Fly Eye radar. Detection through high scattered media

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ABSTRACT

Longer radio frequency waves better penetrating through high scattered media than millimeter waves, but imaging resolution limited by diffraction at longer wavelength. Same time frequency and amplitudes of diffracted waves (frequency domain measurement) provides information of object. Phase shift of diffracted waves (phase front in time domain) consists information about shape of object and can be applied for reconstruction of object shape or even image by recording of multi-frequency digital hologram. Spectrum signature or refracted waves allows identify the object content. Application of monopulse method with overlap closely spaced antenna patterns provides high accuracy measurement of amplitude, phase, and direction to signal source. Digitizing of received signals separately in each antenna relative to processor time provides phase/frequency independence. Fly eye non-scanning multi-frequency radar system provides simultaneous continuous observation of multiple targets and wide possibilities for stepped frequency, simultaneous frequency, chaotic frequency sweeping waveform (CFS), polarization modulation for reliable object detection. Proposed c-band fly eye radar demonstrated human detection through 40 cm concrete brick wall with human and wall material spectrum signatures and can be applied for through wall human detection, landmines, improvised explosive devices detection, underground or camouflaged object imaging.

Keywords: Fly Eye radar, multi-beam, multi-frequency, monopulse, simultaneous, no-scanning detection, passive, tracking, ground penetrating, sense and avoid, landmines detection

1. INTRODUCTION

Proposed system based on nature inspired Fly Eye antenna array presented in Figure 1 [1]. To compensate for its eye's inability to point at a target, the fly's eye consists of multiple angularly shifted sensors which gives the fly the wide-area visual coverage it needs to detect and avoid the threats around it. Each sensor is coupled with a detector and connected separately to memory.

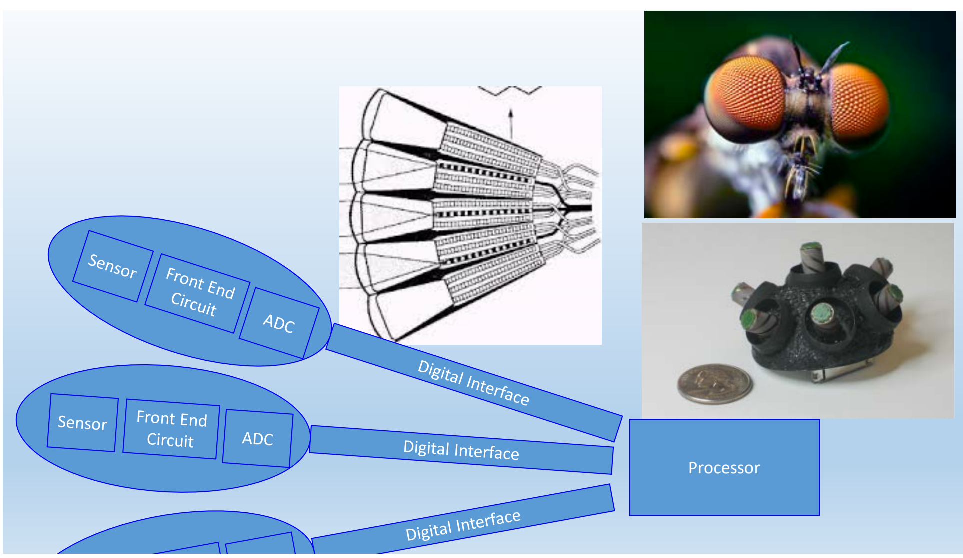


Figure 1. Concept of Fly Eye antenna array. Overlap angular shifted directional antennas cover entire sky. Each antenna integrated with front end circuit and connected to direction finder processor by digital interface.

Application of fly eye antenna array provides high-accuracy amplitude and phase measurement with minimal distance between antennas [2]. Array of directional antennas presented in Figure 1. Fly Eye directional antenna modules architecture provides:

- Array of angular shifted directional antennas with overlap antenna patterns covering wide area of observation or entire sky and provide high-accuracy direction finding or navigation;
- Monopulse method with simultaneous multi-directional high-accuracy measurement of angle of arrival in 360 degree by azimuth and elevation area provides high-speed, high-accuracy imaging and mapping possibility;
- Monopulse array of angular shifted directional antennas is not phase/frequency dependent and can be ultra-wideband or multi-band. Wide frequency band will provide possibility to use multiple different ambient RF energy sources for passive radar systems;
- Phase shift of diffracted waves (phase front in time domain) consists information about shape of object and can be applied for reconstruction of object shape or even image by recording of multi-frequency digital hologram.
- Spectrum signatures of received signals provide possibility to detect and track human, weapon, different objects, explosive materials, gas contamination areas;
- Directional antennas may be installed closely or loosely distributed over the perimeter of the carrier platform or between separate robotic carriers in swarm.

2. FLY EYE RADAR APLICATIONS

2.1 Applications areas

Possible Fly Eye radar applications presented in Figure 2.

Multi beam wide angle of view Fly Eye antenna array can be applied for sense and avoid system for simultaneous detection and tracking multiple targets. Detection of targets with multiple beams provides possibility of automatic steering transmitting power in separate beams and suppress ground clutter for low altitude aircraft or adjust detection range in separate directions for radar application in urban/mountain area.

Long wavelength good penetrating RF/microwave system do not required high transmitting power for ground, through camouflage, grass, tree branches penetrating, can be light weight and positioned on small drones for mine detection. Spectrum signature of buried objects can be applied for identification of objects material, where identification will be invariant to object position. Preliminary recorded library of buried object will allow automatic identification of objects without operator.

High accuracy measurement of amplitude and phase provides possibility to reconstruct images of objects with resolution 2-3 orders better than wavelength. Non-scanning, non-switching monopulse systems allows to receive continuous information from multiple targets simultaneously.

Correlation and adaptation algorithms allows increase sensitivity of system and make system even passive, with using ambient electromagnetic power sources. Reference beam provides additional information about media and can be used for separation of object from high scattered media.

