Handheld microwave bomb-detecting imaging system

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ABSTRACT

Proposed novel imaging technique will provide all weather high-resolution imaging and recognition capability for RF/Microwave signals with good penetration through highly scattered media: fog, snow, dust, smoke, even foliage, camouflage, walls and ground. Image resolution in proposed imaging system is not limited by diffraction and will be determined by processor and sampling frequency. Proposed imaging system can simultaneously cover wide field of view, detect multiple targets and can be multi-frequency, multi-function. Directional antennas in imaging system can be close positioned and installed in cell phone size handheld device, on small aircraft or distributed around protected border or object. Non-scanning monopulse system allows dramatically decrease in transmitting power and at the same time provides increased imaging range by integrating 2-3 orders more signals than regular scanning imaging systems.

Keywords: Handheld, imaging, fly eye radar, monopulse, multi beam, digital hologram, high resolution, bomb detection, automatic identification of hidden object,

1. INTRODUCTION

Millimeter imaging radars required high power, heavy and harmful for human health transmitters because bad penetrating of millimeter wave signals. Fly Eye imaging radar is based on the application of a long wavelength low power RF/Microwave signals. Long RF/microwave wavelength provides enhanced camouflage, foliage, walls penetration. Low microwave transmitter power over a broader range of exploration through the use of radar technology, providing increased detection probability, classification and precision imaging.

1.1 Radar imaging technologies

The penetration of long wavelength RF/microwave energy is much better than shorter wavelengths. It can be applied for bomb detection, human detection and for imaging with few orders smaller transmitting power. But in existing radars image resolution for RF/microwave relatively long waves is limited by the diffraction limit (Abbe diffraction limit). In Figure 1 is presented images of a bomb and a human body made with long wavelength radar sensors. The resolution of the image is approximately equal to the wavelength which in this case is one foot.

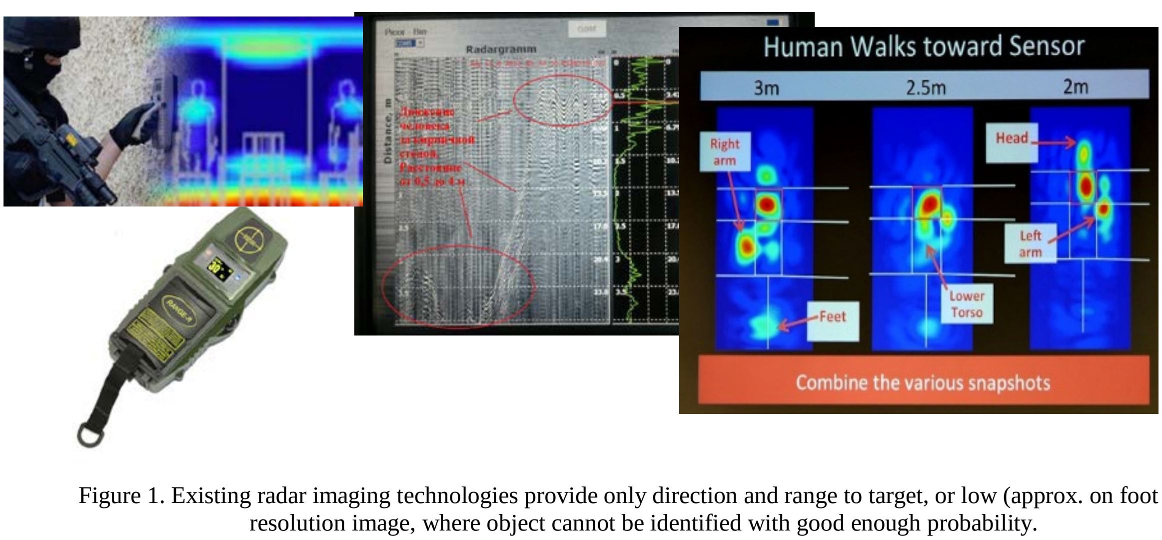

Figure 1. Existing radar imaging technologies provide only direction and range to target, or low (approx. on foot size) resolution image, where object cannot be identified with good enough probability.

Existing low power RF/microwave systems with relatively long wavelengths cannot image objects smaller than their wavelength [1,2]. The radiation is diffracted by such objects. The phase front of the diffracted waves actually carries information about the shape of the object but conventional imaging systems do not take advantage of this information. This lost information can be reconstructed from a multi frequency digital hologram by the combination of interferograms. The result is the ability to image details orders of magnitude smaller than the wavelength of the radiation being used.

Impulse radars usually emit short pulses. The return time and amplitude after reflection are recorded. Imaging may be complicated by multiple reverberations. The images do not resemble optical images making their interpretation more difficult.

Figure 2. Imaging radar systems are large and cannot provide good enough resolution and automatic detection of hidden objects.

Imaging scanning systems have become widespread in many areas of science and technology, such as computer vision, telemedicine, geology and archeology, nondestructive testing, security systems, and others. In these systems the synthetic aperture is formed by mechanical scanning or electronic switching of distributed antennas, which leads to recording large amounts of data with low information content. In the last decade the theory of synthetic aperture radars has been developed which allows reconstructing images of objects from a reduced number of measurements in comparison with traditional methods.

