Active and Passive Radio Frequency Imaging Using a Swarm of SUAS

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ABSTRACT

Active and passive radio frequency imaging techniques such as synthetic aperture radar are an important tool in military intelligence gathering in a wide range of specific applications. Such sensors have hitherto been fielded singly or at most in bistatic pairs, however there are substantial benefits in operating a larger number of sensors together. Recent advances in the technology of small unmanned aerial systems (SUAS) and sensor component technologies have made this conceivable for the first time. This paper provides an insight into the use of distributed radio frequency imaging techniques using a small swarm of airborne sensors. Theoretical analysis and numerical methods are used to show how the quality of spatial, temporal and spectral information developed is increased by the use of multiple sensors, and how the information generated may be controlled through the organisation and motion of the sensors in the array – the basis of future autonomous operation in which the array is self-optimised according to the intelligence task and the environment. Initial imaging results based on computer simulation are included in the paper; the first test flights are due to be undertaken around the time of the meeting. The paper also provides an overview of the practical aspects of realising active and passive radio frequency imaging with a swarm of aircraft – the challenges of the compact coherent sensor technology, the practicalities of installing and operating RF sensors on SUAS, and the signal processing techniques involved in generating imagery.

1.0 INTRODUCTION

Remote intelligence gathering has always been a critical aspect of military and security operations, and airborne sensors operating against the ground environment an important tool in achieving this. In the Cold War and Gulf War eras it was sufficient to have sensors that could locate and classify large military formations, and the emphasis was in achieving long detection range, wide spatial and temporal coverage, and low reporting latency. The current military and security threat is substantially different with the emphasis on countering insurgence, counter terrorism and smaller scale military activities. The ground environments within which intelligence has to be gathered has also changed with an emphasis on semi-urban and urban areas, surveillance into compounds, inside buildings and even into underground facilities. This requires intelligence gathering systems capable of delivering very high levels of information to distinguish the presence and activities of adversaries from those of the surrounding population, and capable of penetrating and interpreting very complex environments.

Figure 1: Suspicious objects within a building - from UK MoD CDE 'What's inside that building?'

Active and passive radio frequency imaging has properties that are particularly well suited to military surveillance – operation in all weathers, penetration of obscurants, operation at night, the ability to penetrate the ground, foliage and man-made structures, and specific capabilities such as directly sensing motion and small scale changes in the environment. Radio frequency imaging sensors are thus a useful complement to optical sensors and the disadvantages of radar sensors – poorer spatial resolution and more difficult exploitation – are accepted in order to obtain wider benefits, particularly flexibility of operation.

Radio frequency imaging sensors have hitherto been fielded singly or sometimes as a bistatic pair, because of the high cost of the sensors themselves and that of the manned or unmanned aircraft on which they are hosted. There are, however, substantial benefits in interoperating radio frequency sensors in larger numbers, as part of a sensor swarm. These benefits exceed the scaling of capability achieved with swarms of optical sensors as data can, in principle, be combined coherently across the sensor array to realise substantial enhancements in spatial sensing capability. Thus bringing together radio frequency imaging technologies and sensor swarm concepts not only increases the operational flexibility of the swarm and scales the throughput of a single radio frequency sensor, but substantially increases the interpretability of radar imagery.

QinetiQ is currently undertaking a research and demonstration project under Dstl's Disruptive Capabilities portfolio, in which we are developing miniature active/passive, coherent radio frequency imaging sensors, sufficiently small be flown on large quadcopters, and signal processing techniques to exploit the sensors as a single, distributed, moving and morphing, coherent sensing system. We are working towards an initial demonstration in September 2016, probably using three airborne sensors, but the sensors and aircraft are sufficiently cheap to deploy as a larger sensor swarm in future work. This paper provides an insight into this project.

The next two sections provide a brief introduction to radio frequency imaging and explain the challenges of using it in difficult environments such as compounds, buildings and underground facilities. Section 4 identifies diversity of measurement from a swarm of sensors as a key aspect of imaging in these situations, and shows how the performance of a distributed sensing system may be predicted. Section 5 addresses the sensor and platform technologies required for a sensor swarm and describes the sensor system currently being developed for Dstl. Section 6 provides an overview of forthcoming experimentation and demonstration work applying this system to the problem of remote sensing in challenging environments.