Array of directional antennas in passive radar will receive direct microwave signals from the ambient sources and reflected from objects part of these microwave signals. The radar signals reflected from moving with high speed projectiles will consist of a Doppler frequency shift in determined narrow frequency band. Application of bandpass filter with narrow bandwidth for Doppler signals will allow dramatically increase signal/noise ratio and detect small arms fire with high probability of detection.

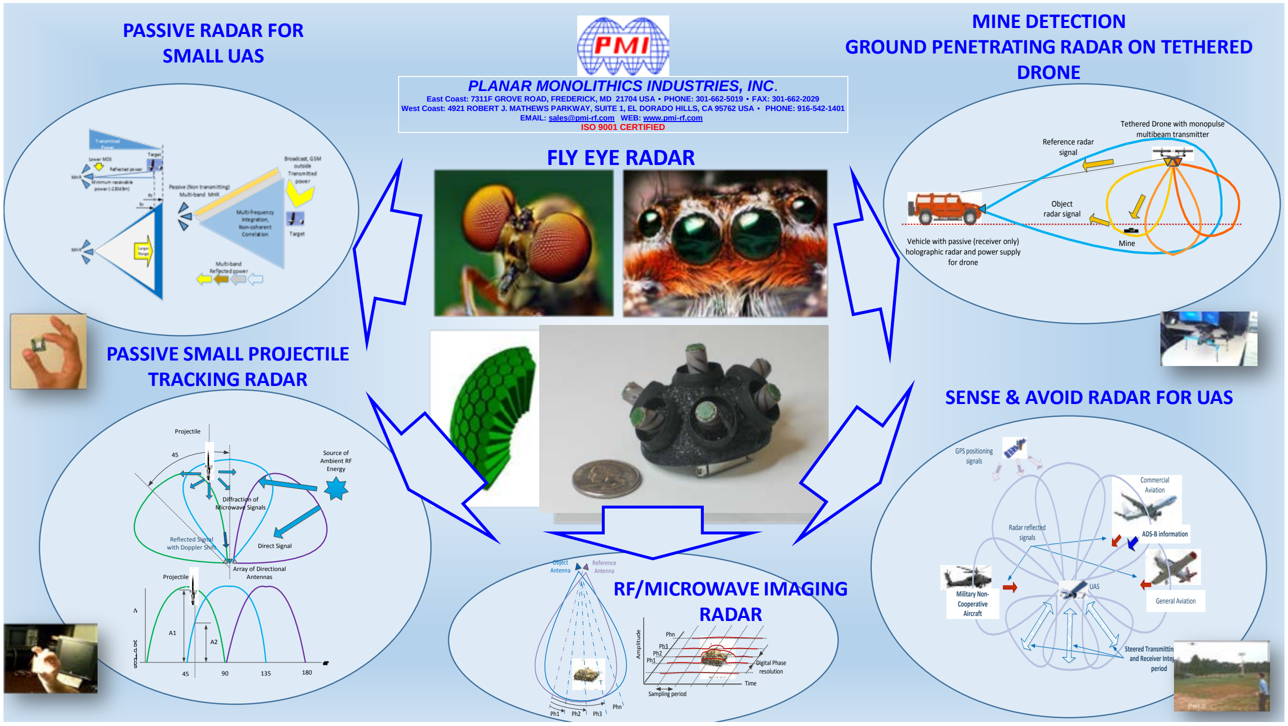


Figure 2. Fly Eye antenna array can be applied for sense and avoid radar system, ground penetrating radar, for detection of small projectile, as tracking and imaging radar. System can be active, with transmitter or passive, using ambient RF energy source.

2.2 Sense and avoid radar system

Sense and avoid radar system must be multi-beam and monopulse for simultaneous non-scanning and detection of multiple targets in entire sky.
Multibeam monopulse radar concept:

- Multibeam monopulse radar with array of directional antennas can be positioned on Unmanned Aircraft System (UAS). Radar signals simultaneously transmitted and received by multiple angle shifted directional antennas with overlap antenna patterns the entire sky, 360 degrees for both horizontal and vertical coverage;
- Digitizing of signals in separate directional antennas relative to reference signals provides high-accuracy high-resolution range and azimuth measurement and allows to record real time amplitude and phase of reflected from non-cooperative aircraft signals;
- High resolution range and azimuth measurement provides minimal tracking errors in both position and velocity of non-cooperative aircraft and will be determined by sampling frequency of digitizer;
- Automatic steering of transmitting power allows dramatically decrease ground clutter;
- High speed sampling with high-accuracy processor clock provides high resolution phase/time domain measurement even for wide Field of View (FOV) directional antennas;
- Fourier transform (frequency domain processing) of received radar signals provides signatures and dramatically increases probability of detection for non-cooperative aircraft;
- Steering of transmitting power and integration, correlation period of received reflected signals for separate antennas (directions) allows dramatically decreased ground clutter for low altitude flights;
- Open architecture, modular construction allows combination of radar sensor with Automatic Dependent Surveillance – Broadcast (ADS-B), electro-optic, acoustic sensors.

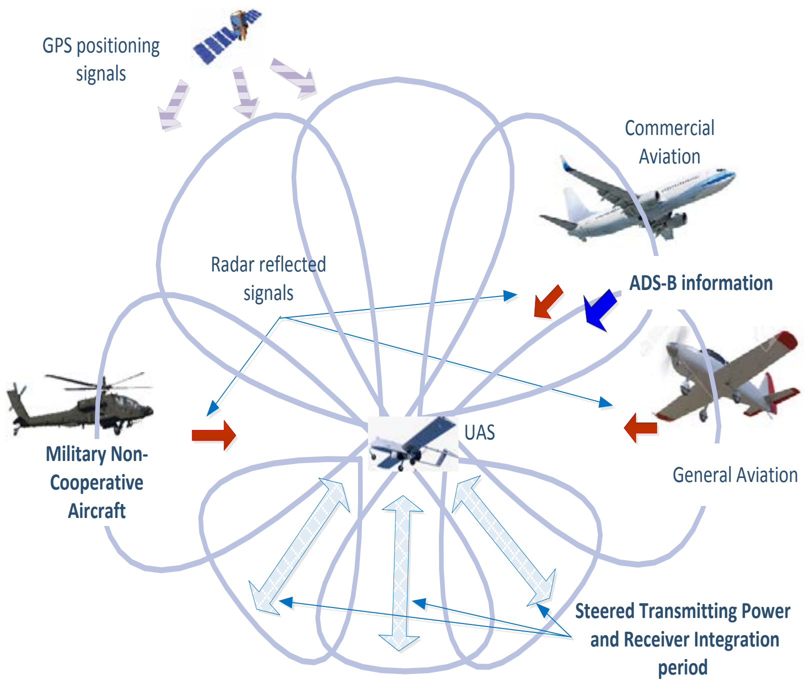


Figure 3. Concept of sense and avoid radar system based on Fly Eye antenna array. Automatic steering of transmitted power in separate beams allows dramatically decrease ground clutter for low altitude UAS.