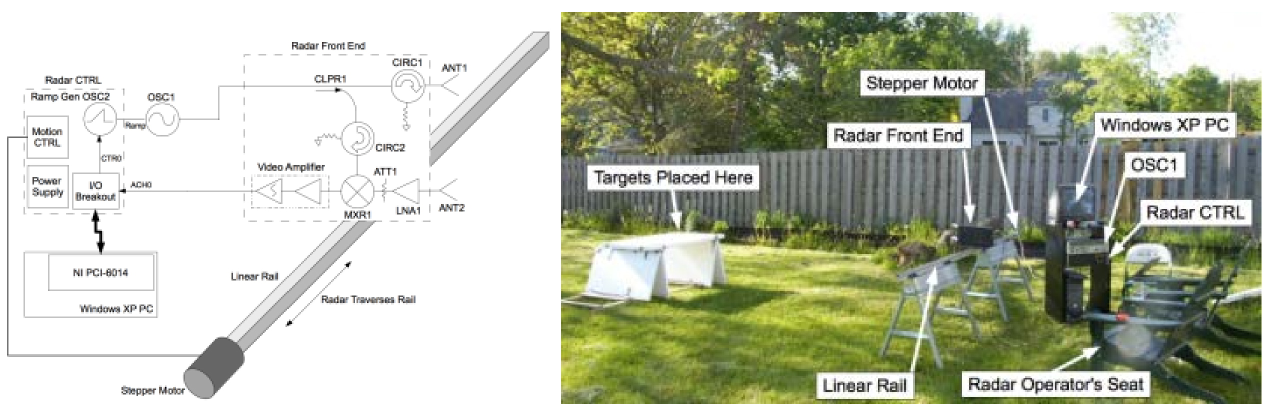

Figure 3. X-band Synthetic Aperture Radar (SAR) mounted on 8’ long linear stage. .

According to this theory, the majority of real-world objects can be represented as a sparse decomposition relative to a certain basis, that is, just a few key coefficients are sufficient for recording most of the image spectrum energy. To implement this representation of the image data we need to solve the problem of finding the basis with the least number of decomposition coefficients using special optimization algorithms. The **synthetic aperture** theory continues to develop, it may have many applications in radar holography, and nondestructive testing of dielectric details by microwaves, concealed targets detection by subsurface radar [3,4].

1.2 Handheld imaging radar

Proposed handheld imaging radar presented in Figures 4-5, is the next step in developing the passive monopulse direction finder receiving a signal simultaneously in a pair of antennas covering the same field of view and then comparing the signal ratios (Figure 5). Monopulse angle information always appears in the form of a ratio. The ratio value is independent of the signal and any common noise or modulation present [1]. Using the proposed system, as presented in Figure 4, images are created and recorded using a real time digital hologram sampled through an ultra-wideband monopulse antenna array with wide field of view capabilities.

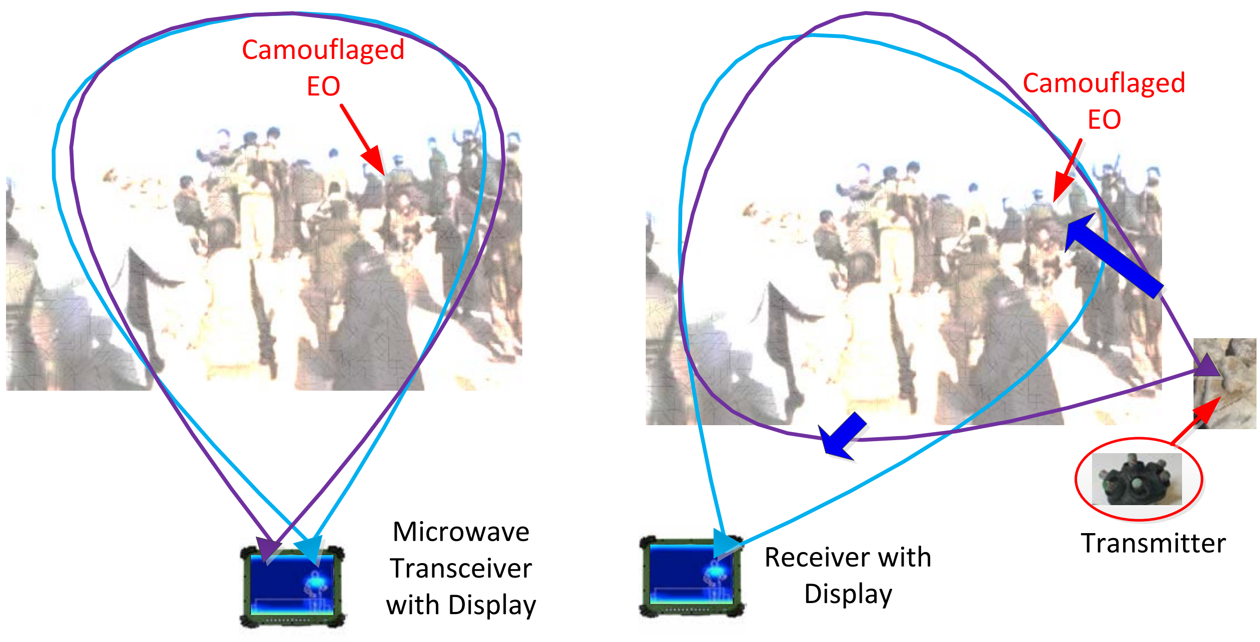

Figure 4. Concept of Handheld Microwave Bomb-detection and imaging system based on the ultra-wideband monopulse antenna array offering wide field of view capabilities. Reference antenna is used to record real time digital holograms and perform 3D image reconstruction.

The ultra-wideband directional monopulse antenna array is angular shifted and has overlapping antenna patterns. One antenna can be used as a reference for high-accuracy amplitude/phase measurements. Each antenna is integrated with a front end digitizer circuit and is connected to an image processor through a digital interface. This allows for storage of amplitude and phase components of received signals as a digital hologram with high accuracy in the ultra-wide frequency band.