2.0 OVERVIEW OF RADIO FREQUENCY IMAGING

Radio frequency (RF) imaging is a well-established sensing technique used widely in both civil and military applications. RF imaging is similar in principle to optical imaging in that it sets out to generate a high resolution ‘picture’ of the environment and objects within it, based on their interaction with electromagnetic (EM) waves. The primary difference between RF and optical imaging is the wavelength used which differs by about five orders of magnitude. This results in very different properties in terms of propagation between the object environment and the sensor, interaction of EM waves with the object environment, and the angular resolution achieved with a particular sensing aperture. This last issue leads in RF imaging to the use of the flight path of the aircraft as an extended ‘synthetic aperture’ as the only practical means of achieving fine angular resolution. Resolution in a second radial dimension is achieved using propagation time measurement resulting in the familiar high resolution, two-dimensional synthetic aperture radar (SAR) image.

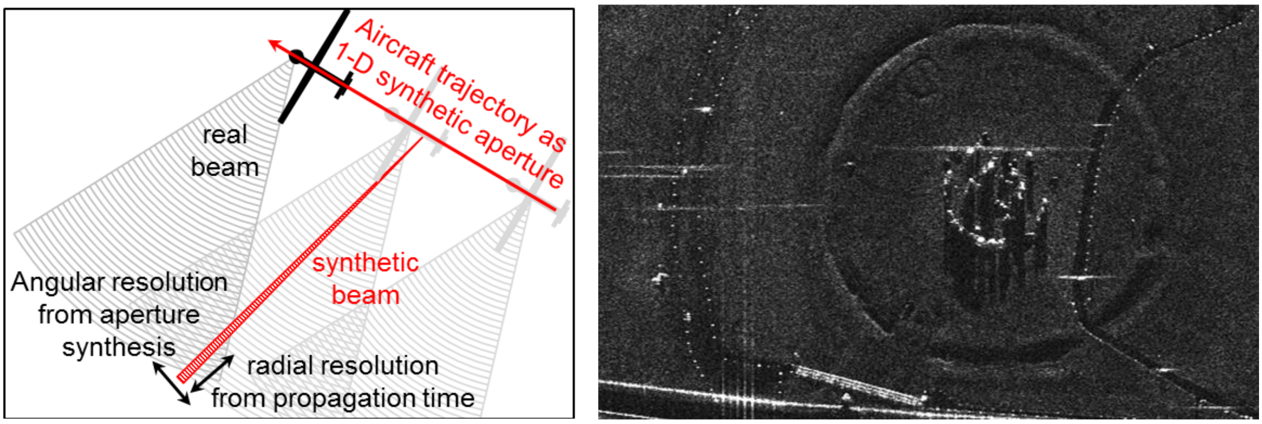

Figure 2: Synthetic aperture radar principle and typical image – Stonehenge, Wiltshire, UK

Optical imaging is usually passive, relying on natural illumination, whereas the most common radio frequency imaging technique, SAR, provides its own illumination using distinct transmit and receive functions. SAR can be operated with a single sensor and platform providing both transmit and receive functions (monostatic SAR), or with transmit and receive functions realised on different platforms (bistatic SAR). There are a number of possible reasons for taking a bistatic approach: as an electronic protection measure, to expose target scattering behaviour favourable to the sensing system, or for practical reasons of system design. Passive radio frequency imaging is also possible, exploiting non-cooperative radio emissions such as television, communications or navigation signals. Two receivers are generally required for passive operation, sometimes but not always on the same platform, for synchronisation with the illuminator. Adding further receivers and platforms to any of these active or passive configurations may serve to enhance the level of spatial information realised.