2.3 Passive radar

Passive Fly Eye antenna array system provide entire sky all-weather momentary awareness and targeting capability. Radar with a phase antenna array can scan the entire area of observation and receive 1 target hit pulse every one second. One pulse hits the target per scan. For monopulse radar, pulses with a 1 microsecond width may be transmitted and reflected from the target every 10 microseconds. This means that monopulse radar can transmit to and receive 100,000 pulses per second from any target direction. Integration of the received 100,000 pulses will dramatically increase information about the target.

- Monopulse multi-beam method provides simultaneous high-accuracy ratio measurement for 360 degree by azimuth and elevation;
- Array of angular shifted directional antennas is not phase dependent and can be multi-band and multi-function;
- Directional antennas may be installed closely or loosely distributed over the perimeter of the carrier platform or between separate robotic carriers in swarm;
- Receiving 2-4 orders more signals than regular scanning systems provides 2-3 orders longer passive radar range;

Continuous target observation and integration of the reflected signals increases radar range and decreases minimum receivable power because of lower Minimum Detectable Signal (MDS). As result the range of detectable target R_r will approach the range of detectable transmitted power Rt in low power monopulse radar as presented in Figure 4. If range of detectable target R_r approaches range of detectable transmitted power R_t, then low power monopulse radar will be "invisible" for regular scanning radars with narrow high power beam and RF guided missiles.

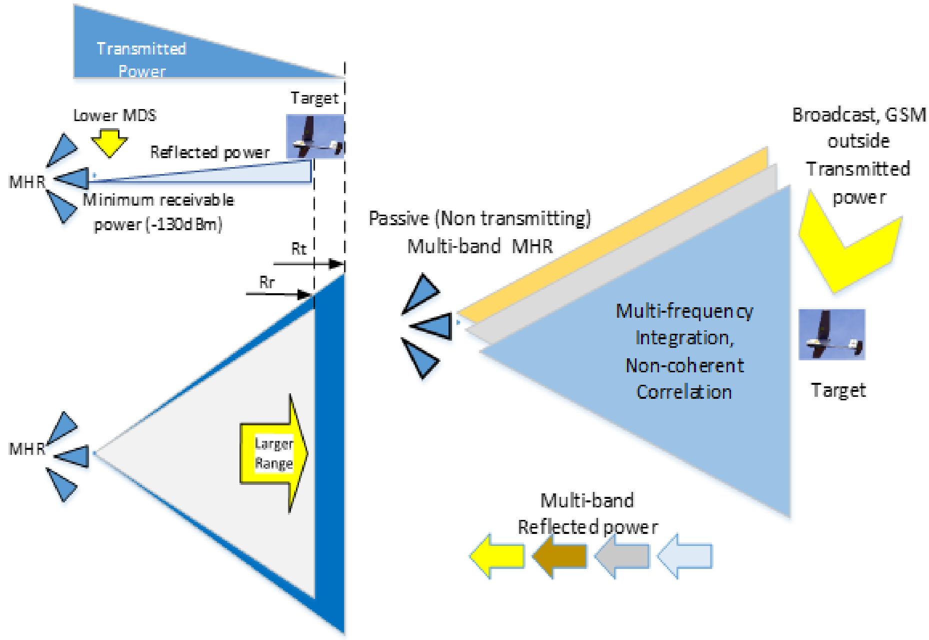


Figure 4. Monopulse radar can provide one pulse per microsecond (approx. three order faster then scanning radar). As result range of detectable target R_r will approach to range of detectable transmitted power R_t and minimum detectable signal will be lowered. Multi-frequency and SMART modulation allow for the creation of **passive (not transmitting) radar**, which receiving reflected from target outside transmitted energy of Broadcast, TV stations or Global System for Mobile Communications (GSM).

2.4 Ground penetrating radar

Tethered drone with Ground Penetrating Radar (GPR) can provide safe for human mine detection for long time if power source will be installed in car. Low frequency waves with good ground penetration allows decrease transmitter power up to hundred milliwatt for one meter depth of exploration. As result low frequency low transmitting power GPR transmitter can be positioned on small tethered drone and provide maximum targets cross-section. Resolution of digital hologram and corresponding image resolution will be determined by sampling frequency of digitizer and not depends from radar beamwidth. High speed sampling with high-accuracy processor clock will provide high resolution of images even for low frequency radar waves. Holographic digital phase/time domain processing of received signals allows to restore images of detected objects. Fourier transform (frequency domain processing) of received radar signals provides signatures and information not only about shape, but about material of buried objects.

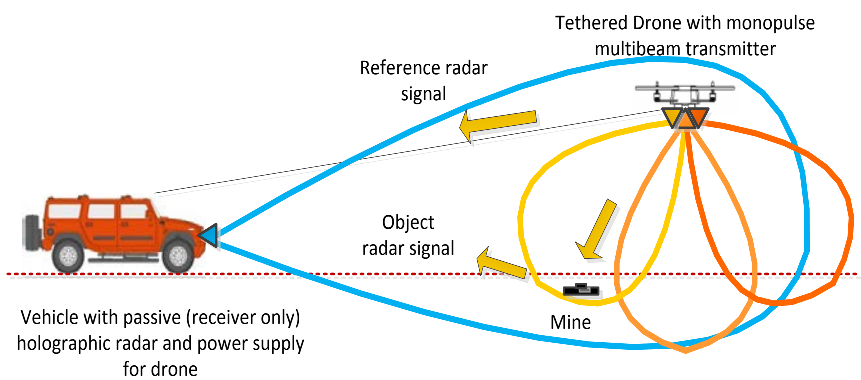


Figure 5 Ground penetrating radar positioned on tethered drone can provide safe multi-hour mine detection with high reliability because convenience closure to ground position.

