Headline: **Security Screening flat panel passive millimetre wave imagers**

Summary:
Technology developments in digital beam-forming passive millimetre wave imagers are discussed together with their potential to deliver low profile, light weight sensors that could change the future of personnel security screening and all weather flying.

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Introduction

Passive millimetre wave (PMMW) imaging is the ideal dual use technology. The transparency of clothing and atmospheric obscurants in the millimetre band offers the potential for new security screening equipment, effective in detecting both metal and non-metallic threats, such as plastic and ceramic weapons, and for providing all weather imaging capabilities for air vehicles. The millimetre wave band extends from ~30 GHz to ~300 GHz and a wide range of prototype imagers have emerged in this band over the past 10 years. However none of these have dominated the market due to the high cost of the technology, the poor sensitivity and image resolution, and the large physical volume of lenses, mirrors and mechanical scanners. Furthermore, with the small number of users of this spectral band, the cost of this technology falling in the near future in unlikely.

Aperture synthesis

Falling costs and rising performances of microwave communication receivers and high speed digital signal processors offer an opportunity to break the deadlock in passive imaging technology by operating at frequencies below 40 GHz, through the implementation of aperture synthesis techniques[1]. Aperture synthesis is a technique whereby electric fields are sampled over an aperture and then processed electronically into an image. Dispensing with focussing lenses, mirrors and scanners can reduce the imager volume by orders of magnitude, as illustrated in Figure 1, whereby the PMMW imager is reduced to having essentially only planar dimensions. Interests in the technique developed initially in the 1940's, when large collection apertures were required to create radio astronomy images at tens of MHz, requiring many hours of signal integration[2]. Since then, the technique has dominated radio astronomy and more powerful technology has enabled greater numbers of channels, better image resolution, higher frequencies and shorter integration times. Furthermore, digital technology is now offering much greater versatility to the technique. However, until recently the power of the electronic technology to build a real-time PMMW imager using this technique was unavailable.

Aperture synthesis for PMMW imaging

The aperture synthesis technique involves distributing an array of antennas and receivers over an aperture and correlating electric fields at each of these locations with the field at every other location. This is done at a rate of twice the radio frequency bandwidth (satisfying the Nyquist criterion) and the results are accumulated for an integration time. Thus, for an array of n antennas distributed over an aperture, there are $n(n-1)/2$ correlations, forming a two dimensional spatial function. In classical aperture synthesis, the far field image is generated by taking the Fourier transform of the accumulated correlation function. In near field PMMW imaging the transform is more general and described by a matrix multiplication, whereby a calibration matrix is evaluated by sweeping a noise source in front of the imager. For security screening, the technique enables a number of image planes to be created simultaneously. This means all objects, regardless of their position in front of the imager will be in focus. This is effectively voxel imaging, enabling a two dimensional perspective image of the subject to be created from any direction, by collapsing one dimension of the voxel image. This offers a big advantage over conventional quasi-optical imaging, where the depth of field, at typically 5cm, requires subjects to remain motionless for several seconds during image acquisition. The closeness of the subjects to the imager also means they can be imaged with a spatial resolution sufficient for security screening, typically ~1 cm, at low frequencies (<40 GHz), significantly minimising hardware costs. Furthermore, a moving subject can be imaged without blurring, as the electronic beam-forming process takes place on a time scale faster than physical movement, greatly improving the throughput of the security screening portal.

Imager sensitivity

The radiometric sensitivity of passive millimetre wave imagers needs to be in the region of 100 mK to 1 K, to enable detection of critical non-metallic and thin plastic threats for security screening and a range of obstacles for all weather flying aids. The sensitivity of an aperture synthesis system is given by Eq. 1, where T_A is the scene radiation temperature (typically close to ambient at 300 K), T_N is the receiver noise temperature (typically ~200 K at frequencies below 40 GHz), B_{RF} is the radiation frequency bandwidth, t_F is the integration time and F is the fraction of the aperture which is filled with receiving antennas. The fraction F is given by Eq. 2 where n is the number of antennas, A_{ANT} is the effective collection area of a single antenna and A_{SYN} is the total aperture area over which the antennas are distributed.

$$\Delta T_M\,[K] = \frac{T_A + T_N}{\sqrt{B_{RF}\,t_F}}\,\frac{1}{F} \quad (1) \qquad\qquad F = \frac{nA_{ANT}}{A_{SYN}} \quad (2)$$

For indoor use, the scene contrast is typically 15 K, being approximately the radiation temperature difference between the building interior (set for example by the air-conditioning) and the human body. For outdoor use, contrast is typically 150 K in the lower frequency part of the millimetre wave band, being the temperature difference between ambient and the cold sky. Generally, outdoor contrast falls with increasing frequency as the atmospheric absorption rises. Understanding these sensitivities and contrasts for particular scenarios enables good systems to be designed for specific applications.