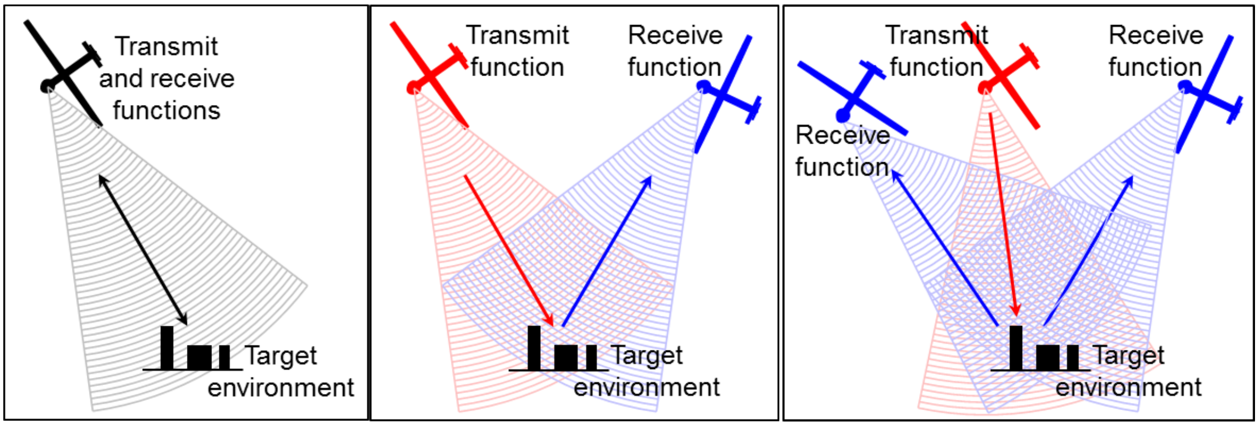

Figure 3: Monostatic, bistatic and multistatic active SAR concepts

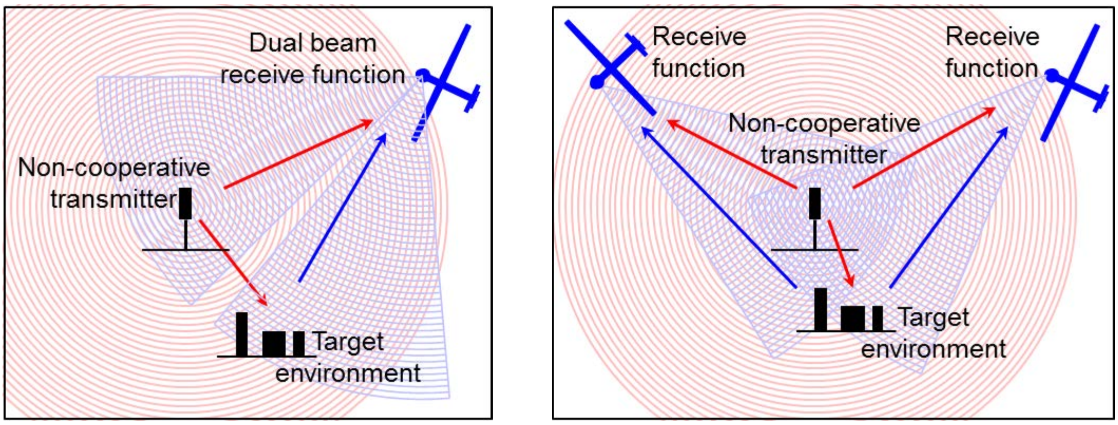

Figure 4: Passive SAR concepts – monostatic and bistatic variants

All of the active and passive RF imaging concepts identified employ aperture synthesis – integration of the received signal over a segment of aircraft trajectory, typically of tens of seconds duration. This integration process is coherent, sensitive to both the magnitude and phase of the signal, as it is in an optical lens. Coherent integration is only possible if the entire sensing system, including propagation paths, is stable to a small fraction of the RF wavelength on a scale of the synthetic aperture time. This places stringent demands on the measurement of position and time, requiring aircraft to be equipped with high grade navigation systems, and sensors to include stable frequency references and means of relating time between sensors. Actual requirements depend on the choice of RF frequency and the system concept involved.

System concept	Position measurement accuracy on the scale of the synthetic aperture time	Time stability/measurement accuracy on the scale of the synthetic aperture time
Monostatic active or passive SAR	Second order and higher to sub-wavelength accuracy (zeroth and first order terms result in geolocation errors but not defocus)	No requirement (accuracy requirements exist on the scale of the propagation time, i.e. order 1ms at most, but these are easily met using standard radar technology)
Bistatic active or passive SAR	Second order and higher to sub-wavelength accuracy (zeroth and first order terms result in geolocation errors but not defocus)	Second order and higher to sub-period accuracy (zeroth and first order terms result in geolocation errors but not defocus)
Multistatic active or passive SAR	Zeroth order and higher to sub-wavelength accuracy	Zeroth order and higher to sub-period accuracy

Table 1: Position and time measurement accuracy and stability requirements for various system concepts

RF imaging has a number of properties that are beneficial in intelligence gathering and are not present in optical imaging:

- operation in all weathers, through obscurants, day and night;
- penetration of natural and man-made structures – to an extent determined by the frequency;
- spatial resolution independent of range provided the collection geometry is maintained;
- extension to volumetric imaging by selecting flight profiles to achieve a sparse 2-D aperture;
- sensitive to specific target attributes – changes, motion, vibration, physical structure.

3.0 RADIO FREQUENCY IMAGING IN CHALLENGING ENVIRONMENTS

The primary challenges in developing and operating an RF imaging system are energy and information – detecting objects in the presence of system noise and co-channel interference, and obtaining sufficient information to overcome the complexity of the environment and realise usable intelligence. The energy challenge equates to that of obtaining sufficient signal to noise ratio at the required operating range; the information challenge equates largely to that of obtaining sufficient spatial resolution, although the system may also resolve in other domains. Operating frequency is the most important system design variable altering the balance between energy and information.