2.5 Passive small projectile tracking radar

There are lot of ambient RF/microwave sources: different kinds of communication, radar, navigation and datalink transmitters, and same time lot of moving with different size and speed objects are in battlespace. How passive Doppler radar can detect small projectile in so noisy battlespace? Small arms projectile has specific limited range of velocity which is relatively constant. Doppler frequency shift for small arms projectile and limited range of ambient RF/microwave sources lay in specific narrow band and can be used for arm fire location.

Array of directional antennas in passive Doppler radar will receive direct microwave signals from the ambient sources and reflect from objects part of these microwave signals. The reflected radar signals from moving objects will consist of a Doppler frequency shift. The Doppler frequency is calculated as shown in Equation 1:

$$F_d=2V(F_t/c)\ \mathrm{Cos}\theta \qquad (1)$$

Where: F_d - Doppler frequency; V - Velocity of the target; F_t - Transmit by ambient signal source frequency; c - Speed of light (3 X 108 m/sec); θ - The angle between the object moving direction and the axis of the ambient signal source.

For GSM 1900 MHz and projectile velocity 2500-3500 ft/s, Doppler frequency band will be narrow: 9-12 KHz only. For 2500 ft/s velocity and ambient sours frequency band 1-5 GHz, Doppler frequency band will be approx. 5-25 KHz. Application of bandpass filter with narrow bandwidth (4 KHz only for one ambient source) for Doppler signals will allow dramatically increase signal/noise ratio and detect small arms fire with high probability of detection. If wavelength of microwave ambient source larger than projectile, projectile will create diffraction of microwave signals as shown in Figure 6. Low frequency narrow band Doppler frequency filter will provide incredible selectivity and will allow to detect and locate small arms fire with high probability and accuracy.

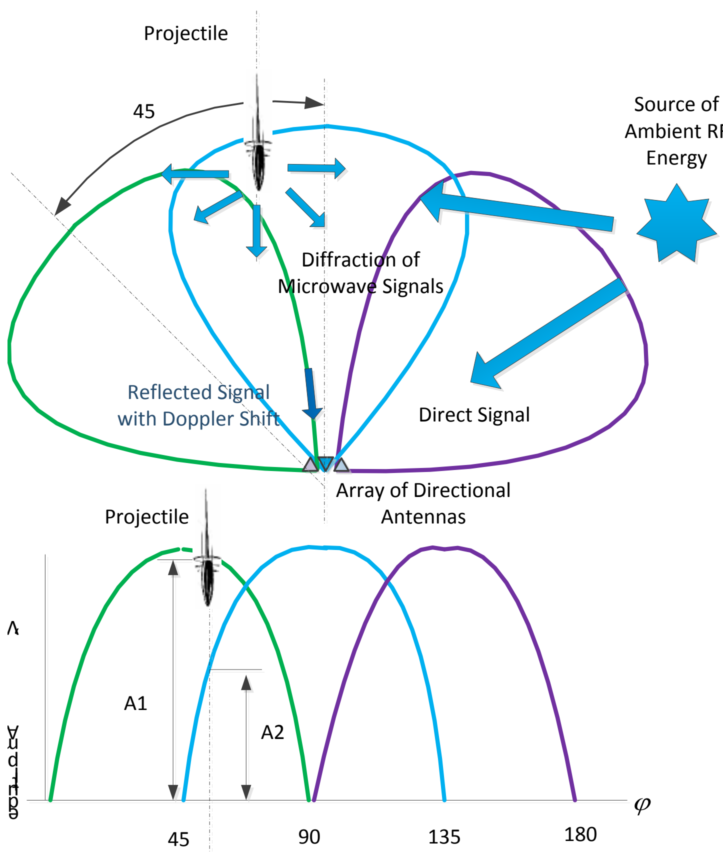


Figure 6. Detection of small projectile with passive Doppler radar. Overlap angular shifted directional antennas provides high accuracy direction to projectile in time smaller than one microsecond.

2.6 Imaging radar

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. A wide, low frequency, non-scanning beam covers the entire object providing high resolution phase measurement relative to a reference beam. No need for scanning means image acquisition times in the order of microseconds thereby minimizing movement artifact. This imaging system uses ultra-wide band antennas combined with an in-chip digitizer and processor which are linked to a laptop size processor and display. There is no need for precision optics, precision mechanical parts or expensive CCD cameras.

A key point about this imaging system is that the image resolution is much smaller than the wavelength of the electromagnetic radiation used.

- Proposed new concept of RF/microwave imaging system will provide all weather high-resolution imaging with good penetrating of a foliage and even ground capability;
- Image resolution determined by processor and sampling frequency and do not limited by diffraction;
- Non-scanning monopulse system allows dramatically increase imaging range by integration 2-3 orders more signals than regular scanning systems;

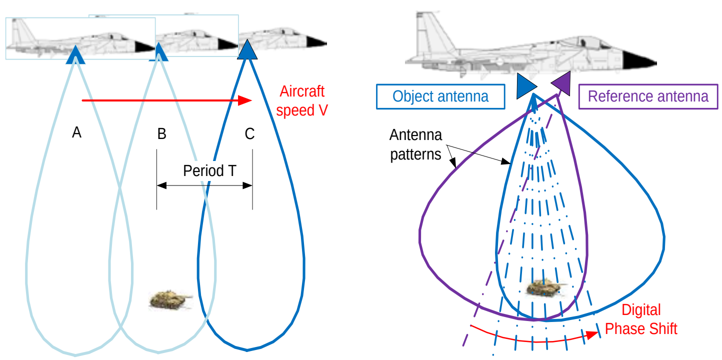


Figure 7. Synthetic Aperture Imaging Radar (SAR) required moving of narrow beam antenna relative to object with multiple expositions. Fly Eye antenna array provides all information about object with reference abeam and one only exposition.