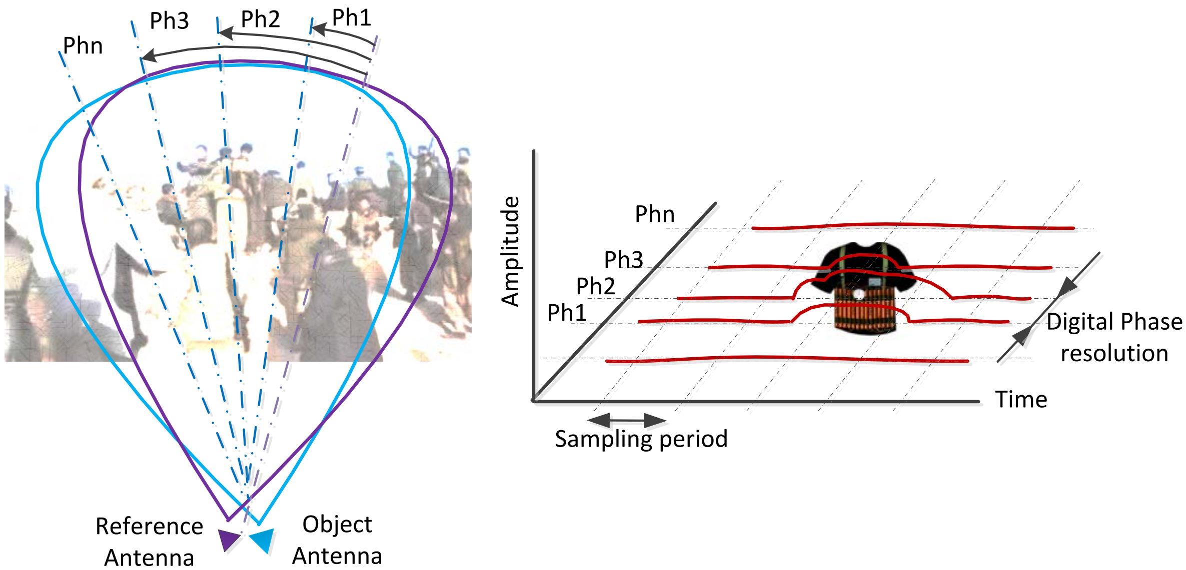

Figure 5. Reconstructing the digital hologram image by processing real time recorded microwave signals in time/phase domain. Reference antenna provides high accuracy phase and amplitude information. Image is reconstructing from phase shifted interferograms. Image resolution is independent of beam width and diffraction limitation constraints, but rather determined by sampling period and digital phase resolution.

2. FLY EYE IMAGING RADAR SYSTEM

2.1 Imaging radar concept

The proposed microwave imaging system is the next step in developing the passive monopulse direction finder proposed by Stephen E. Lipsky in the 1970's [5]. The monopulse ultra-wideband directional antenna array is angular shifted directional antennas with overlapping antenna patterns [6]. One antenna can be used as a reference for high-accuracy amplitude/phase measurements. Each antenna is integrated with a front end digitizer circuit and is connected to an image processor through a digital interface. This allows for storage of amplitude and phase components of received signals as a digital hologram with high accuracy in the ultra-wide frequency band.

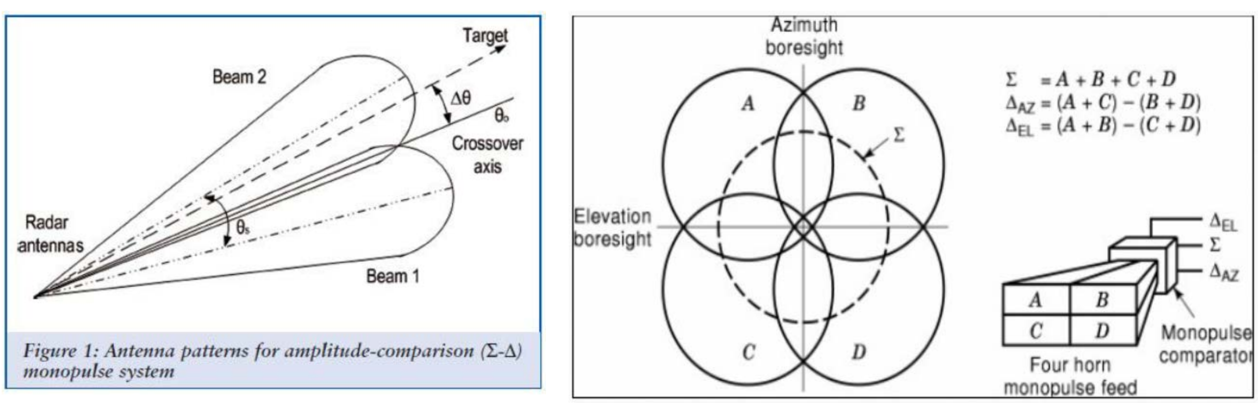

Figure 6. Figure captions are indented 5 spaces and justified. If you are familiar with Word styles, you can insert a field code called Seq figure which automatically numbers your figures.

Monopulse is the concept of receiving a signal simultaneously in a pair of antennas covering the same field of view and then comparing the signal ratios (Figure 6). Monopulse angle information always appears in the form of a ratio.

The ratio value is independent of the signal and any common mode noise or modulation present. The proposed monopulse microwave imaging system can work in passive, monostatic or bi-static regimes. Images are created and recorded using a monopulse radar system, as presented in Figure 7 and a real time digital hologram is sampled through an ultra-wideband monopulse antenna array with wide field of view capabilities.