For a given synthetic aperture time, angular resolution is inversely proportional to frequency, i.e. finer resolution is achieved at higher frequency. While there is no direct relationship between radial resolution and frequency, it is generally easier to achieve wider bandwidth and thus finer resolution at a higher frequency. However, it generally becomes more difficult to generate high transmitter powers as frequency increases and propagation and system losses also rise, reducing the signal to noise ratio achievable at a given range. For systems operating in an open environment with direct line of sight to target objects, subject only to tropospheric propagation losses, a frequency of around 10GHz is typically used for very long range, stand-off systems, and higher frequencies up to around 30GHz for shorter range systems.

The changing nature of military operations discussed earlier has resulted in less emphasis on intelligence gathering in open conditions and a greater emphasis on surveillance of challenging environments – under foliage, in congested urban areas, and even inside buildings. RF imaging systems operating at 10GHz or higher have only limited ability to penetrate man-made and natural structures, making them less well suited to emerging intelligence needs, and systems operating at lower frequencies more suitable. Systems have been developed to operate at frequencies as low as 100MHz for specialised applications and useful capabilities have been demonstrated for relatively simple problems and environments, for example detecting man-made objects under foliage. However, many environments that are challenging from a propagation perspective are also extremely complex, for example a building interior. Tackling such complexity demands very fine spatial resolution. This is not achievable at frequencies as low as 100MHz and frequencies in the 300MHz to 3GHz range generally represent a better compromise.

The choice of an optimum radio frequency for surveillance in a challenging environment pre-supposes that spectrum is available in which the system may be operated without interfering with or suffering interference from other users of the spectrum. This turns out to be a massive issue as the surveillance systems are competing with modern communications systems – radio and television broadcast, cellular communications, wireless networks and other forms of short range communication – that have identical requirements of wide bandwidth and the ability to penetrate man-made and natural structures. There is virtually no available spectrum in the 300MHz to 3GHz range over which an active RF imaging system designed to cope with challenging environments would naturally be operated. One obvious solution is to move from active surveillance systems to passive systems that exploit, on a non-cooperative basis, the same communications emissions that preclude active surveillance. Another viable approach is to adapt the operation of an active system to utilise whatever spectrum is available in a particular situation. It may be even be possible to utilise adaptive active and passive approaches simultaneously.

Thus RF imaging systems designed to operate against challenging environments will operate at lower frequencies than those designed principally for imaging in open conditions, and will adapt operation according to local use of the spectrum, employing active and/or passive imaging techniques as appropriate. Regardless of the technique employed, the challenges in developing such a system will be energy and information – choosing a frequency at which propagation through the environment is sufficiently favourable to meet the energy challenge, and then maximising the information gathering ability of the system. The key to maximising information turns out to be measurement diversity which is the subject of the next section.

4.0 MEASUREMENT DIVERSITY AND SENSOR SWARMS

The level of information delivered by a radio frequency sensing system, operating at a given frequency, is determined by the degree of measurement diversity achieved, i.e. the range of conditions under which the interaction of electromagnetic radiation with the environment and objects within it is measured. Interactions are sensitive to the polarisation of incident and reflected radiation, and RF imaging is a coherent system measuring both magnitude and phase, so a single interaction measurement should comprise a complex scattering matrix. In practice, only one combination of incident and reflected polarisation may be measured, in which case the measurement reduces to a complex scalar scattering coefficient. Measurements can be made in many different domains: frequency, direction of transmitter, direction of receiver, and time. So an ideal system is one that can measure the full scattering matrix over all of these domains, generating a multi-dimensional measurement set. The extent of measurement support in each domain is an important measure of the information gathering capability of the system, leading to ideas such as the 'data dome' in which the measurement direction covers the complete upper hemisphere.