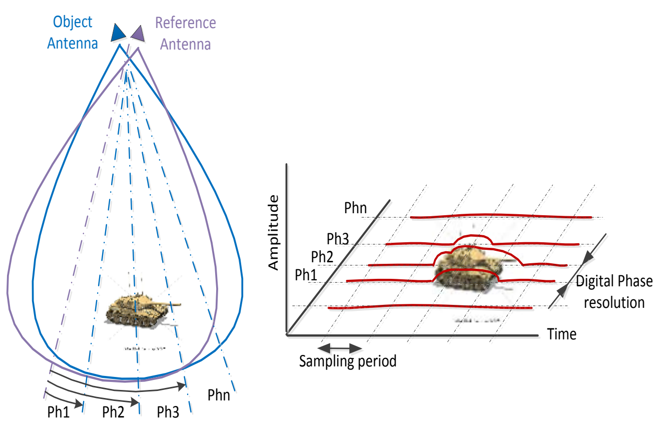


Figure 8. Reconstruction of object image with reference beam. Recording of digital hologram provides 3D information about all object.

3. IMAGE RECONSTRUCTION PRINCIPLE

Conventional low power RF/microwave systems with relatively long wavelengths are limited in their resolution by the diffraction limit (Abbe diffraction limit). They cannot image objects smaller than their wavelength. 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.

Digital hologram

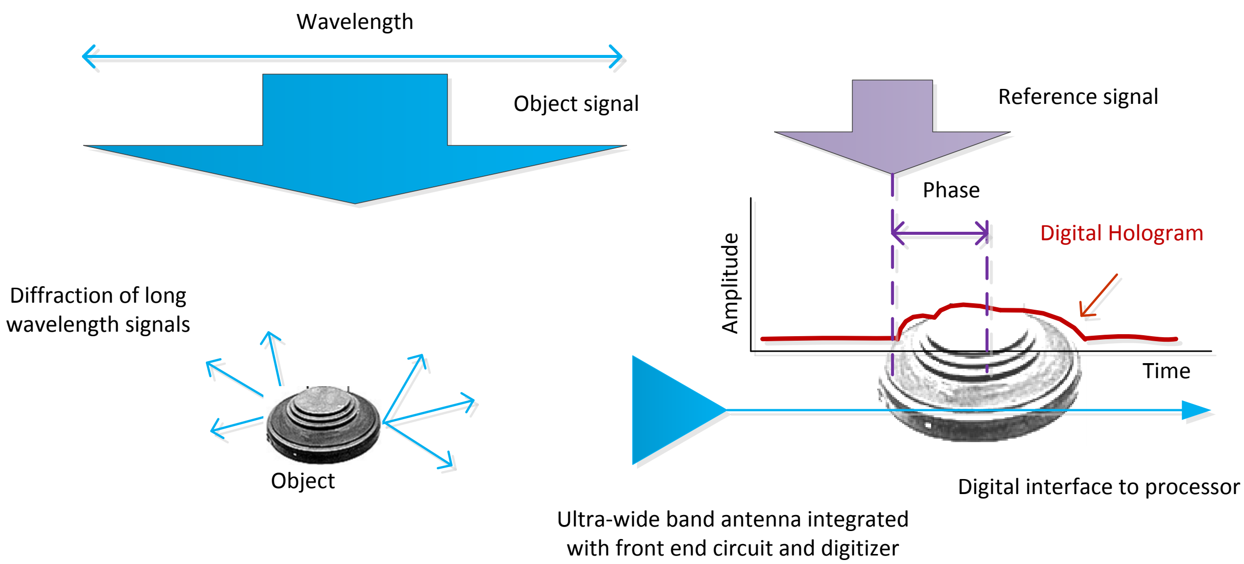


Figure 9. Real time recording of digital hologram as combination of interferograms. Each received interferogram contains amplitude and phase information, pertaining to the object, in the form of diffracted radiation within the receiver plane and can be digitally recorded by sampling as a 1D plot and interpreted as digital hologram.

Proposed in 1998, digital holographic radar, the digital equivalent of an optical hologram, provided radar image in the range/Doppler plane, range/azimuth plane, and /or range/elevation plane according to the type of radar application [9]. The unique feature of this invention is the use of two dimensional (2-D) and three dimensional (3-D) digital graphical techniques to display the reconstructed images.

The proposed radar imaging system consists of two directional antennas where one antenna can be interpreted as a reference beam if the transmitted signals are coherent. Each received interferogram contains amplitude and phase information, pertaining to the target, in the form of diffracted radiation within the receiver plane and can be digitally recorded by sampling as a 1D plot and interpreted as a digital hologram (Figure 6). Linear combinations of interferograms forming complex digital holograms provide for image reconstruction. The phase of each interferogram is shifted from one interferogram sample to the next and create the 2D hologram.

Two pairs of orthogonally positioned antennas results in a 3D hologram, consisting of phase and amplitude information of the illuminated target from several different directions. Phase shift between axis X and Y planes (Figure 7) is determined by the physical angle between antennas. Due to the difference in phase shifts between reference and reflected signals returned by multiple objects located at different depths, it is possible to achieve higher contrast for the object by switching through frequencies in the selected bandwidth.

Through Fourier transforms of the received signals, similar results are obtained by phase shifted measurements of primary signal frequency components. In the proposed imaging radar, the reference wave can be provided by direct transmitter-to-receiver connections as depicted in Figure 6 or by an antenna array.

4. DETECTION IN HIGH SCATTERED MEDIA

4.1 Advances of reference signal in high scattered media

The proposed microwave imaging system is the next step in developing the passive monopulse direction finder proposed by Stephen E. Lipsky in the 1980's [6]. The monopulse method with reference antenna provides 2-3 orders better resolution by high-accuracy time domain measurement.

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 10 and a real time digital hologram is sampled through an ultra-wideband monopulse antenna array with wide field of view capabilities.

The monopulse ultra-wideband directional antenna array is angular shifted directional antennas with overlapping antenna patterns [12-18]. 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.