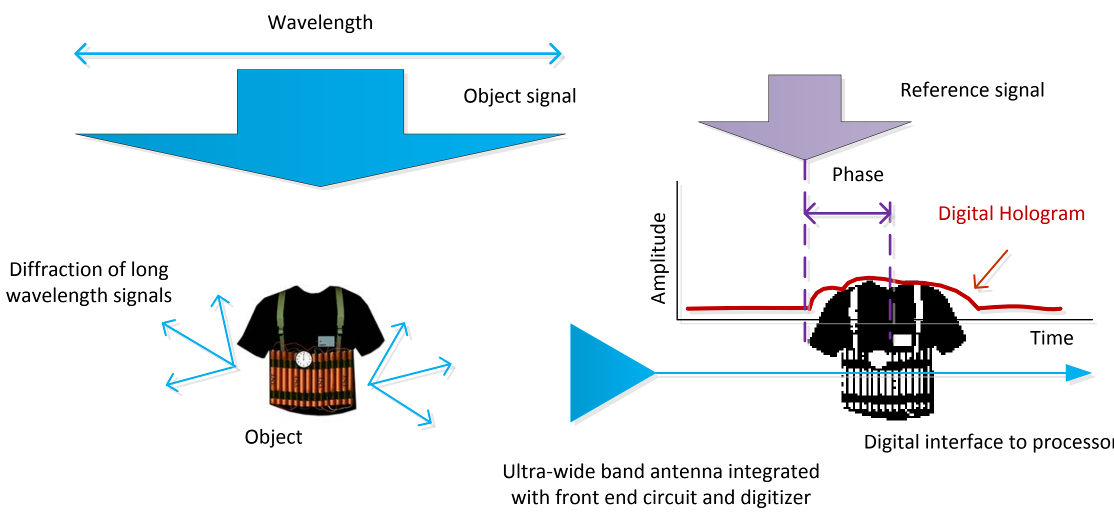

Figure 7. Figure 6. Real time recording of digital hologram as combination of interferograms. Each received interferogram contains amplitude and phase information, pertaining to the object, in the form of diffracted radiation within the receiver plane and can be digitally recorded by sampling as a 1D plot and interpreted as digital hologram.

Advances of handheld bomb-detection imaging system:

- Proposed microwave bomb-detection and imaging system will provide all weather high-resolution images in smoke and dust conditions with enhanced penetration of camouflage, foliage and underground devices up to 0.5 meters below the surface;
- Digitized signals in antenna module provides phase/frequency independence. As a result, the system can be ultra-wide band, multi-band or step frequency modulated. Fourier transform of wide band reflected signal provides reliable identification and classification of EO, UXO and IEDs.
- Image resolution is determined by processor and sampling frequency and is not limited by electromagnetic wave diffraction;
- System can be set up and deployed in moments consisting of a few seconds.
- System will be controlled with open source software and can be operated wirelessly from a laptop;
- System will provide real time imaging of objects without the need for safety zones as transmitting microwave power is minimal; physically comparable to common cell phone operation;
- Optionally, proposed system can be used for camouflaged human detection in foliage or ground buried mine detection;

3. IMAGE RECONSTRUCTION ALGORITHM FOR HIGH SCATTERED MEDIA

3.1 High-speed sampling

Digital radar target imaging with high resolution monopulse radar was first introduced in the 1980's [6]. A monopulse radar system optically displays radar information in 3-D for visual identification of targets. By visually displaying radar target information in 3-D, the radar operator can quickly discern from its shape whether a particular object is a threat. The system receives data from a high resolution monopulse radar system having wideband monopulse tracking capability. Data is processed out to a display such that its three outputs are representative of the three-dimensional coordinate information defined by the physical target. Results are then displayed in a three coordinate display apparatus. Image resolution in narrow beam radars depend upon radar frequency and radar aperture. Increasing the frequency up to mm, sub-mm wave range and creating a synthetic aperture by sweeping antennas along the object surface provides a technological benchmark for comparing image resolution against SAR applications. However, short electromagnetic waves have bad penetration in harsh weather conditions. PMI proposed monopulse radar imaging uses digital holograms, whereby, image resolution is determined by receiver bandwidth (number of received high-frequency harmonics), sampling frequency, sampling accuracy, and accuracy of digital phase shift (Figure 8). The availability of better processors overtime will provide enhanced image resolution directly correlated with anticipated improvements in commodity technologies.

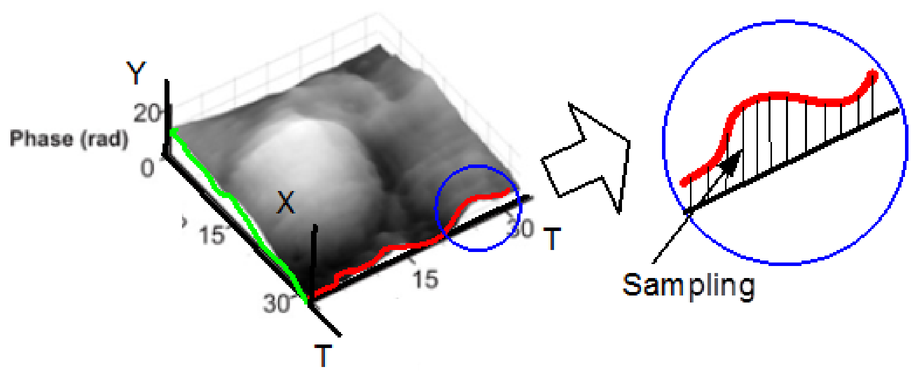

Figure 8. Image resolution is determinate by sampling frequency and digital phase shift.

Let's estimate sampling frequency for holographic image reconstruction. Electromagnetic waves move through air at a speed of approximately one foot per nanosecond. By this we conclude, that one foot of resolution can be received with a 1 GHz processor. To receive image resolutions up to 3 cm, the samples must be collected at 100 picoseconds intervals, which corresponds to a 10 GHz processor.

The Nyquist-Shannon sampling theorem states that for a true representation of waveform X, greater than two samples per period are required. For Analog to Digital Converters (ADC), this implies the clock frequency (Fs) must be two times greater than the analog input frequency (Fin), for a true representation of the analog input signal.

To state the last sentence in equation form, if Fin < Fs/2, then Fin can be accurately represented by the digitizer. Fs/2 is commonly referred to as the Nyquist Frequency.

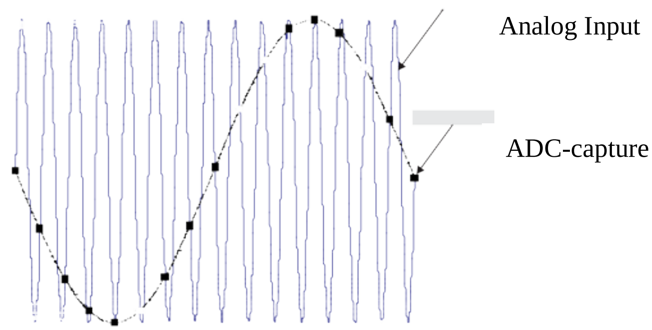

Figure 9. Received radar signal waveform can also be restored with adequate resolution by Undersampling Fin > Fs/2. Undersampling will allow for reduced ADC sampling frequencies.