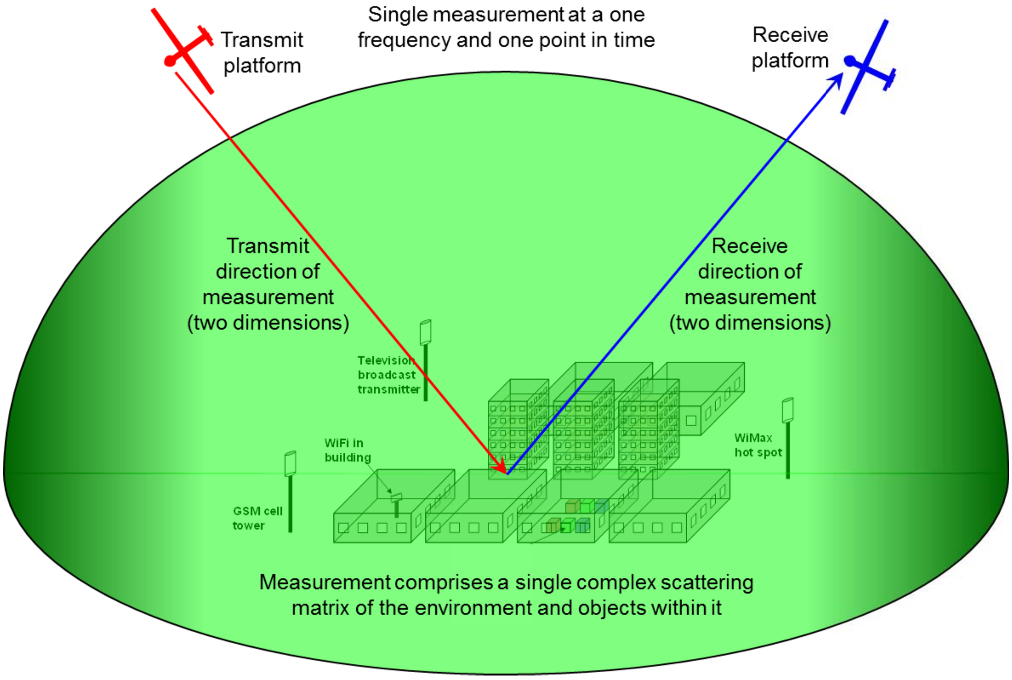

Figure 5: RF imaging measurement and the 'data dome'

Any practical system will fall short of this ideal through limitations concerning the extent of measurement in a particular domain and coupling between measurement domains. For example, a monostatic SAR measures over the limited range of frequencies comprising the bandwidth of the system, often only a 10% fractional bandwidth, and couples all remaining measurement domains (two dimensions of transmit direction, two dimensions of receive direction, and time) into a single measurement dimension – time as the aircraft flies a linear aperture. Thus the system only measures in two dimensions, limiting its information gathering ability. From this discussion, the potential of RF imaging systems to generate substantially more information is immediately apparent. The ability of an imaging system in this respect is termed 'measurement diversity'. Maximising measurement diversity is the key to applying RF imaging to challenging environments.

Hitherto, achieving extensive measurement diversity has been difficult because of the cost and relative inflexibility of operating manned aircraft. However, small UAS and miniature RF sensors now offer the potential to overcome these limitations, at least at short range – through the number of aircraft that may be deployed, high angular motion rates arising from short range, and ease of repositioning in three dimensions to perform multiple data collection legs using 'repeat-pass' imaging.

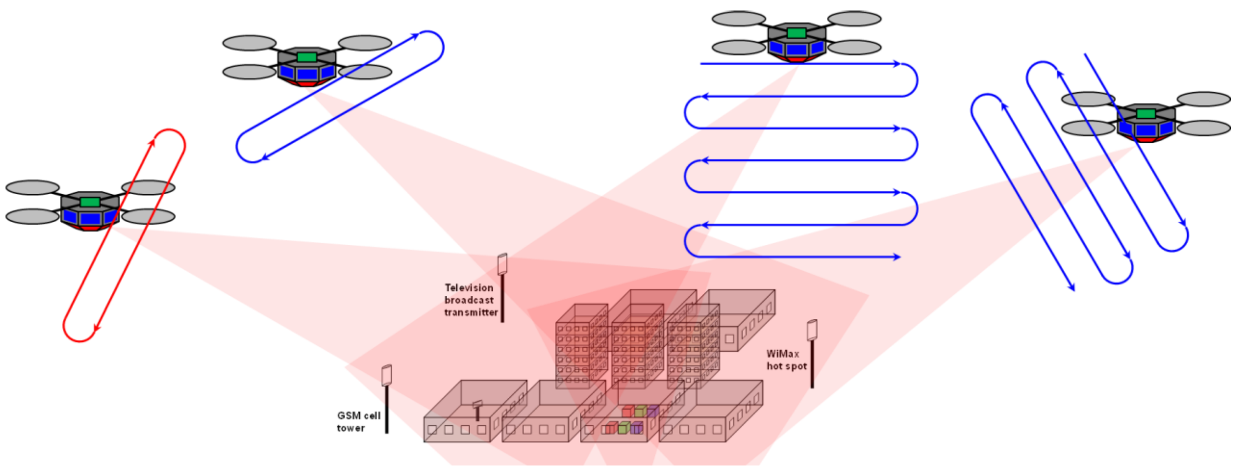

Figure 6: Use of multiple SUAS and multiple measurement legs to achieve measurement diversity