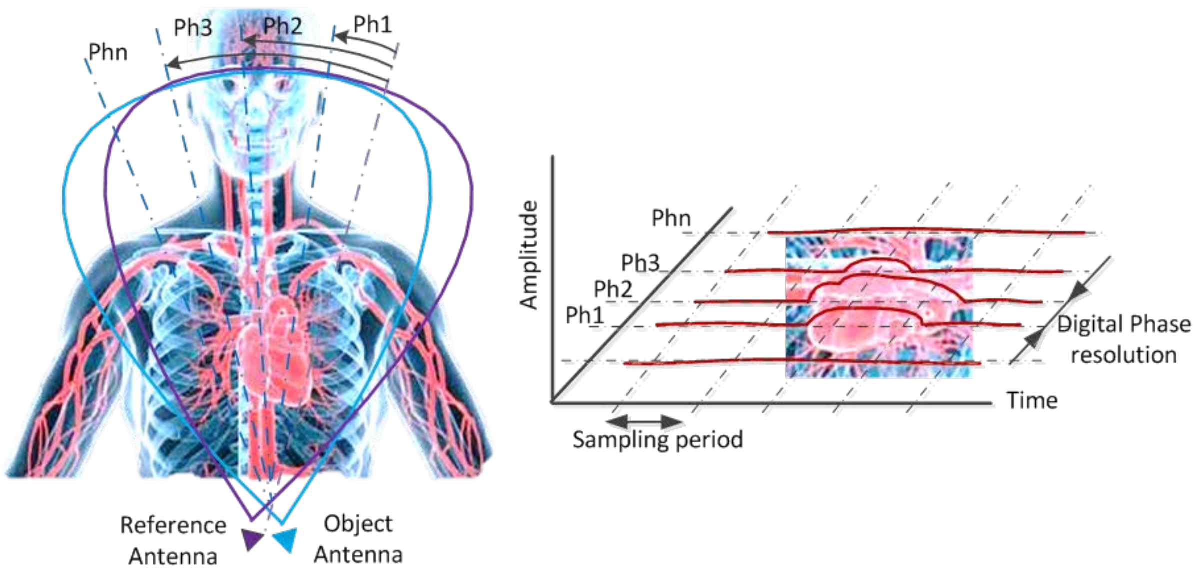


Figure 10. Application of monopulse method for radar imaging. Reconstructing the digital hologram image by processing real time recorded microwave signals in time/phase domain. Reference antenna provides high accuracy phase and amplitude information. Image is reconstructing from phase shifted interferograms. Image resolution is independent of beam width and diffraction limitation constraints, but rather determined by sampling period and digital phase resolution.

4.2 Improving of SNR by coherent integration

There are a few accuracy parameters need be take into account to determine approximate reconstructed image resolution. Range accuracy and range resolution are parameters usually using in radar systems. **Range accuracy**, δR, is related to range resolution, ΔR, as [10]:

$$\delta R \cong \frac{\Delta R}{\sqrt{2\,\mathrm{SNR}}} \quad [\mathrm{m}] \quad \text{for } \mathrm{SNR} >> 1 \tag{2}$$

Accurate range measurement is different (though related) to range resolution.

The ability to accurately extract the round-trip time of flight depends on the **range resolution**, ΔR, and on the signal-to-noise ratio, SNR.

It can be shown that range accuracy, δR, is related to bandwidth, B, and SNR as:

$$\delta R \cong \frac{c}{2\,B\,\sqrt{2\,\mathrm{SNR}}} \quad [\mathrm{m}] \tag{3}$$

For example, for SNR » 1.

Consider a radar with B = 2000 MHz and an SNR of 20 (13 dB). The achievable range resolution, ΔR, is 0.5 m and the achievable range accuracy, δR is 1 cm.

In general the uncertainty associated with any measurementis related to the **measurement resolution**. For measurement with resolution ΔM, the accuracy, δM, is:

$$\delta M \cong \frac{\Delta M}{\sqrt{2\,\mathrm{SNR}}} \quad \text{for } \mathrm{SNR} >> 1 \tag{4}$$

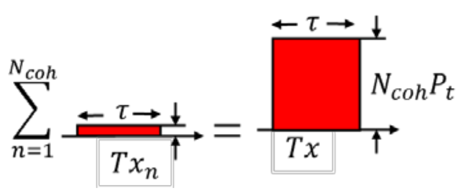
Pointing accuracy. High accuracy phase measurements provide high accuracy imaging. If antenna lobes are overlapping or closely spaced, a monopulse antenna array can produce a high degree of pointing accuracy within the beam, adding to the natural accuracy of the conical scanning system. Whereas classical conical scanning systems generate pointing accuracy on the order of 0.1°, monopulse radars generally improve this by a factor of 10, and advanced tracking radars like the AN/FPS-16 are accurate to 0.006° [11]. High resolution measurement data allows for the reconstruction of high resolution images.

By coherently adding echo signal energy from consecutive pulses weare effectively increasing the illumination energy. This may be thought of as increasing the transmitted power, P_t.

The radar transmitter has peak output power and a pulse duration τ the transmit pulse energy is: Pt ·τ .

Coherently integrating echoes from 10 pulses (N_{coh} = 10) produces an SNR equivalent to the case where P_t is 10 times greater.

Alternatively, coherent integration permits a reduction of the transmit pulse power P_t equivalent to the N_{coh} while retaining a constant SNR [10]:



(5)

Coherent integration provides significant SNR improvement. To realize the full benefits of coherent integration the underlying assumptions must be satisfied:

- Noise must be uncorrelated pulse to pulse .Signal phase varies less than 90° over integration interval;
- The second assumption limits the integration interval for cases involving object moving relative to the radar.
- Coherent integration can be used if phase variation is removed.

Processes involved include range migration and focusing.
For a 2.25-kHz PRF, N_{coh} = 100,000 or 50 dB of SNR improvement.

4.3 Advance signal processing algorithms

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 Figure11. But object and scattered media signals cannot be separated by gating.

