory equipment, connectorized components and evaluation board Tx/Rx modules. The entire system will be controlled using computer-controlled test equipment and a data acquisition unit (DAQ). The fabrication of circuit hardware to support the experiment will be minimal as this is not yet the handheld prototype. The handheld “prototype” will take the form of an integrated design on single a printed circuit board and using surface mount components.

The signal generation will be studied in several ways:

- Waveforms such as FMCW [10], SFCW [11, 28] will be modeled and reproduced in Keysight Advanced Design System (ADS) or MATLAB. This will allow careful modeling of the system components. An example SFCW waveform is shown in Fig. 7b.
- Waveforms like SFCW will be generated using a pulsed network analyzer for preliminary experimentation on walls.
- Signal generation can be implemented using a low-cost COTS direct conversion transmitter for generating FMCW and SFCW applications. For UWB signals, it is be possible to use the DecaWave EVK1000 UWB generator board as in [12, 13].

A systems analysis will be used to identify the specifications of the PA, LNA and mixer depending on the outcomes of the EM wall experiments described previously. A figure of a Doppler radar system diagram modeled in Keysight ADS is shown in Fig. 9.

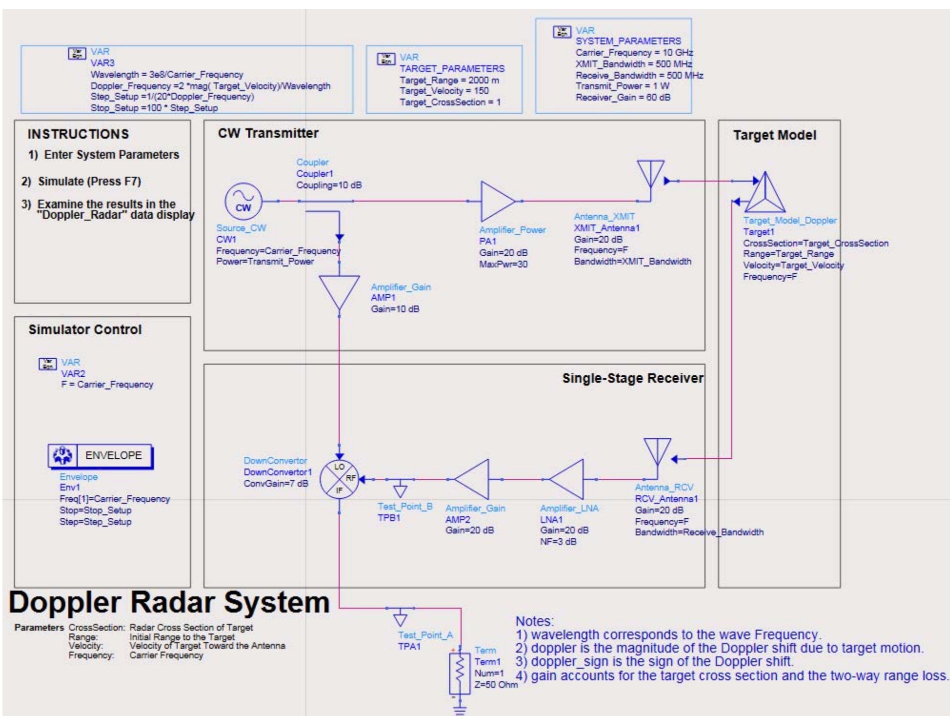


Fig. 9. Keysight ADS Doppler radar system block diagram

The fidelity of the radar signal will deteriorate as it passes through the incident wall (attenuation and dispersion) in both the transmit and receive directions. The deterioration is compounded with the reflection of both the front and rear interfaces of the incident wall. Therefore, special care attention should be placed on the design of the PA to transmit adequate power under the any wall conditions.

