Passive Radar Imaging

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ABSTRACT

Passive radar has seen a surge in interest partly driven by technology that is beginning to mature and partly driven by increasing pressure on the use of the electromagnetic spectrum. To date most research has been concerned with systems, emitters of opportunity, detection, localization and tracking performance. Many further applications would result if high-resolution imaging can form part of the armoury of passive radar. In this paper we begin to examine the potential for imaging and also introduce a novel narrow band technique, consistent with exploitation of typical illuminators of opportunity.

1.0 INTRODUCTION

A major and continuing theme of radar development has been the improvement of spatial resolution, be it to enhance detection through reduction of competing clutter or the generation of full two-dimensional imaging for scene and object recognition. Indeed, two dimensional radar imaging has become a workhorse of the surveillance and remote sensing communities. In particular, Synthetic Aperture Radar (SAR) is now a mature technology and is widely used in operational systems. SAR uses wideband waveforms to obtain high range resolution and aperture synthesis via platform motion to obtain high cross-range resolution. Inverse Synthetic Aperture Radar (ISAR) provides a natural counterpart to SAR for imaging discrete objects based upon their own movement rather than that of the illuminating radar system. Tomography provides a third approach for generating high resolution in two-dimensions [1]. However, in general, it requires more elaborate measurements and has not had the popular success enjoyed by SAR and ISAR.

Passive radar, although not truly a new technique, is currently receiving considerable attention in the research literature as, effectively, a "bandwidth free" RF sensor highly compatible with operation in an increasingly congested electromagnetic environment. Continued improvements in digital technology are making passive radar an increasingly competitive alternative or supplement to existing active radar systems. However, most passive radar research (and commercial systems) have concentrated on detection, location and tracking with little being reported on high resolution and imaging. Nevertheless, passive radar imaging is extremely attractive for many applications. Indeed, if two-dimensional imagery can be generated on a relatively routine basis then passive radar has immense potential to become a low cost alternative or supplement to a range of remote sensing and surveillance functions.

In this paper we examine the environment and subsequently begin to explore the options for imaging using a passive radar construct. In addition we introduce a new imaging technique, termed "Doppler Imaging", which may sit alongside more the traditional methods and play a role as part of a portfolio approach enabling passive radar imaging.

2.0 THE RADAR ENVIRONMENT FOR PASSIVE IMAGING

Figure 1 shows a schematic representation of a passive radar system with a single ground based receiver and two ground based transmitters. More generally there may be more transmitters and receivers and the receiver could be ground based and/or airborne.

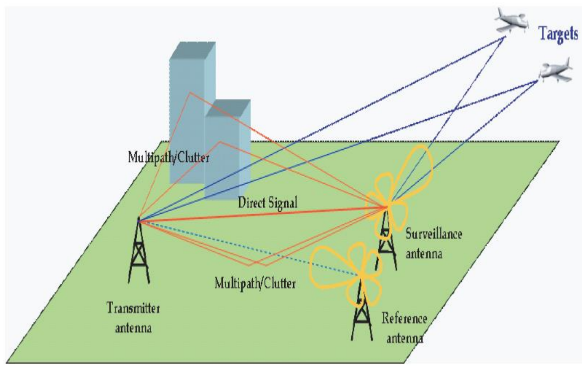

Fig1. The Passive radar Concept

The key components of passive radar are (i) transmitters of opportunity that individually emit multiple signals of differing design, (ii) a variety of power aperture products but with most signals being emitted on a continuous basis and over broad areas, (iii) multiple transmitters of opportunity that are spatially distributed, (iv) signals that in general are relatively narrow band (most typically between 50kHz to 20MHz), (v) signals that are broad in azimuth coverage, often being omnidirectional whilst simultaneously preferentially illuminate the surface of the earth, (vi a mixture of analogue and digital modulation. These are the characteristics that will ultimately determine imaging parameters as well as detection performance.

Thus overall, passive radar operates within a complex, diverse, but spectrally incomplete and varying electromagnetic environment. Consequently the ways in which imagery can be formed requires a careful understanding of this environment to establish performance limits of useful passive imaging. Further, imaging performance is likely to be a function of geometry and changes in geometry over time due to the receiver and/or the target being in motion.

Figure 2 shows an overview “spectral map” of the area around the Ohio State University, Columbus Ohio. It has been generated using a wide band log periodic antenna connected, via a simple receiver to a digitizing oscilloscope having a 2.5 $GSas^{-1}$ sampling rate. The measurements have a frequency resolution of 1MHz and the angular resolution of the antenna is approximately 70°. However, as the measurements were performed in an indoor environment, the voracity of the angle dimension is poor and is only reproduced in two dimensions. The plot shows all measured emissions from DC to 2.5GHz (in two portions: one form DC to 1 GHz and the other from 1 GHz to 2.5 GHz). It provides a coarse indication of the occupancy within this part of the electromagnetic spectrum.