Whole-environment scattering matrices measured over multiple dimensions may be an acceptable way of describing the information-gathering ability of an imaging system but they are not effective as an information product from which intelligence questions can be answered. The traditional data representation used for this purpose is the image – a two-dimensional spatial attribution of backscatter. SAR image formation algorithms compute each image pixel value by determining the extent to which the measured scattering data is consistent with the behaviour of an isotropic scatterer centred at a physical location corresponding to the pixel. This is achieved by integrating measurement data with the complex conjugate of the measurement behaviour expected of the hypothetical scatterer. The integration is performed over a defined extent of one or more measurement dimensions, often with an apodisation function.

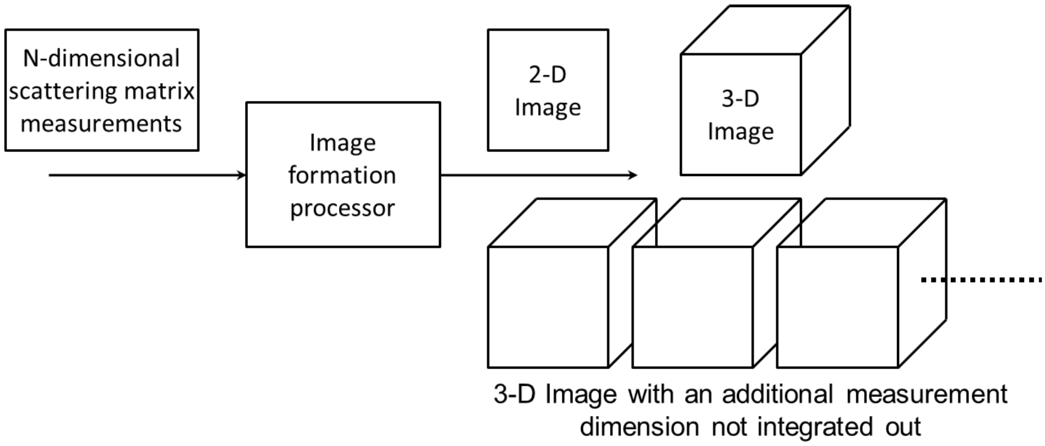

Figure 7: SAR image formation process and possible image products

The extent of scattering matrix measurements integrated is termed the measurement support and determines the properties of the image. For example, processing for a stand-off monostatic SAR integrates over time (actually a dimension of aircraft trajectory) and frequency to give the familiar two-dimensional, ground-referenced image product. Scatterers at different heights project into the image plane with some sensitivity to height (a height of focus limitation) but no resolution of height, as such. A more capable collection system may acquire data over additional measurement dimensions and may require a 3-D volumetric image to represent data in a spatial sense. Even a volumetric image may be insufficient to fully represent the measurements, not all of which may necessarily be integrated out in the image formation process. These additional measurement dimensions may be retained as additional image dimensions, for example frequency, bistatic angle or time could sometimes be retained in this manner, increasing the level of information represented in the image product.

The information gathering ability of an RF imaging system may be formalised, at least in terms of spatial resolution, using a numerical method to predict the system point spread function – the theoretical response of the system to a single point scatterer. The extent of measurement support from which the image is to be formed is transformed to the Fourier spatial domain by computing the instantaneous wavevector – essentially the vector grad of the measurement phase field – and using a mathematical device, the stationary phase approximation, to equate instantaneous wavevector with spatial frequency. An inverse Fourier transform is then used to compute the theoretical point spread function.