Figure 9 is an example of ADC undersampling (Nyquist < Fin), as less than two samples are captured per period. To state the last sentence in equation form, when Fin > Fs/2, the ADC is undersampling the input waveform. Undersampling allows for an aliased representation of the waveform to be captured [7-9].

3.1 Imaging algorithm

An algorithm for the creation of high resolution 3D images from a digital hologram is presented in Figure 9. Digital information from multiple object antennas can be transferred to the image processor by fiber optic cable. 3D images are created by combining phase shifted interferograms. Resolution of images is increased by multi-frequency phase domain processing.

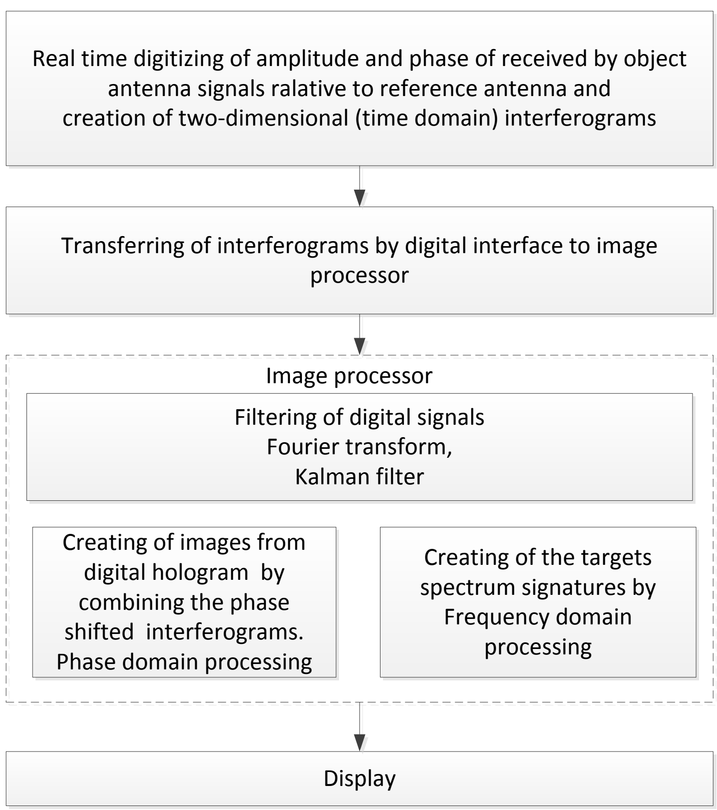

Figure 10. Algorithm for creating high resolution 3D images from digital hologram.

3.2 Advance algorithms for high scattered media

The cross-sectional area is a function of the objects true geometric cross-section, as well as, the contrast in electrical properties. The back-scattered gain is primarily controlled by the geometrical attributes of the object. Radar responses are a function of both physical property contrast and geometry. For small objects the amount of energy scattered increases as the fourth power of the target dimension. When the target gets large, the response plateaus out and approaches that of a planar boundary (i.e. the Fresnel reflection coefficient).

Gating of radar signals enhance SNR and provides better resolution in high scattered media Figure 11. But object and scattered media signals cannot be separated by gating.

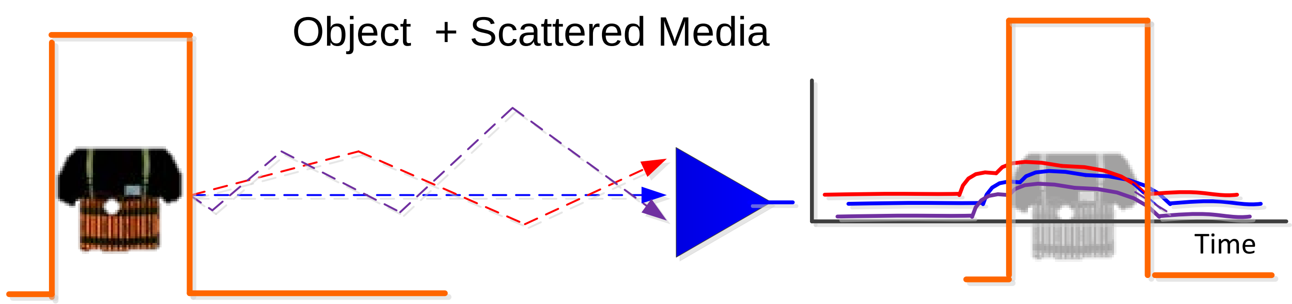

Figure 11. Gating of radar signals enhance SNR and provides better resolution in high scattered media.