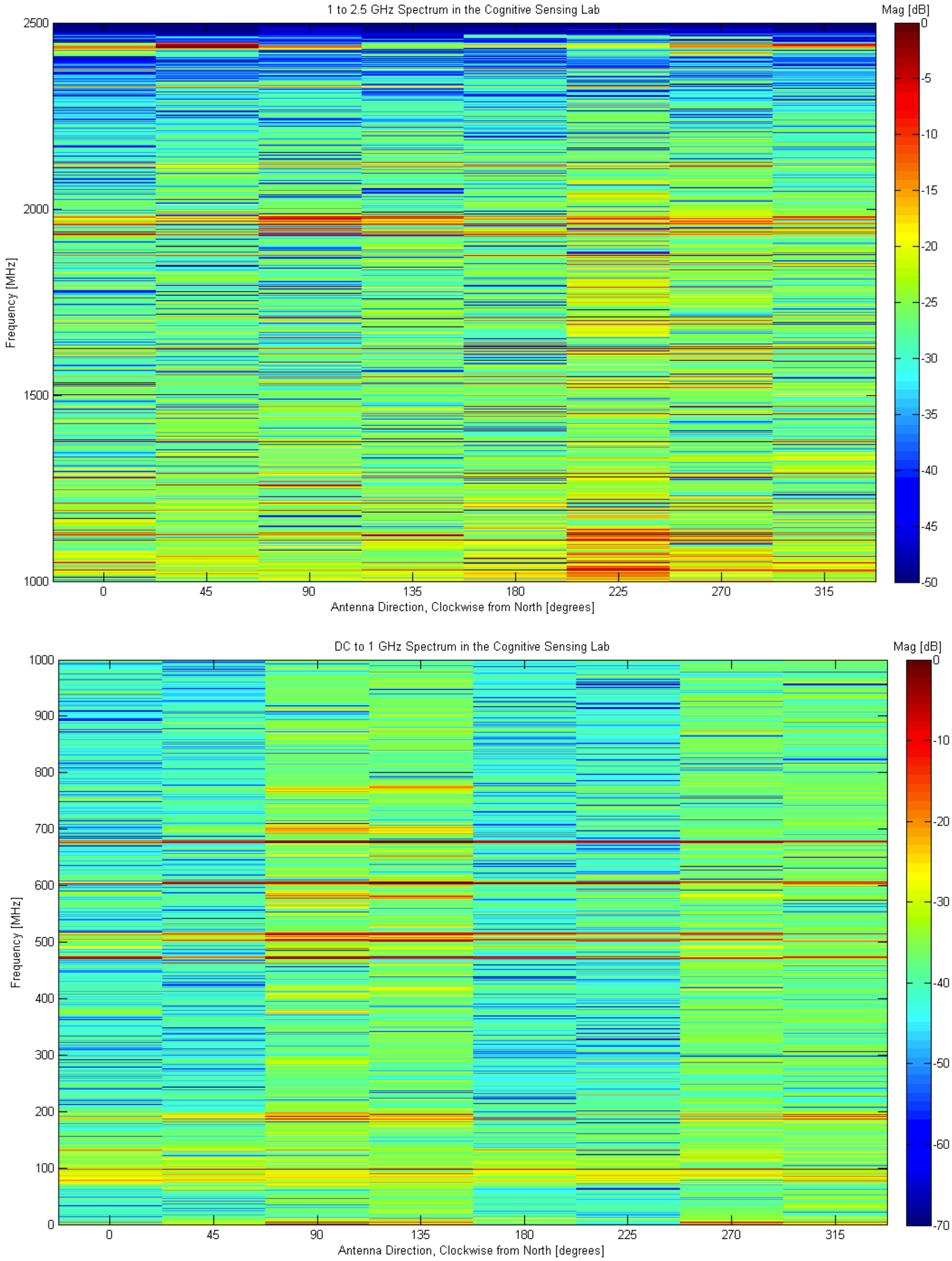

Figure 2. Spectral map of the Columbus area. The upper portion shows the spectrum from 1 to 2.5 GHz and the lower portion the spectrum from 0 to 1Ghz.