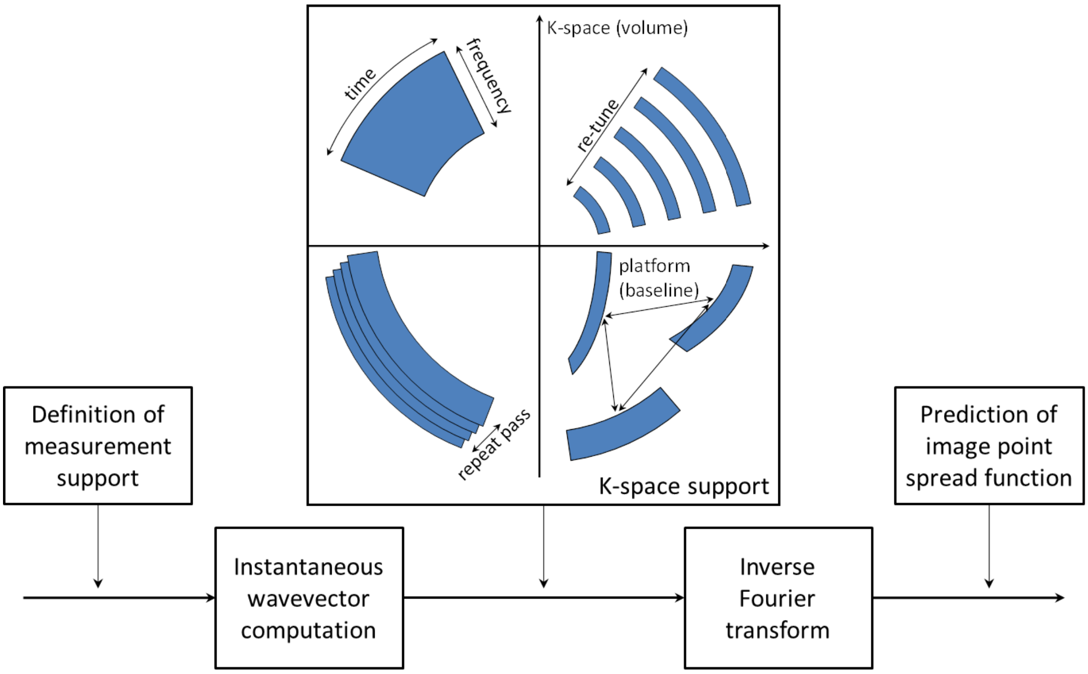

Figure 8: Numerical evaluation of the system point spread function

Numerical prediction of this type is informative as it allows the composition of the imaging system and the manner in which it is operated to be related directly to the spatial information obtained and thus its intelligence gathering ability. Figure 8 above shows the manner in which many different aspects of the system and its operation manifest themselves in the spatial frequency domain: flying a simple aperture, operating over a bandwidth, employing frequency agility or different sensors operating on different frequencies, employing multiple sensors, and repeating collection legs with different geometries.

Two examples of this prediction process are given on the next page. The first is of a simple bistatic SAR operating at 1GHz with a 120MHz bandwidth, flying apertures giving 90° of angular measurement with each aircraft. A resolution of about 0.1m x 0.6m is predicted in two dimensions. The second example shows the use of two additional receive platforms and repeated collection legs at different altitudes to give a predicted resolution in three dimensions of 0.1m x 0.1m x 0.6m – a substantial increase in information. The predicted form of the imaging function, with high sidelobes, results from sparse support in the spatial frequency domain which in turn is a consequence of the manner in which the collection system is operated. In particular, the headline resolution numbers relate to the total extent of support in the spatial frequency domain, whereas the usable information should probably be scaled according to the sparsity of support in the spatial frequency domain. A full discussion of this issue is beyond the scope of this paper but is the subject of on-going consideration.

The ability to undertake forward prediction of this type is very important as it forms the basis of future methods to optimise the information gathering ability of a swarm of RF imaging sensors by optimising the positioning and operation of individual sensors, potentially in real time.