Number of image pixels

The number of Nyquist sampled pixels in an aperture synthesis image ranges from n^2 for a zero redundant array of n antennas to 4n for a fully filled aperture (F=1). A zero redundant array is a highly sparse array, using the smallest number of receiver channels possible to reproduce, alias free, spatial information in the scene up to the diffracted limit commensurate with the aperture size. The fully filled array uses the highest number of receiver channels that can be fitted into the aperture and offers the highest radiometric sensitivity. In practice the choice of array geometry and its filling fraction will depend on the radiometric sensitivity and spatial resolution for the particular application.

Demonstrator system overview

A real time aperture synthesis PMMW demonstrator has been developed to investigate trade-offs, optimisations, calibration and stability of this architecture of imager[3]. Satisfying the Nyquist criterion on the temporal sampling in the receiver channels requires the rate of mathematical operations in the correlator to be $2n^2B_{RF}$. However, as radiometric emission is essentially broadband noise, digitisation and correlation can be done in single bits, meaning these tasks can be performed using commercially-available off the shelf (COTS) field programmable gate arrays (FPGA). A schematic of the complete demonstrator system is illustrated in Figure 2. The sparse antenna array, designed from 32 individual 2x2 patch antennas on a hexagonal gird to minimise aliasing associated with sampling across aperture is illustrated in Figure 3. Waveguide horn antenna arrays have also been developed in order that comparisons can be made between the two types of antennas. The receivers are sensitive at 22.5 GHz with a 300 MHz radiation bandwidth and are packaged in dual channel slim-line modules, as illustrated in Figure 4. With an antenna array filling factor of 34 % it delivers a 20x20 pixel image and has a 0.5 K sensitivity at video frame rates (25 /s). In-phase and quadrature digitisation at several hundred MHz is achieved via two stages of heterodyne down-shifting. Flexibility exists in the system to investigate different array geometries, ranging from those with sparsity less than zero redundant arrays in two dimensions to fully filled arrays in one dimension.

Exploiting new technologies for an old technique

The opportunity exists now to develop a new architecture of PMMW imager based on aperture synthesis which occupies a fraction of the volume of conventional quasi-optical imagers. The demonstrator project discussed here represents a test bed for optimisations of receivers, antennas and their array geometries. Prototype imagers based on this architecture are likely to follow with typically 300 receiver channels, replacing the FPGAs with ASICs and using MMICs in the receivers to minimise volume and power consumption. The opportunity is that the antenna array, receivers and the digital electronics will be integrated into a substrate, a centimetre or so thick, using production techniques from the mobile communications and computer industries to minimise costs. Imagers could then be integrated into the confined spaces of entrances to form security screening portals, developed in to hand held wands for proximity screening of personnel and baggage, or integrated as tiles into the skins of air vehicles for all weather flight, as depicted in Figure 5.

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2. Thomson, A.R. & Moran, J.M., *'Interferometry and Synthesis in Radio Astronomy'*, Wiley, 2004
3. http://www.qinetiq.com/home_tsb.html

Acknowledgments

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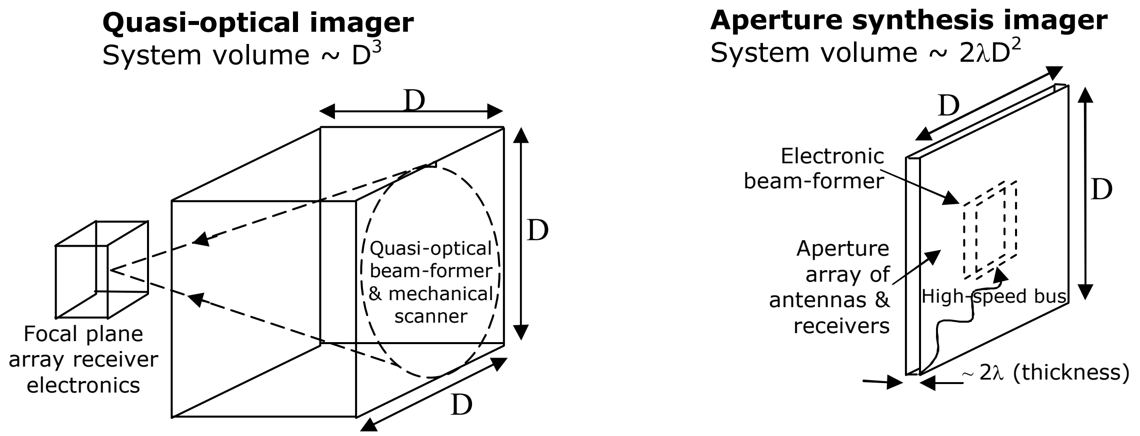