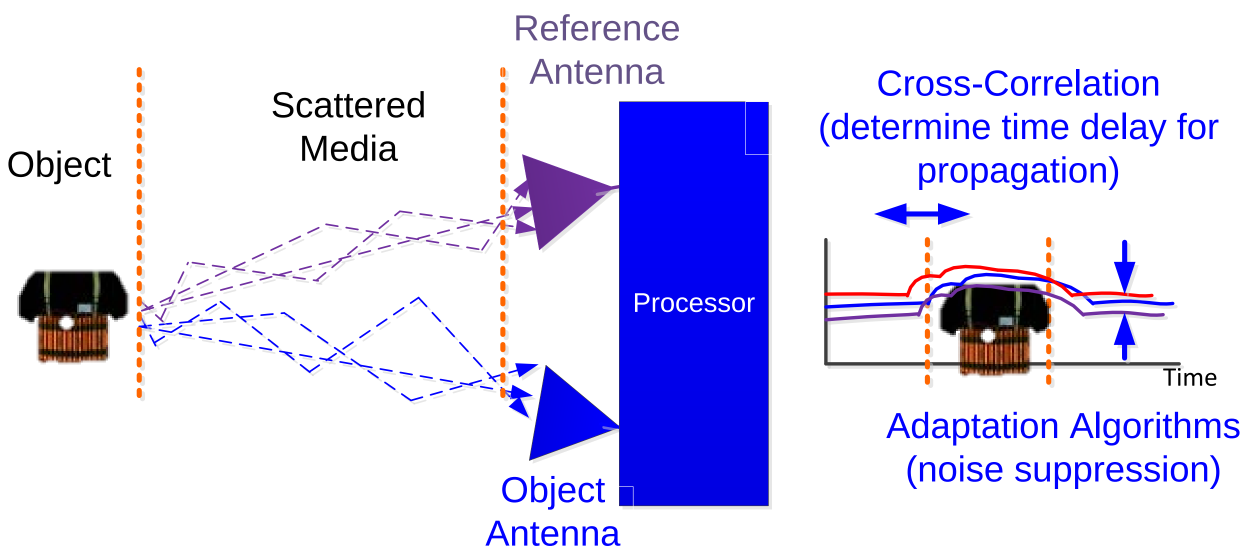

Figure 12. Additional (reference) antenna allows to separate object and scattered media signals in radar receiver. Cross-correlation and adaptation algorithms provides dramatically enhancing of image resolution.

Reference antenna (monopulse method) allows to separate object signals and scattered media signals in processor (Figure 12). Cross-correlation process provide adjustment of time delay caused different time of electromagnetic waves propagation in high scattered media. Adaptation algorithms can provide noise suppression by separation of signals from object area and scattered media area.

3.3 Option 1. Image reconstruction

Reconstruction of object image from digital hologram. In this case spectrum components with their amplitude and phase information recorded in digital form in time/frequency domain (interferograms) summarized with time shift corresponding to their phase, like described in chapter 2.4. Conceptual design of handheld imaging radar presented in Figure 13.

An algorithm for the creation of high resolution 3D images from a digital hologram is presented in Figure 10. Digital information from multiple object antennas can be transferred to the image processor by fiber optic cable. 3D images are created by combining phase shifted interferograms. Resolution of images is increased by multi-frequency phase domain processing.

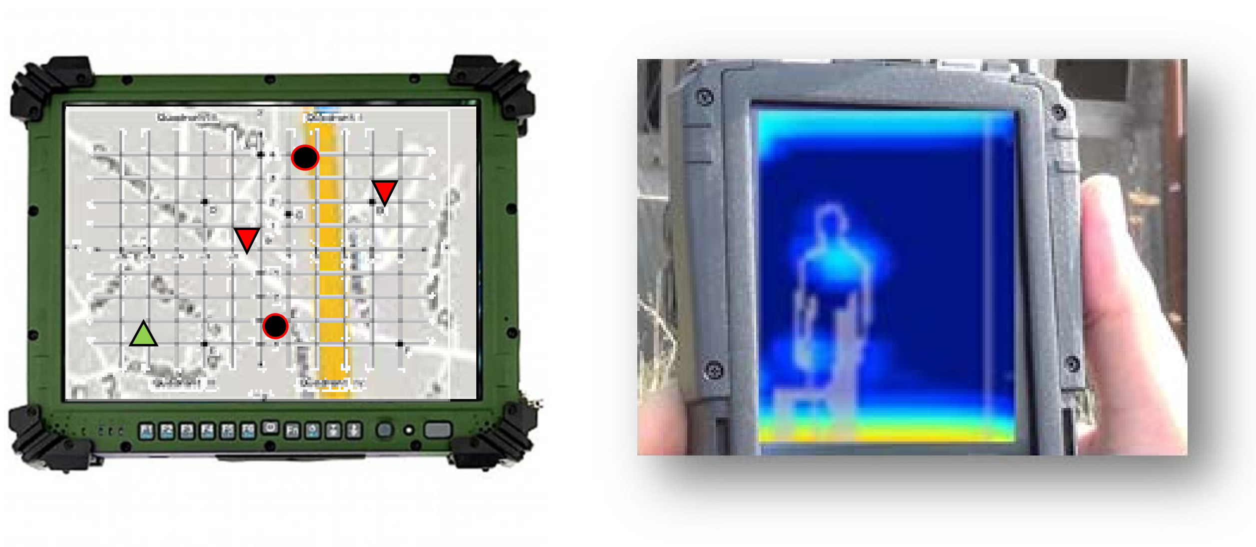

Figure 13. Additional (reference) antenna allows to separate object and scattered media signals in radar receiver. Cross-correlation and adaptation algorithms provides dramatically enhancing of image resolution.

3.4 Option 2. Invariant to position object identification

Nature of hidden object can be identified by spectrum of diffracted signal components (Figure 14). Spectral signatures can be recorded in a library and applied to the identification of different objects or object's content.

Difference between Doppler spectrum signature and diffraction components spectrum signature:

Doppler frequency shift appears when the object, or some parts of the object are moving relative to the receiving antenna. Doppler frequency appears only when the object moving. Spectrum components depend on the speed of the motion of different parts of the object relative to the position of the radar receiving antenna. Doppler spectrum signature critical to position of object in space and relative to receiving antenna [10].