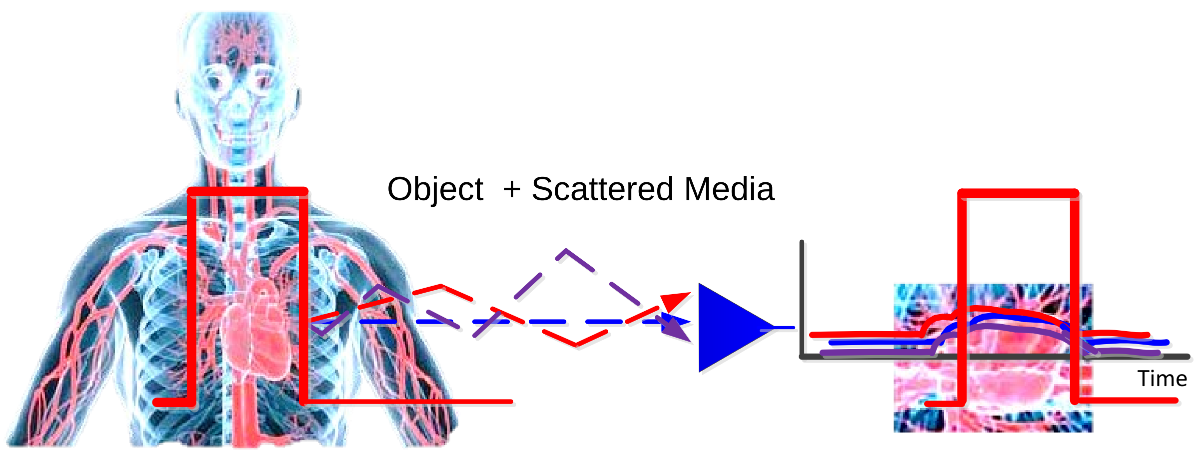


Figure 11. Gating of radar signals enhance SNR and provides better resolution in high scattered media. Gating in time domain allows to cut signals received from object area, but signal still will be scattered by media. Gating cannot separate object signals form scattered media.

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.

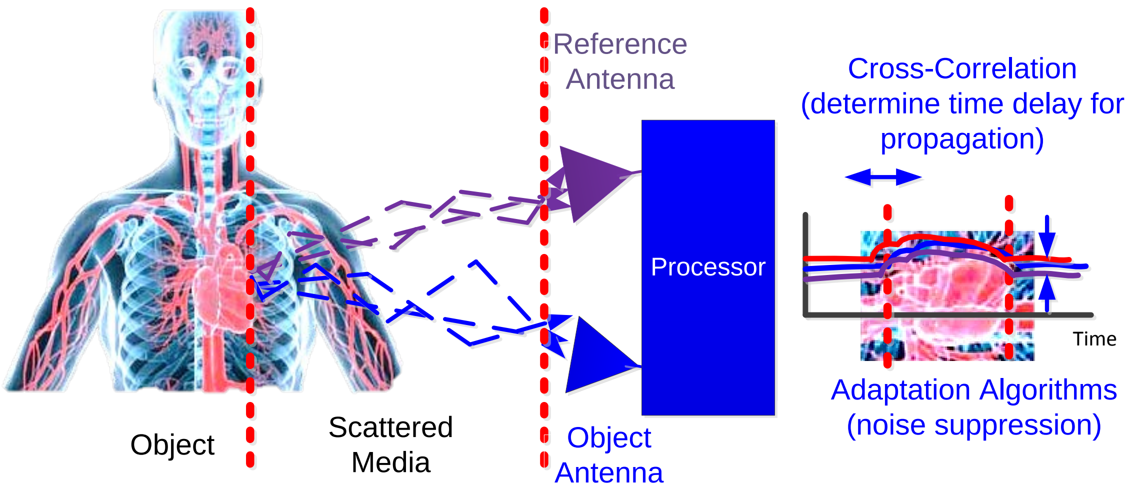


Figure 12. Additional (reference) antenna allows to separate object and scattered media signals in radar receiver. Cross-correlation and adaptation algorithms provides dramatically enhancing of image resolution.

5. TEST RESULTS

5.1 Signal processing options

Ultra-wide band Software Defined Radio (SDR) has been used for a real time recording of the diffracted waves in the time domain to create a digital hologram.

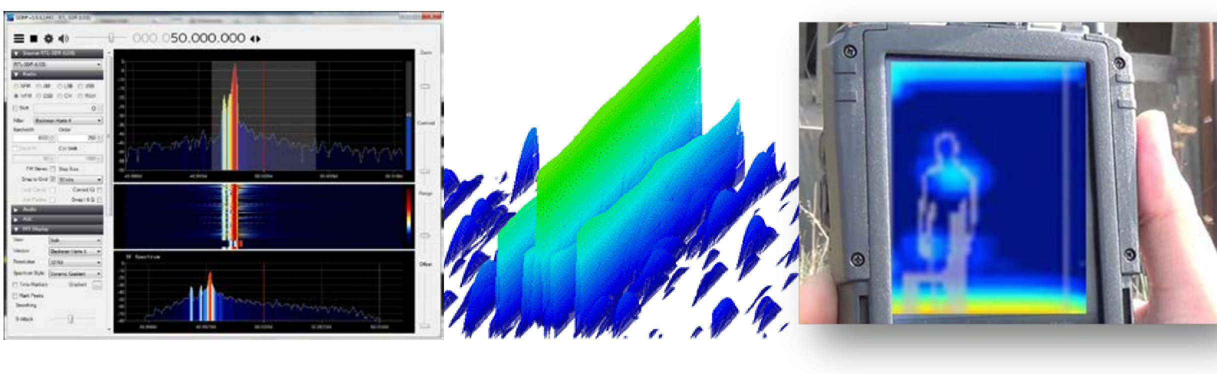


Figure 13. Frequency domain signal received with ultra-wide band SDR was transferred to three-dimensional time-frequency domain and to image of object.

Option 1. 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.

Option 2. Nature of buried objects 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 mines and IED.