Figure 1. A mechanical scanning imager has a quasi-optical beam-former before the receiver electronics (left), whilst the aperture synthesis imager has a digital beam-former after the receiver electronics (right). As the antennas, receivers and digital beam former can be packaged into a thin electronic substrate, the aperture synthesis imager offers a massive footprint reduction and as such can be integrated into walls for security screening and the skins of air vehicles for poor weather operations.

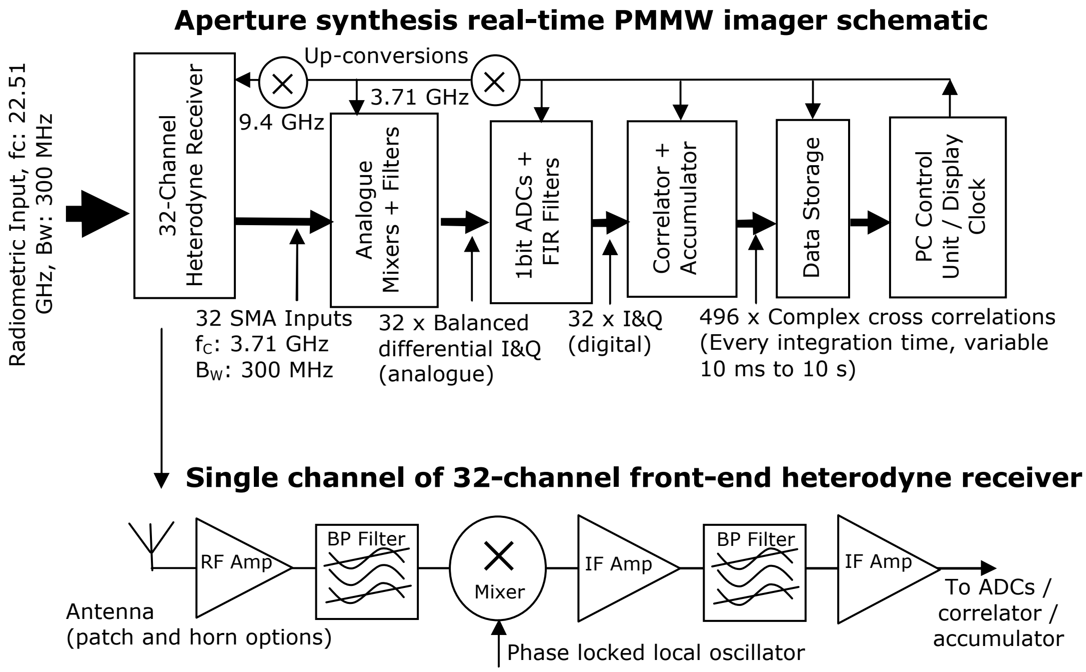


Figure 2. Schematic of the 32-channel real-time aperture synthesis PMMW imager demonstrator system (upper) and one of the single channel front-end heterodyne receiver

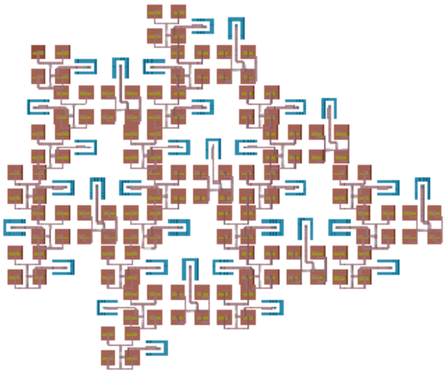


Figure 3. The sparse antenna array for the demonstrator comprising 32 individual 2x2 patch antennas. Each patch antenna is only 2 mm thick.