Fig 2 shows that most of the higher power signals are at 1 GHz or below with some GSM band signals at just below 2 GHz and Wi-Fi at 2.4 GHz. The signals below 1 GHz consist of digital TV transmissions in the region of 450 to 700 MHz and a mixture of analogue and digital VHF FM signals spanning 85 to 105 MHz. Figures 3 and 4 show the DTV and VHF bands in more detail. From both figures it is evident that the bandwidth of individual signals within the 2.5 GHz span is variable, as are the band free parts of the spectrum. The VHF band is unusual in the US, as it contains both analogue transmissions as well as a relatively new hybrid digital "HD Radio" waveform. These are typically transmitted in a configuration that is near contiguous in the frequency domain as shown in Figure 5 making for a waveform that can be thought of as a hybrid analogue and digital mix. The bandwidths at VHF vary from 50 kHz to nearly 400 kHz whilst the DTV signals have a much wider and fixed bandwidth of 6 MHz.

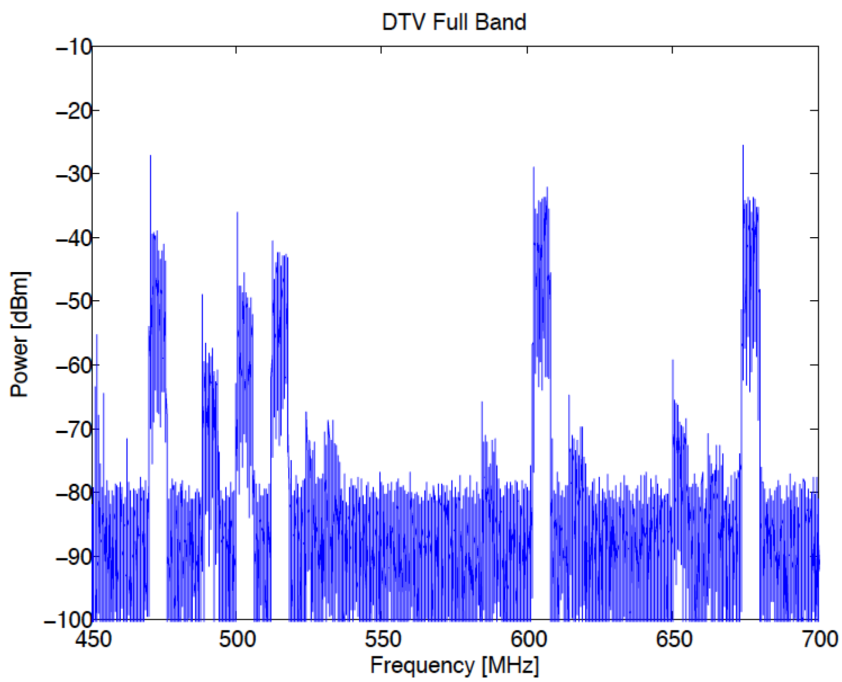

Figure 3. Digital TV signal emissions in the Columbus area

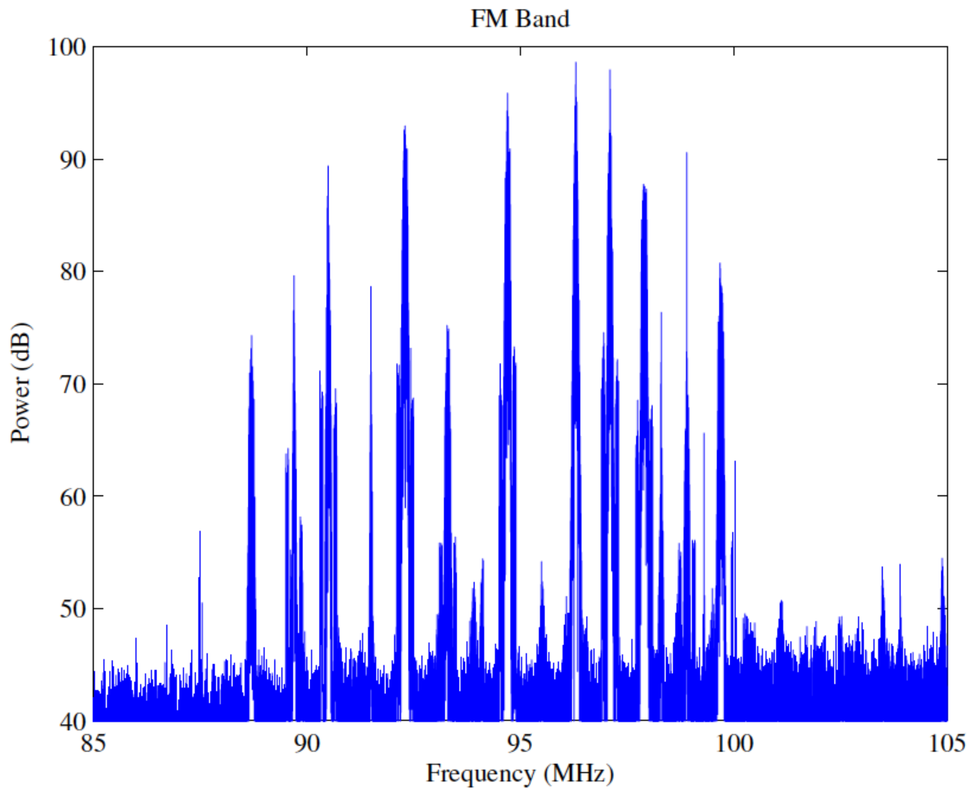

Figure 4. Analogue and digital VHF transmission in the Columbus area