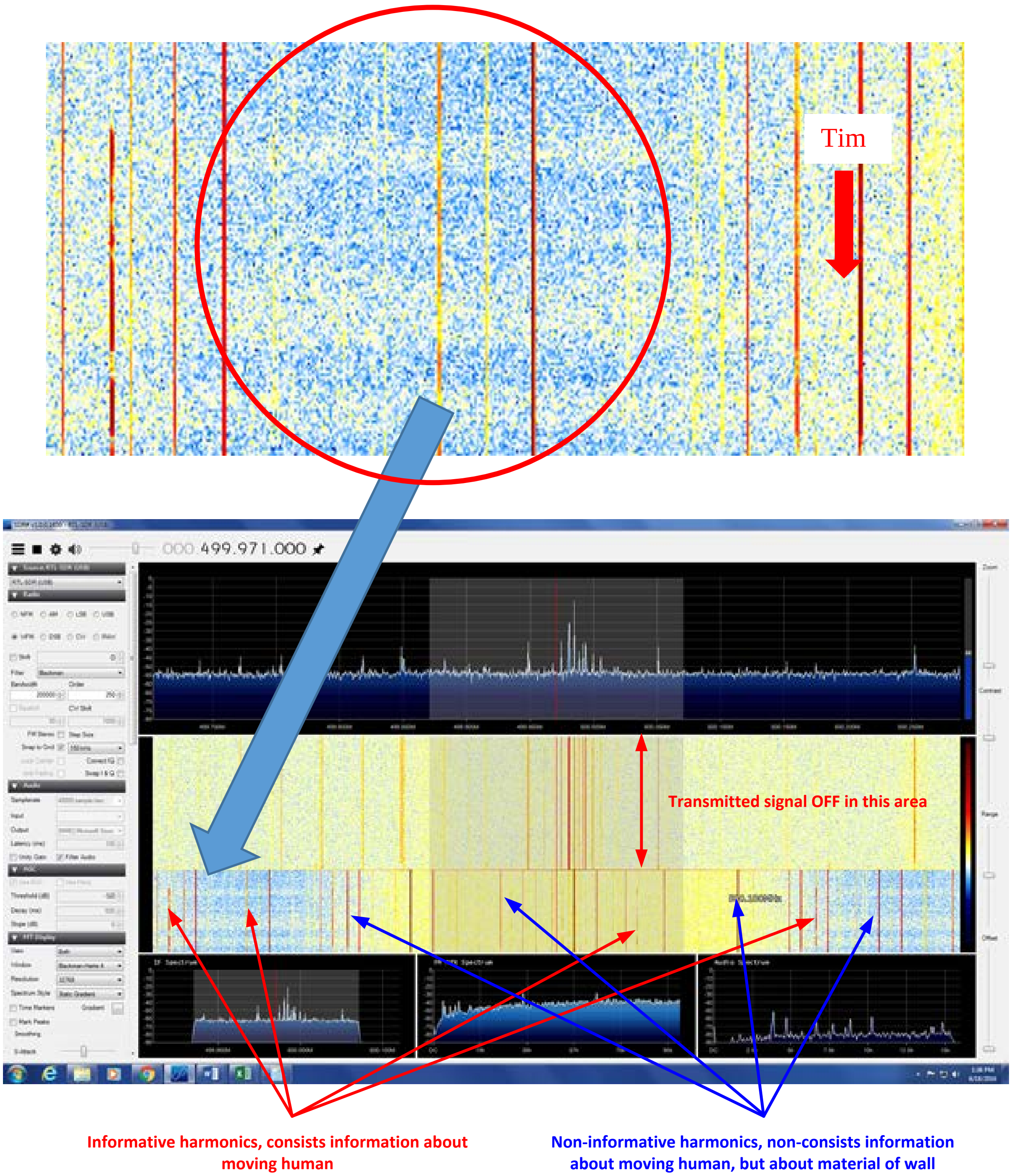

Figure 14. Test of low microwave frequency micro radar for penetrating through 40 cm concrete wall (a). Directional antenna and spectrum/time (waterfall) test result (b).

In Figure 14 is presented test results for detection of a human body with Software Defined Radio (SDR). Spectrum of the reflection from the human body and received by SDR signals is presented in two different scales: ultra-wide band, and in SDR receiver bandwidth. The signal's spectral content presented in the time domain is presented in separate window. The spectrum of the reflected signals consists of diffraction components which can be used for the reconstruction of the object image and for identification of object and media content. There are a few algorithms to separate spectral signatures of object and media, like cross-correlation and adaptation briefly described in section 3 of this paper.

4. TEST OF PROPOSED IMAGING SYSTEM

4.1 Architecture of imaging radar sensors

To extend high frequency limit and provide high sensitivity over the broadband of frequencies, Stephen E. Lipsky proposed to integrate detector and mixing elements with antenna [8]. Multiple angularly spaced directional antennas in proposed micro-radar are coupled with front end circuits and separately connected to a direction finder processor by a digital interface (Figure 15). If the lobes are overlap or closely spaced, micro-radar can produce a high degree of pointing accuracy within the beam, adding to the natural accuracy of the conical scanning system. Whereas classical conical scan systems generate pointing accuracy on the order of 0.1 degree, monopulse radars generally improve this by a factor of 10, and advanced tracking radars like the AN/FPS-16 are accurate to 0.006 degrees [11].