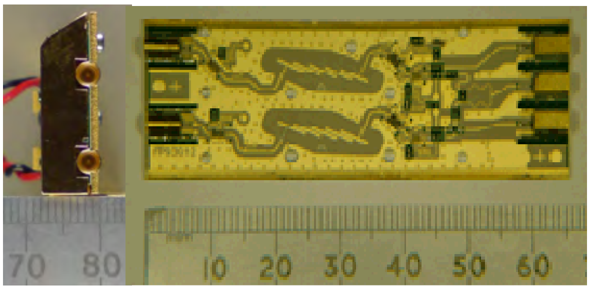
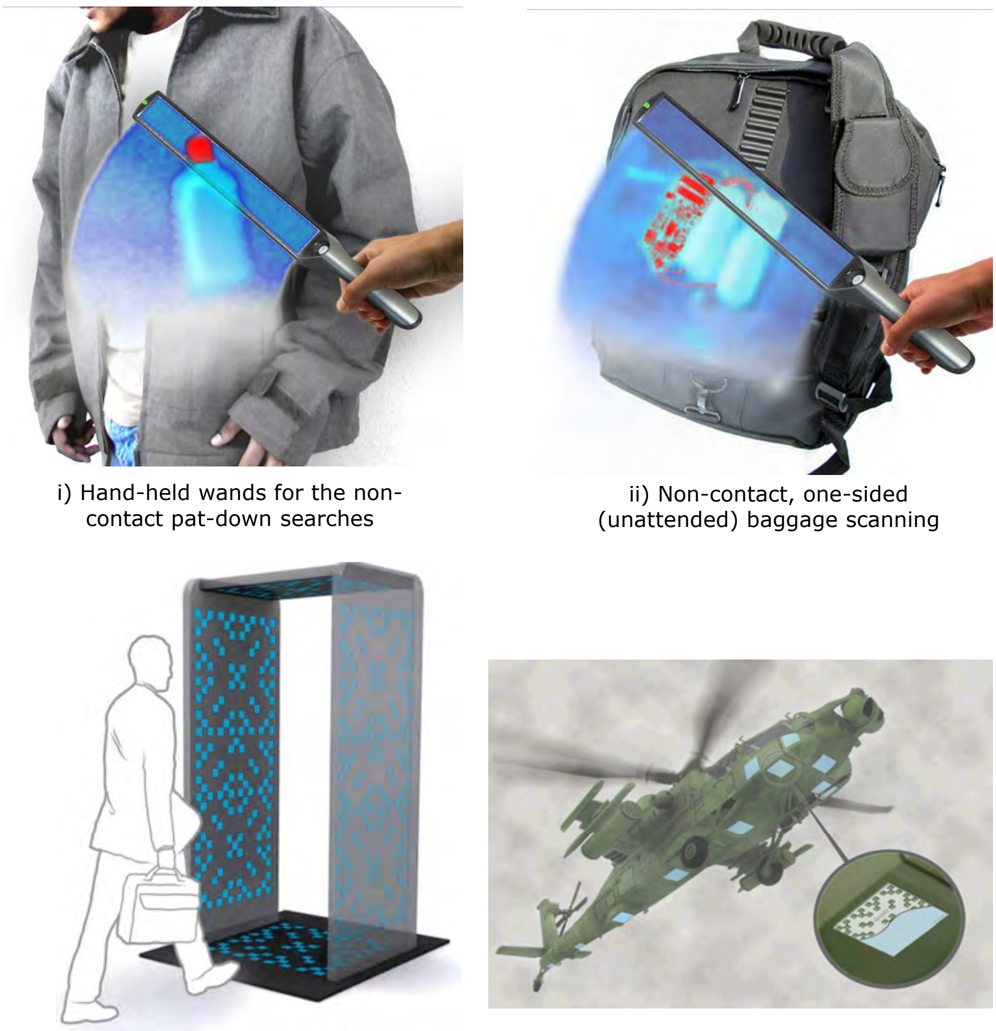


Figure 4. Pairs of the 32-channel receivers are integrated into slim-line (5 mm thick) dual receiver modules. A circuit board of one of these shown here is 1.5 mm thick and 6 cm long, with two sockets for antennas illustrated on the left.



i) Hand-held wands for the non-contact pat-down searches

ii) Non-contact, one-sided (unattended) baggage scanning

iii) Security screening portal

iv) All weather flying aids for helicopters

Figure 5. Depictions of PMMW imaging systems using digital aperture synthesis technology for security screening against both metal and non-metallic threats and as air-platform flying aids