These figures are indicative that, merely in terms of spectral occupancy, the electromagnetic environment is one of complexity with individual transmissions possessing vastly different properties. They also highlight that, in frequency, they spectrum has only partial occupancy with the parts being of limited and varying bandwidth. Whilst these are measurements from in the Columbus area, the degree of diversity present will not be untypical of measurements made within North America. In addition, the spatial location of individual transmitters has to be included as part of the baseline understanding of the electromagnetic environment. Together with transmit power and coverage these will determine maximum operating ranges as well as the range of options for image formation and resulting image quality parameters. Figure 6 shows the locations of the high-powered transmitters in the Columbus area. The transmitters are both numerous and broadly distributed with a greater number of VHF transmitters and DTV and a non-uniform distribution of location that reflects a combination of population density and line of site coverage. It is by mapping and characterizing the local electromagnetic environment in this way that the options for image generation can start to be properly examined.

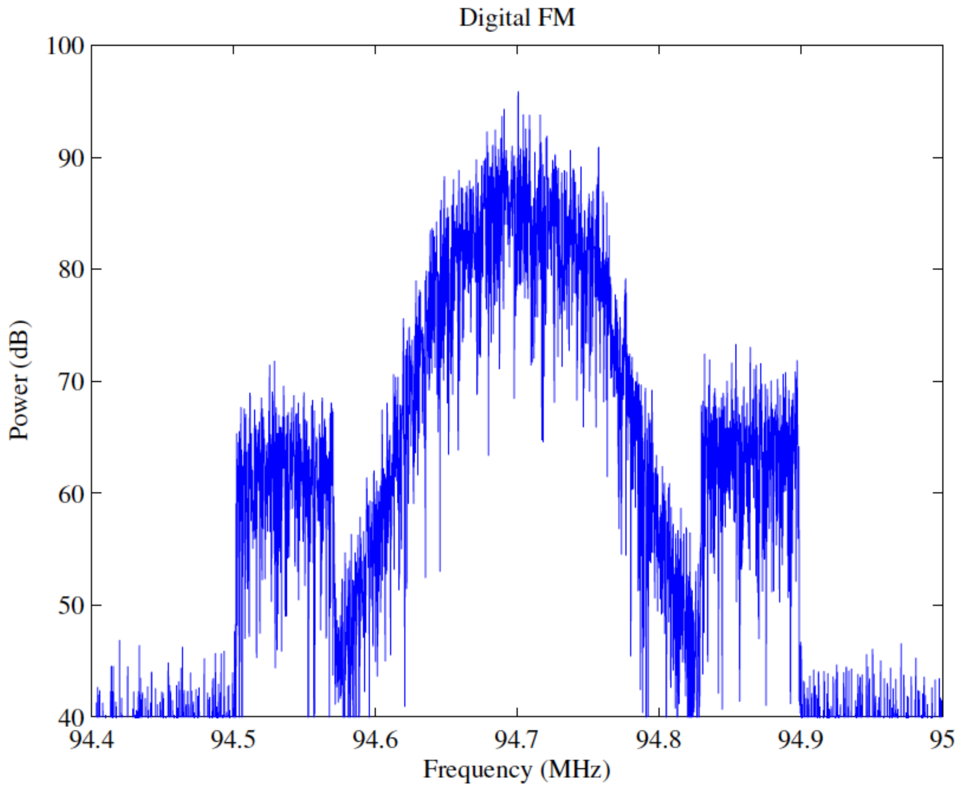

Figure 5. An example of an analogue (central portion) and digital (outer portion on left and right) VHF band waveforms from the Columbus area