Antenna system and configuration

Within the literature, a plethora of antennas have been used in various studies. These antennas include the horn [6, 7, 18, 19], Archimedean spiral [11, 17], Yagi [13] and Vivaldi [8, 9, 10, 22]. Of these types, the Vivaldi (aka Tapered Slot Antenna), with an extremely broadband, narrow beamwidth antenna, is one of the most suitable options. Furthermore, the Vivaldi antenna with corrugated edges achieves a bandwidth greater than a decade for UWB [8]. An example of a Vivaldi antenna and is shown in Fig. 10. If implemented in an array, the Vivaldi antennas can achieve a beamwidth down to 4-degrees in the E-plane [22].

Fig. 10. 2-4GHz Vivaldi Antenna for through wall applications [22]

A compact Vivaldi antenna can be designed in Keysight ADS (or Ansys HFSS) to operate over the frequency band determined by the through wall laboratory experiments. The design parameters include the bandwidth, the width, length and taper of the design. The resulting antenna can be fabricated using simple microstrip technology. Antenna losses and size reduction can be achieved by proper selection of the microwave substrate (by its substrate thickness and permittivity) and frequency. The antenna pattern can then be tested in an anechoic chamber or in a free space range. Once these Vivaldi antennas are constructed, SAR imaging experiments will be performed and polarization can also be investigated.

Electronic control, processing and visualization

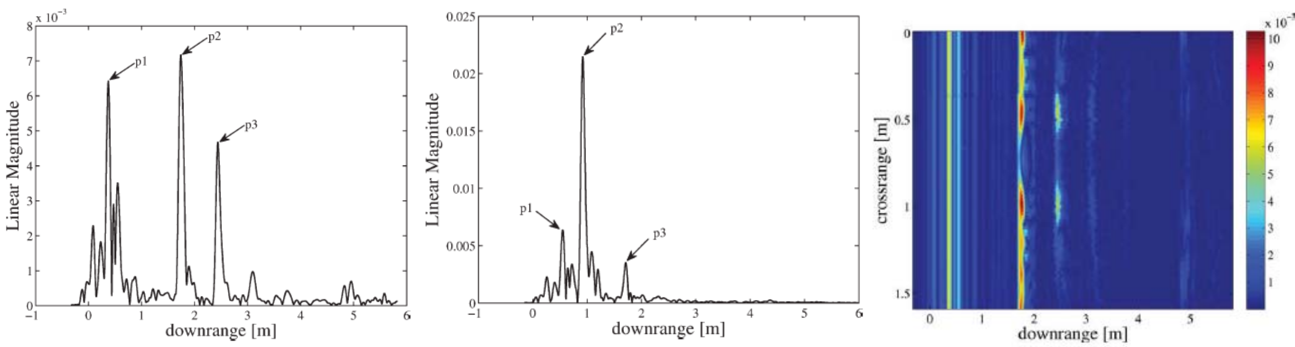
Initially, the system control and data acquisition will be performed by a laptop PC running industrial grade lab instrumentation control software. A network analyzer and data acquisition unit (DAQ), will be used to control the radar system and perform the data acquisition. Then data will be post-processed and visualized using MATLAB as was done in [8, 9, 10, 17]. During this feasibility study, there will be no GUI development. The digital control, signal processing and visualization will be migrated to a portable microcontroller and portable LCD display in a future phase.

Beyond the RF hardware, the signal processing will be a major aspect of the investigation, which includes imaging, interpretation and image improvement techniques. There are a number of ways to display the data for the end user. These are:

- A-Scan showing the 1D downrange target location

- B-Scan showing the 2D downrange and cross range image
- Simple readout showing distance to first wall and distance to second wall
- Ultra-simple “affirmative” or “negative” Boolean indicator