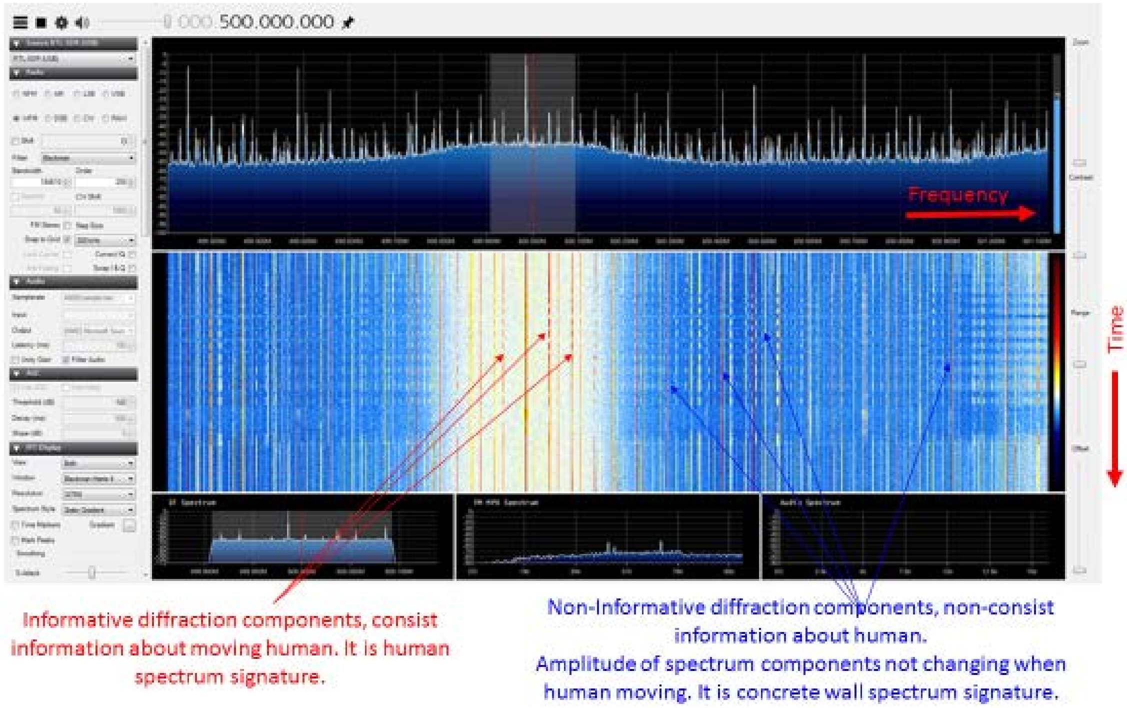


Figure 14. Spectrum of diffracted components can be separated to informative diffractive components consist information about human, and non-informative diffractive components, consist information about concrete wall.

5.2 Doppler spectrum and diffraction components spectrum

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.

Diffraction components is result of diffraction of long wavelength RF signals on small object (size of object smaller than RF wavelength). Diffraction spectrum components not depend from object speed (excluding Doppler shift).
Diffraction spectrum consists information about object material or content because long wavelength penetration inside object.
Size of array of directional antennas depends on antenna frequency, maximum transmitted power, gain, number of antennas, antenna bandwidth and can be decreased by application of high dielectric constant materials. Active directional antennas are small in size and can provide a gain of 20-30dB on each channel. Miniature ultra-wide band antennas and antenna arrays presented in Figure 15.

Digital processing of data, received from separate directional antennas will increase dynamic range, tracking accuracy and number of aircraft that can be simultaneously tracked in multiple frequency bands [13-26].

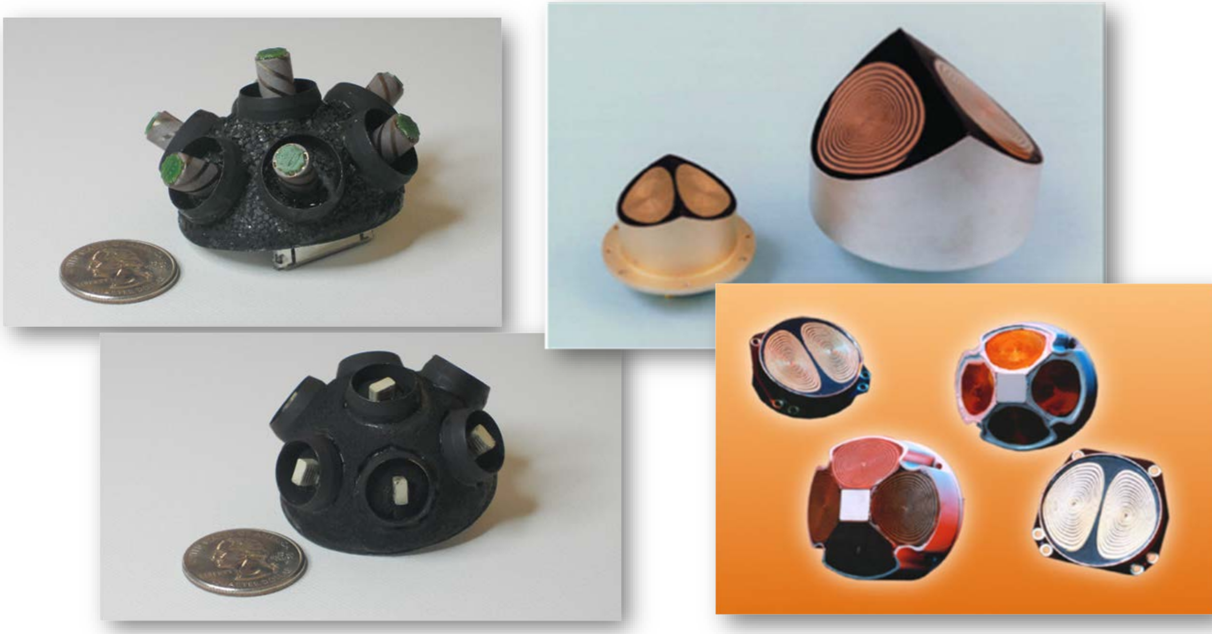


Figure 15. Fly Eye antenna array designed by PMI Inc. and antenna arrays designed by Cobham Inc.

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