(a) FM radio transmitters (b) Digital TV transmitters

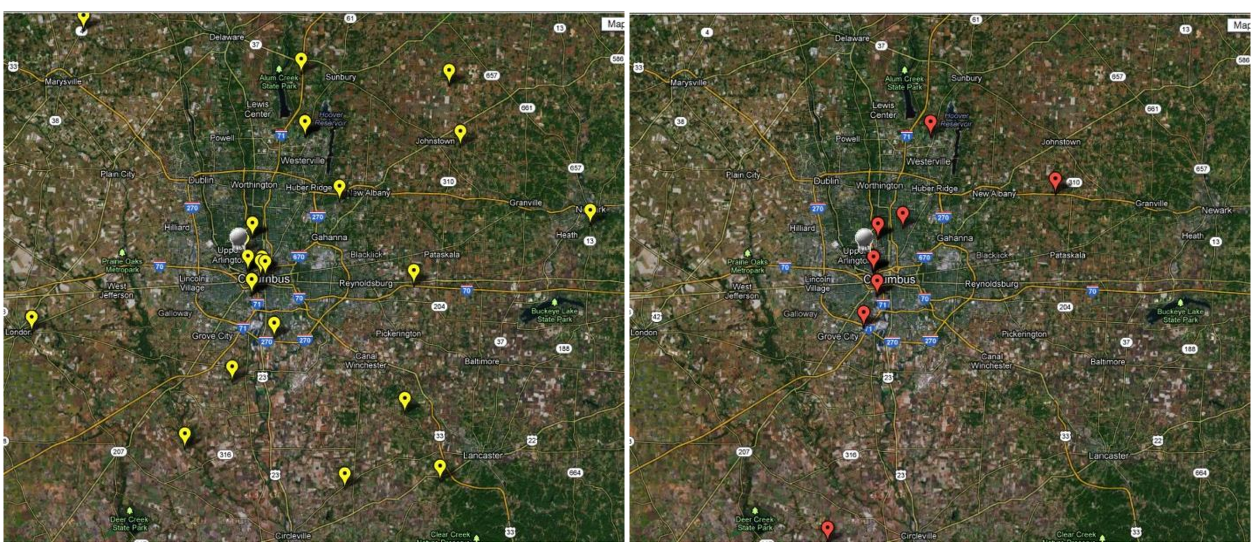

Figure 6. The locations of transmitters in the Columbus area

3.0 IMAGING APPROACHES

In many ways passive radar is no different to any other form of radar system in that it operates using the principle of echolocation. The bistatic or more generally the multistatic nature of the geometry complicates matters slightly, but this is of a deterministic nature and can be catered for. Further, the design and specification of the transmissions is not under the control of the radar designer; although this might seem a distinct disadvantage it does have some favourable aspects and is perhaps is better thought of a system design constraint. For example most transmitter sites will transmit signals at multiple frequencies that both enhances sensitivity and provides built in diversity.

Radar imaging, in particular, can be formulated in a variety of different ways. For example, wide bandwidths can be used to acquire line of site resolution and aperture synthesis, resolution across line of site. The requirement for wide bandwidths is problematical for passive radar as signal bandwidth is pre-determined. For example, Fig 5 shows a 3 dB bandwidth of the order of 50 kHz for both the analogue and digital components that equates to a poor range resolution of 3 km. Even using a hybrid combination across both the analogue and digital portions of the signal still only lead to a range resolution of nearly 1 km. Inspection of Fig. 4 shows that the VHF signals occupy a total bandwidth of approximately 10 MHz which improve matters considerably but still only yields a best range resolution of 15 m, not high by the standards of today. There are two additional aspects of these signals that have to be taken into account. In passive radar, range resolution is both a function of bandwidth and geometry. The spatial distribution of transmitters will also determine the range resolution both due to the bistatic geometry but also due to the different projection of resolution for different transmitters. Further, the sparse nature of the spectrum at VHF means that ambiguities are likely to result and have to be catered for. Things seems a little more optimistic in the digital TV bands where Fig. 3 shows that there is a reasonably dense cluster of signals from 470 MHz to 520 MHz which might be concatenated to enable a best range resolution of 3 m, approaching a more promising regime. Super resolution may still not enable the full band range to be used and this is an area of on going research [2].

Cross range resolution may be obtained using SAR and/or ISAR techniques. This might be used either to form one (e.g. a cross-range profile) or two-dimensional imagery. SAR and ISAR are mature technologies that are routinely used to form two-dimensional images of the ground or of moving objects and both utilize relative motion between the sensor and the object being imaged to synthesize an aperture that provides the basis for enhanced resolution. Thus we might consider segmenting imaging into two different categories. In the first we have a static ground based receiver and consequently seek to exploit target motion and in the second we have a receiver on a moving platform and it is the platform motion that synthesizes the aperture. Naturally the latter introduces further system complexity but also allows additional degrees of freedom to be exploited. There is, of course, a third hybrid in which both target and receiver are in motion.