The A-scan for a UWB showing three peaks is shown for both wooden wall and concrete wall situations in Fig. 11a and Fig. 11b, respectively [8]. The points p1 correspond to the coupling between transmit and receive antennas (0.3m). Point p2 corresponds to the reflection of the incident wall (~1.7m) and point p3 identifies the reflection of a target located behind the wall 2.3m). Note that in Fig. 11a, the signals are distinguishable and generally lie within the same order of magnitudee. In Fig. 11b, p1 retains the same magnitude but p2 is about three times larger because the initial incidence on the concrete wall gives a very strong reflection. Furthermore, attenuation by the concrete wall results in a reduced signal strength of p3. The RF system can compensate for this by sending more power or using better LNAs so that p3 does not fall below the noise floor. An example B-scan corresponding to the wooden wall scenario is shown in Fig. 11c. Events p1 (0.3m) and p2 (1.7m) are visible. The 2D image demonstrates the ability to detect the two metal targets in the cross range (2.3m).



(a) (b) (c)

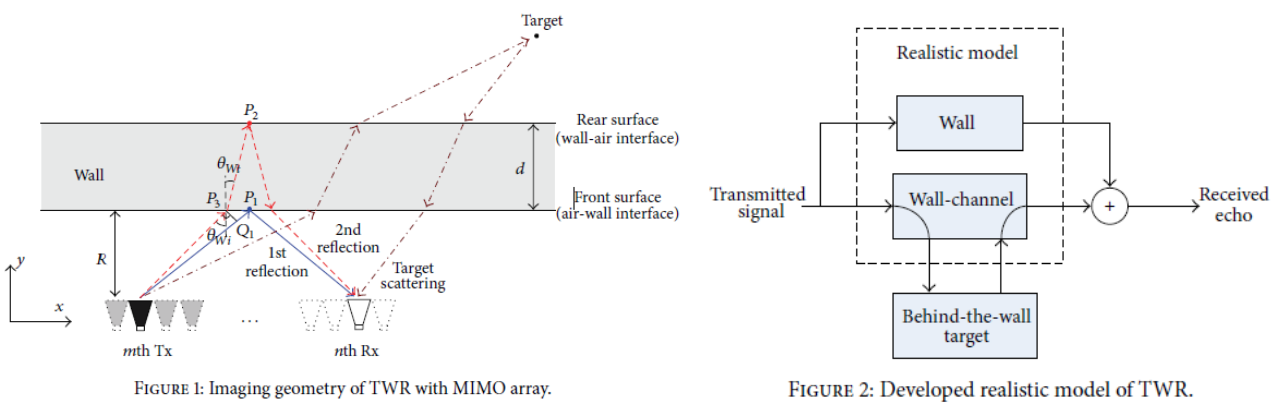
Fig. 11. Radar return data (a) A-scan of targets behind a wooden wall (b) A-scan of targets behind a concrete wall and (c) B-scan of two metal plates behind a wooden wall [8]

Once we have a strong understanding of the A-scan and B-scan, any number of simplifications can be implemented for the end user. Peak search on the A-scan or B-scan can identify the distances to the first wall (p2) and to the first target behind the wall (p3) similar to the Range-R device [2]. In 2D, the downrange and cross range profile of p3 will be used to determine if it’s an opposing wall in the hidden chamber or some other target. If the p3 return is too far away (>20ft), it may be ruled out as part of a different structure. Also, a threshold level or time-gating can be used to remove p1 and p2 and enhance p3. Once p3 is confirmed as a wall, an ultra-simplistic “AFFIRMATIVE” or “NEGATIVE” can be displayed.

Clutter management

In general, there are two types of clutter mitigation: (1) techniques dependent on modulation of the illuminating signal, or "dynamic methods," and (2) techniques dependent on accurate characterization of the clutter environment and target, or "static methods."

One of the main static clutter mitigation techniques is to use a calibrated scene in which coherent scene subtraction is used [6, 8, 9]. The idea is that data is collected in the absence of a target and is then collected in the present of the target. The difference between the two will produce enhanced images of the through-wall target. Another static approach is to develop a realistic model for the wall using a MIMO array which can estimate the position, thickness and permittivity of the wall [17]. From there, the effects of the wall can be compensated to produce a focused image. The reflections, refractions and channel modeling of the wall are shown in Fig. 12.