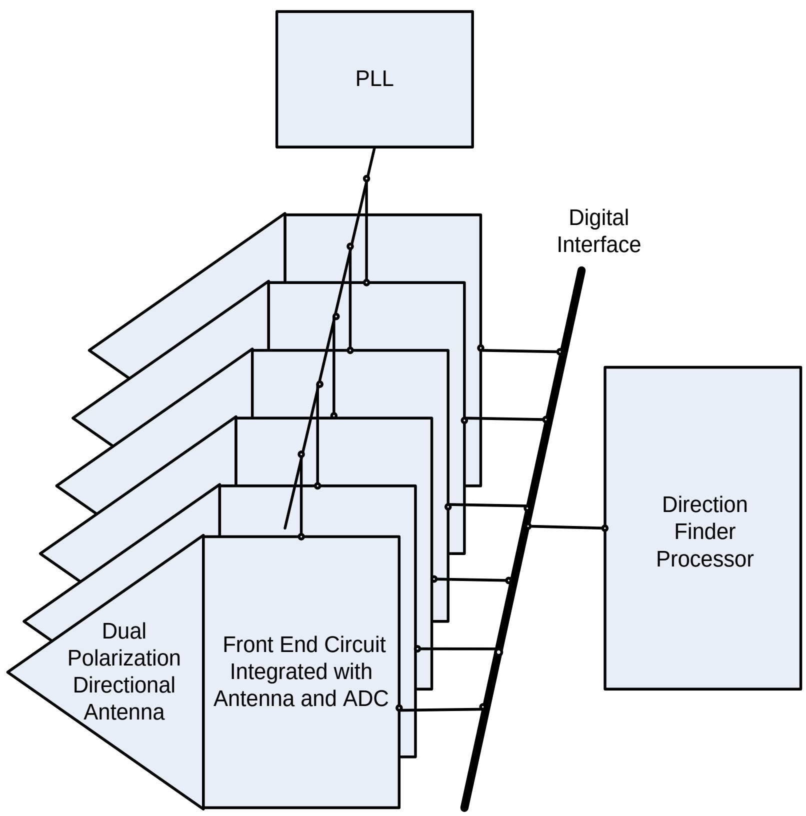

Figure 15. Block diagram of proposed IDF.

Preliminary designed front end circuit integrated with antenna and analog to digital converter presented in Figure 16. Wideband antenna with balun (BAL-0036, 300 kHz – 36 GHz) via limiter, Low Noise Amplifier (LNA) and mixer (ML1-0218SM, 2-18 GHz) connected to Successive Detection Log Video Amplifier (SDVLA); and via buffer amplifier (ADM-0026-59295M, DC - 26,56 GHz) connected to analog to digital converter.

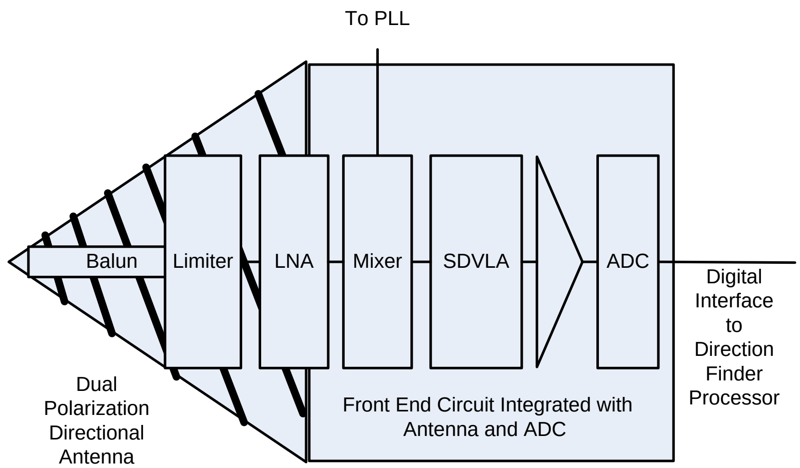

Figure 16. Wideband dual polarization directional antenna integrated with front end circuit and analog to digital converter.

Integration of antennas with front end circuits allows to exclude waveguide lines which limiting system bandwidth and creates frequency dependent phase errors.

Digitizing of received signals proximate to antennas allows dramatically decrease phase errors connected with waveguides. Accuracy of direction finding in proposed micro-radar in this case will be determined by time accuracy of digital processor and sampling frequency.

Result of design and test of a few kinds of miniature directional antennas and preliminary designed passive radar receivers presented in Figure 17 [12-22].

Figure 17. Ultra-wide band monopulse antenna arrays can have different size. Smallest antenna arrays can be applied for handheld bomb detection.

Prototype of handheld imaging radar, receiver and antenna elements presented in Figure 18. Most of elements was designed and produced by PMI Inc.

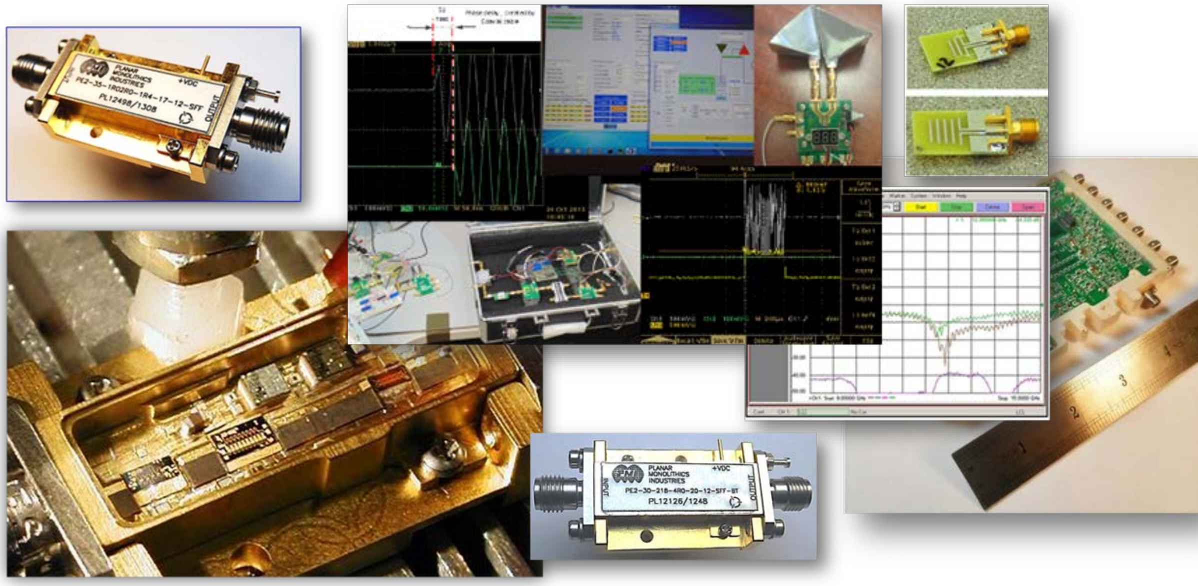

Figure 18. Handheld monopulse radar receiver, amplifiers and antenna elements.

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