The disadvantage of aperture synthesis in combination with wideband waveforms is the incompatibility with the desired waveform parameters with those typically used by transmitters of opportunity. An alternative is the employment of tomography. In tomography an image is constructed using a multiplicity of angular samples that, combined with back projection, allow an objects reflectivity function to be re-constructed. Tomography is a much less mature topic and its take-up has been relatively sporadic. However, in passive radar an object traversing a group of spatially diverse transmitters of opportunity and a receiver (see Fig. 1) will generate a multiplicity of angular measurements and hence tomography may prove to be a component part of passive radar imaging. A new alternative and complimentary approach is to use Doppler imaging [3]. This concept is briefly introduced in the next section and, as will be seen, has a number of characteristics that make it a potentially attractive technique for passive radar imaging. In this way all the above imaging techniques can be collectively utilized to generate imagery in a way that is optimized according to the prevailing electromagnetic and geometrical environment.

4.0 DOPPLER IMAGING

Doppler imaging was first reported by Roulston [4] and more recently Borden [5] and Yarmen [6] have provided a mathematical foundation for the technique. Here, we introduce the concept in a form more applicable to passive radar imaging and show that it can be used as part of aperture synthesis in a complementary manner that adds resolution in range.

Fig. 7 shows a simplified schematic diagram of an aircraft synthesizing, in swath mapping mode, an aperture as it "drags" its side-looking real beam past two targets separated in range. The synthetic aperture extends for the duration over which the target remains in the beam.

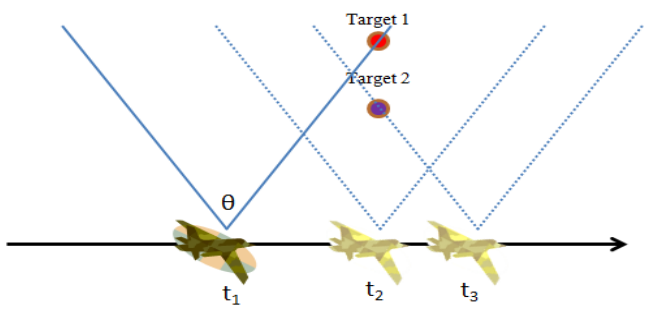

Figure 7. Conventional aperture synthesis

Because the beamwidth determines the maximum Doppler shift, all targets span an equal Doppler shift upon entering/exiting the beam. However, for the target at the nearer range the illumination period is shorter. Thus the time duration of illumination changes and the Doppler slope changes as shown in Fig. 8. This equates to a time dilation of the linear FM used to synthesise an aperture. The degree of dilation is a function of range (all other parameters being fixed) and hence provides a basis for resolving in range.

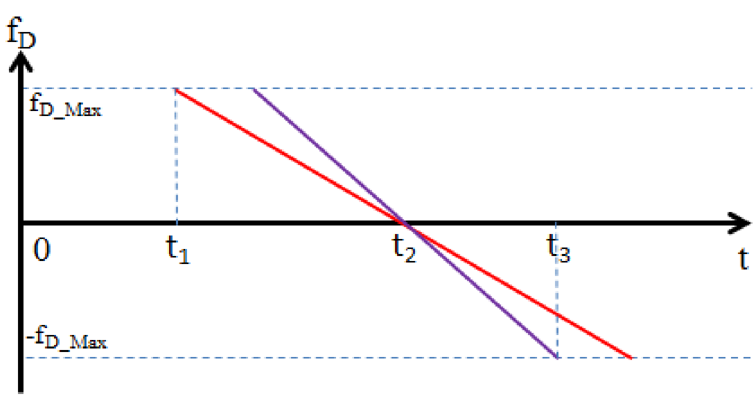

Figure 8. Time dilation of the Doppler bandwidth for two targets separated in down range

I.e. the difference in the frequency-time slope is what permits resolution of the two targets in range. However, note, this is within the formation of a single synthetic aperture, which is also used to acquire resolution in cross-range. In this way two-dimensional imagery can be formed.