(a) (b)

Fig. 12. (a) Imaging geometry of TWRI with MIMO array and (b) wall-channel modeling [17]

Dynamic methods involve removing the signals returned from fixed objects and structures and extracting information only from returned modulated signals. The work in [14] implements a hardware-based clutter elimination system to detect vital signs. The system subtracts any reflections detected at the carrier frequency, leaving behind only the body-modulated heart and breathing rate signals. The work in [11] demonstrates a simple method using differentiation to form an image of a human behind a wall by ignoring strong reflections from the stationary wall. These dynamic techniques require motion at some level. For chambers that are empty, these techniques may not be too effective.

RESEARCH POTENTIAL AND FURTHER INQUIRIES

The portable TWRI sensor has many potential applications in defense, law enforcement, security, search and rescue, and construction.

Echoic Engineering is actively seeking collaboration in the area of Thru-Wall Radar Imaging. Please contact us at www.echoicrf.com or by email at ksyuk@echoicrf.com.

REFERENCES

[1] E. J. Baranoski, "VisiBuilding: Sensing Through Walls," IEEE Workshop on Sensor Array and Multichannel Processing, July 12-14, 2006.

[2] "Range-R Through the Wall Radar," L3 Communications CyTerra, Accessed 2017. [Online]. Available: http://www.range-r.com/

[3] P. K. M. Nkwari, S. Sinha and H. C. Ferreira, "Through-the-Wall Radar Imaging: A Review," IETE Technical Review, pp. 1-9, Sep 2017.

[4] "See Through Wall radar imaging Technology," Reverse Engineering Organized Stalking, Accessed 2017. [Online]. Available: https://redecomposition.wordpress.com/technology/

[5] "Acoustic/video: Acoustic Localization through wall/ceiling/floor," Reverse Engineering Organized Stalking, Accessed 2017. [Online]. Available: https://redecomposition.wordpress.com/acousticvideo/

[6] F. Ahmad and M. G. Amin, "Through-the-Wall Radar Imaging Experiments," IEEE Workshop on Signal Processing Applications for Public Security and Forensics, 2007, Apr. 11-13, 2007.

[7] R. Dilsavor, W. Ailes, P. Rush, F. Ahmad, W. Keichel, G. Titi, M. Amin, "Experiments on Wideband Through the Wall Imaging," Proc. SPIE 5808, Algorithms for Synthetic Aperture Radar Imagery XII, May 19, 2005.

[8] C. R.P. Dionisio, S. Tavares, M. Perotoni, S. Kofuji, "Experiments on Through-Wall Imaging Using Ultra Wideband Radar," Microwave and Optical Technology Letters, Vol. 54, Issue 2, pp 339-344, Feb 2012.

[9] A.R. Hunt (AKELA), "A wideband imaging radar for through-the-wall surveillance," Proc. SPIE 5403, Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense III, Sept 15, 2004.

[10] J. E. Peabody, Jr., G. L Charvat, J. Goodwin, M. Tobias, "Through-Wall Imaging Radar, "Through-Wall Imaging Radar," Lincoln Laboratory Journal, Vol. 19, No. 1, pp. 62-72, 2012.

[11] B. Lu, Q. Song, Z. Zhou, H. Wang, "A SFCW radar for through wall imaging and motion detection," 2011 European Radar Conference (EuRAD), Oct 11-14 2011.

[12] S. Depatla, C. R. Karanam and Y. Mostofi, "Robotic Through-Wall Imaging: Radio Frequency Imaging Possibilities with Unmanned Vehicles," IEEE Antennas and Propagation Magazine, Vol. 59, Issue 5, pp. 47-60, Oct. 2017.

[13] C. R. Karanam and Y. Mostofi, "3D Through-Wall Imaging with Unmanned Aerial Vehicles Using WiFi," IPSN '17 Proceedings of the 16th ACM/IEEE International Conference on Information Processing in Sensor Networks," Apr 18-20, 2017.

[14] K.-M. Chen, Y. Huang, J. Zhang and A. Norman, "Microwave Life-Detection Systems for Searching Human Subjects Under Earthquake Rubble or Behind Barrier," IEEE Trans. on Biomedical Engineering, Vol. 27, No. 1, Jan 2000.

[15] S. Agneessens, P. van Torre, F. Declercq, B. Spinnewyn, G.-J. Stockman, H. Rogier and D. V. Ginste, "Design of a Wearable, Low-Cost, Through-Wall Doppler Radar System" International Journal of Antennas and Propagation, vol. 2012, no. 840924, 2012.

[16] T. Dogaru and C. Le, "Though-the-Wall Radar Simulations for Complex Room Imaging," ARL-TR-5205, May 2010.

[17] T. Jin and A. Yarovoy, A Through-the-Wall Radar Imaging Method Based on a Realistic Model," International Journal of Antennas and Propagation, Vol. 2015, June 2015.

[18] A. Muqaibel, A. Safaai-Jazi, A. Bayram, A.M. Attiya and S.M. Riad, "Ultrawideband through-the-wall propagation," IEE Proc.-Microw. Antennas and Propag., Vol. 152, No. 6, pp. 581-588, Dec. 2005.

[19] C. Thajudeen, A. Hoorfar and F. Ahmad, "Measured Complex Permittivity of Walls with Different Hydration Levels and the Effect on Power Estimation of TWRI Target Returns," Progress in Electromagnetics Research B, Vol. 30, pp. 177-199, 2011.

[20] Ofcom, "Building Materials and Propagation," Sept 14, 2014. Available at: https://www.ofcom.org.uk/__data/assets/pdf_file/0016/84022/building_materials_and_propagation.pdf

[21] F. Felber, "Demonstration of novel high-power acoustic through-the-wall sensor," Proc. SPIE 9456, Sensors, and Command, Control, Communications, and Intelligend (C3I) Tech. for Homeland Security, Defense, and Law Enforcement XIV, 945603, May 14, 2015.

[22] Y. Yang, Y. Wang and A. E. Fathy, "Design of Compact Vivaldi Antenna Arrays for UWB See Through Wall Applications," Progress in Electromagnetics Research, PIER 82, pp.401-418, 2008.

[23] "DCT419S1 Hand Held Wall Scanner," DeWALT, Towson, MD, 2017. [Online]. Available: http://www.dewalt.com/products/power-tools/lasers-and-instruments/hand-held-wall-scanner/dct419s1

[24] P. P. Creasman, D. Sassen, S. Koepnick, N. Doyle, "Ground-penetrating radar survey at the pyramid complex of Senwosret III at Dahshur, Egypt, 2008: search for the lost boat of a Pharaoh,"Journal of Archaeological Science, Vol. 37, Iss. 3, March 2010, pp. 516-524.

[25] M. Gannnon, "Search for Mythical Nazi Gold Train Resumes," Aug. 16, 2016 [Online]. Available: https://www.livescience.com/55780-search-for-mythical-nazi-gold-train-resumes.html

[26] Keysight Technologies, "Basics of Measuring the Dielectric Properties of Materials," [Online]. Available: http://literature.cdn.keysight.com/litweb/pdf/5989-2589EN.pdf

[27] Z. Hlavacova, "Electrical Properties of Some Building Materials," Research and Teaching of Physics in the Context of University Education, pp . 134-140, June 5-6, 2007.

[28] G. Mazzaro, B. Phelan, K. Sherbondy, F. Koenig, "Introduction to Stepped-Frequency Radar," June 7, 2013. [Online]. Available: http://ece.citadel.edu/mazzaro/particip/SFR_Intro_Mazzaro.pdf