We restrict the geometry to that of the x-y plane, although the following formulae can be readily extended to three dimensions and of course to a bistatic configuration. Assume a radar traverses a path along the x-axis, in the positive $\hat{\boldsymbol{x}}$ direction with velocity v. This will be denoted $\boldsymbol{p}(t) = (vt, 0)$. The real beam, of beamwidth θ, shall point in the $\hat{\boldsymbol{y}}$ direction. A target at $\boldsymbol{r} = (0, y)$ will therefore lie within the beam pattern in the interval

$$-\frac{y}{v}\tan\left(\frac{\theta}{2}\right) < t < \frac{y}{v}\tan\left(\frac{\theta}{2}\right) \qquad (1)$$

It is clear from (1) that the duration in which the target is illuminated is a linear function that increases with down range position. The limits of the Doppler spread can be found using the following expression and setting ϕ equal to $\pm\theta/2$

$$f_D = \frac{2v}{\lambda} sin(\phi) \qquad (2)$$

Where ϕ is measured from the perpendicular direction to the radar's direction of travel. The signal must be sampled at a PRF greater than twice the max Doppler, to obey Nyquist. Equation (2) also demonstrates that targets entering or exiting the beam will have equal Doppler shifts regardless of their down range position, since their angle ϕ is identical. A set of filters, matched to each down range position, y, can be constructed as:

$$m_y(t) = e^{-j2k|\boldsymbol{r}-\boldsymbol{p}(t)|} \qquad (3)$$

Where $k = 2\pi/\lambda$, the wavenumber. The length of each filter will be restricted to the time that a point at range y remains in the beam, dictated by (1). The reflectivity function of the scene is constructed by correlation of the matched filters with the received signal, $s(t)$:

$$\Psi(x, y) = \int_{t=a}^{b} s(t) m_y^*\left(t - \frac{x}{v}\right) \qquad (4)$$

where: $\Psi(x, y)$ is the echo response from a patch centered at x,y on the ground.

$s(t)$ is the received signal over the synthetic aperture time

a is the time at which point (x, y) enters the beam

b is the time at which point (x, y) exits the beam

Thus the time-varying Doppler is integrated from a single location on the ground in both range and cross-range thus forming a single pixel. By varying the filter m_y and correlating against $s(t)$, a line of pixels in cross range can be generated. Subsequently, by concatenating multiple, sequential synthetic apertures over a single flight trajectory, a full two-dimensional image may be formed. A simulation has been constructed to investigate the imaging performance using a variety of illuminations and bistatic geometries. Figure 9. Shows an example image in which two corner reflectors have been illuminated with a simulated DTV signal centred at an illumination frequency of 6oo MHz and a signal bandwidth of 6 MHz. The bistatic geometry is "over the shoulder" and the total angle over which data is collected spans plus and minus 22.5^0. The bandwidth of 6 MHz nominally results in a best range resolution of 15m. Figure 9. shows the two targets being clearly resolved when separated by only 10m, hence demonstrating the improvement in passive radar image resolution.

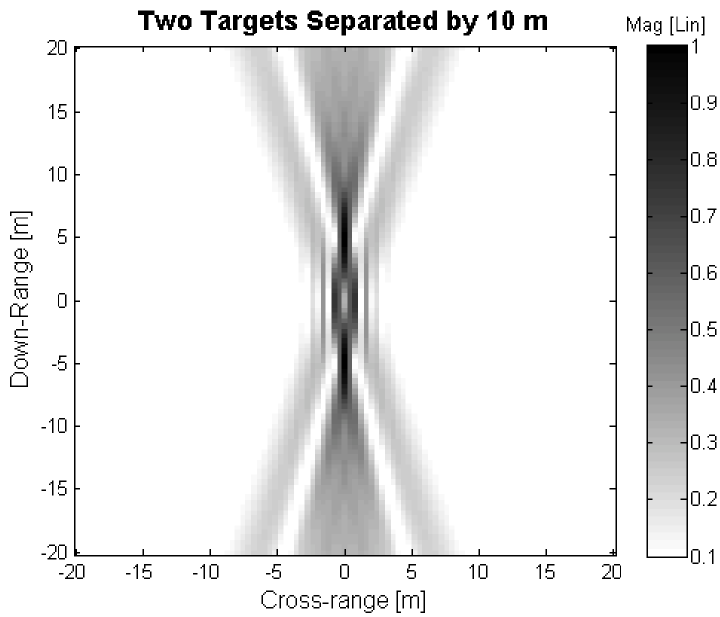

Figure 9. An image of two corner reflectors generated using the Doppler technique.

5.0 DOPPLER IMAGING RESOLUTION LIMITS

The resolving capability of the Doppler technique can be analysed using a Fourier domain representation. This approach can be used to gain insight and provide a basis for predicting limits on forming the point spread function, when given a predetermined frequency and flight path. Here we consider the monostatic or monostatic-like case that provides a measure of the best resolution achievable.

Each narrowband measurement of the scene can be considered as representing a single sample, in k-space, at a radius $R = 2/\lambda$, and angle ϕ as determined by the position of the sensor [7]. A full swath mapping collection will therefore sample an arc in Fourier space that spans the real beamwidth of the antenna, θ_{BW}. This is illustrated in Fig. 9 where the span of this arc in the ΔX and ΔY directions is inversely proportional to the resolution in each direction [8]. The span in the frequency domain can be found through simple geometry and leads to equation (5) and (6).

$$\Delta X = \frac{4}{\lambda} cos\left(\frac{\theta_{BW}}{2}\right) \qquad (5)$$

$$\Delta Y = \frac{2}{\lambda} \sin\left(\frac{\theta_{BW}}{2}\right) \qquad (6)$$

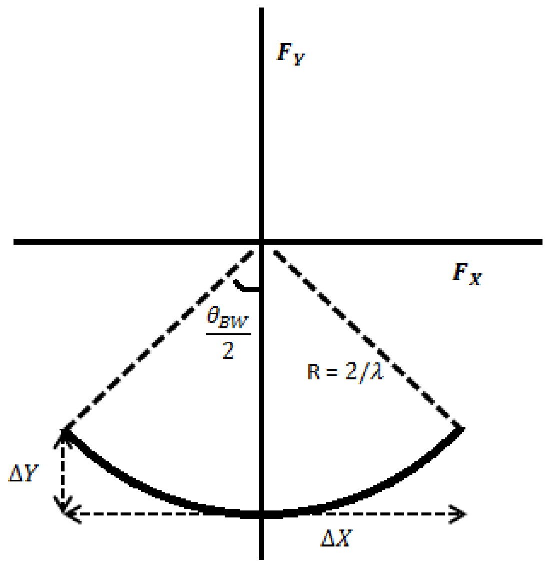

Figure 10. Fourier representation of Doppler imaging

By inverting the frequency domain spans, a reasonable approximation to the cross range and down range resolutions can be found. Denoting the down and cross range resolutions as δ_r and δ_{cr}, respectively gives $\delta_r \cong \frac{1}{\Delta Y}$ and $\delta_{cr} \cong \frac{1}{\Delta X}$ for the form of representation shown in Fig 10. The cross range resolution specifies the null-to-null width, while the down range resolution is that of the -4 dB Rayleigh resolution:

$$\delta_r \cong \frac{\lambda}{2}\csc\left(\frac{\theta_{BW}}{2}\right) \quad (7)$$

$$\delta_{cr} \cong \frac{\lambda}{4}\sec\left(\frac{\theta_{BW}}{2}\right) \quad (8)$$

It should be noted that this frequency domain analysis requires far field measurements so that the wavefronts have minimal curvature within the scene. This restriction ensures that phase errors are minimal and reconstruction of the target is accurate. Although near field measurements may slightly change the structure of the sidelobes, the resolving capability between adjacent scatterers does not vary significantly at closer ranges. Equations (5) and (6) enable the down and cross range resolutions to be computed as a function of beamwidth and carrier frequency. It is clear that the broader the beam (or angle over which an area/object is imaged) the higher the resolution in both image dimensions. Thus for a VHF transmission at 100 MHz and a desired range resolution of 3m, θ_{BW} equals 41^0 and for a DTV transmission at 500 MHz, θ_{BW} equals 63^0. These angular values are substantial but quite consistent with the omni-directional transmissions and broad receive beams typically available for passive radar. At an stand-off range of 10 km this implies an aperture length of 3.74 km for the VHF case and over 6 km for the DTV case and aperture synthesis times of up to 60 seconds may be required depending on platform velocity. Whilst demanding these are not beyond the state of the art for aperture synthesis and of course are only “spot” performance points. The passive nature of the system may well allow for shorter range imaging thus easing the burden of generating high-resolution imagery.

6.0 SUMMARY AND CONCLUSIONS

In this paper we have examined the spectral environment local to the Ohio State University area together with options for generating high resolution two-dimensional imagery. In addition a new, Doppler based, form of imaging has been introduced. Thus together with better known techniques such as SAR, ISAR tomography and hybrid combining some or all of these a route to establishing imaging performance can be found. This will be a function of the local electromagnetic environment as well as a time dependent geometry determined by both target and receiver locations. Further research is required examining the combination of waveform and resolution techniques in order to ultimately compute image performance limits.

Acknowledgment

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