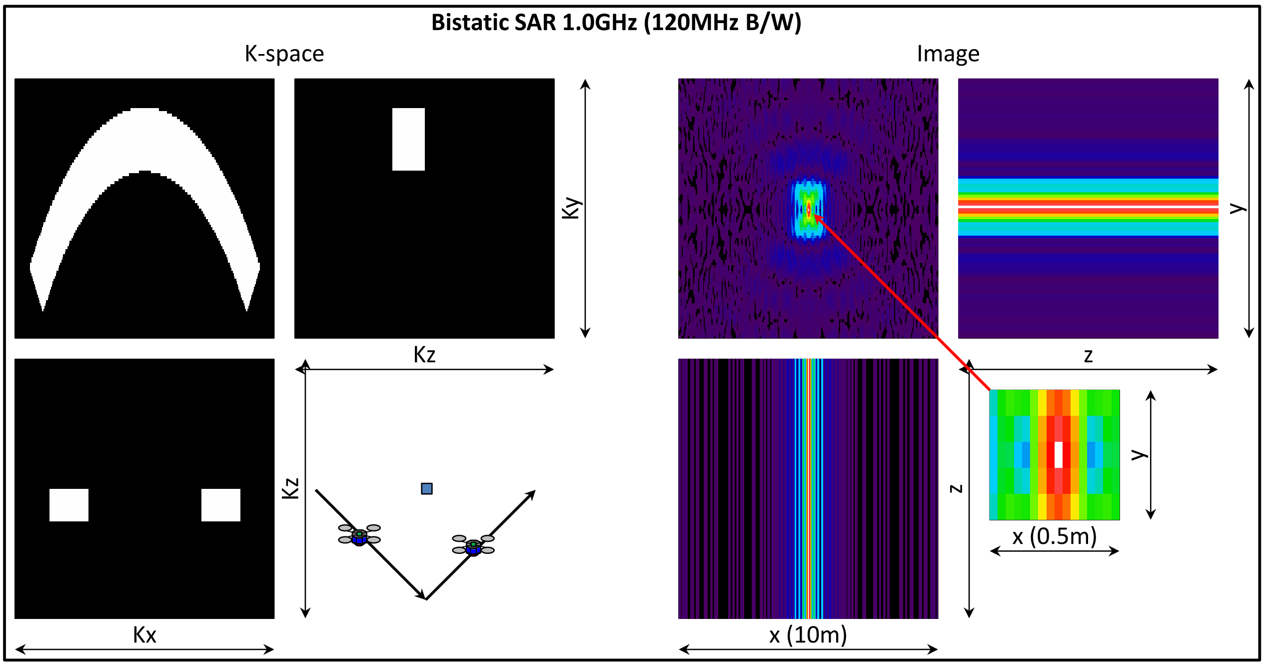

Figure 9: Point spread function prediction for bistatic SAR

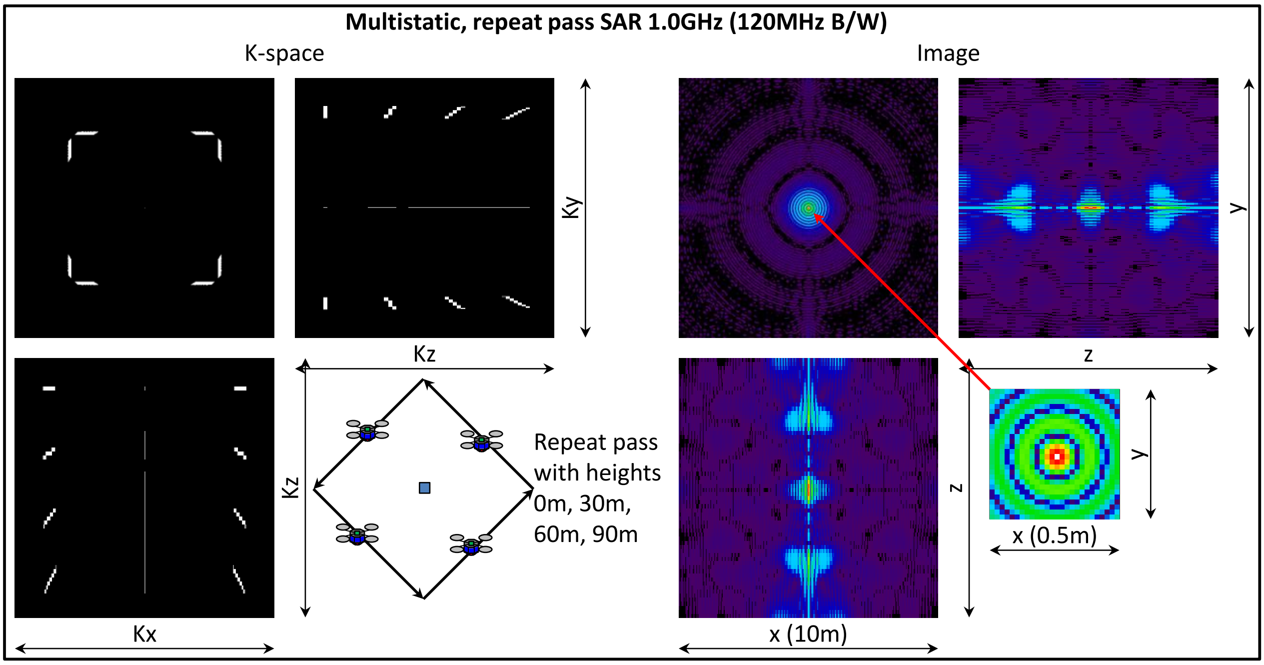

Figure 10: Point spread function prediction for multistatic SAR operated with multiple imaging legs

Performance prediction of this type pre-supposes that measurements from the individual sensors can be combined in a coherent manner. This is dependent on the entire multi-platform system being stable to a fraction of a wavelength, and on the performance of the navigation, timing and frequency reference instruments and processing techniques used to achieve this. These issues were discussed earlier in section 2 of this paper. The remainder of this paper describes a multi-platform, active/passive RF imaging system being developed for UK MoD for experimentation and demonstration purposes. Establishing coherence is one of the major challenges to be addressed, and practical performance limits are yet to be established.

5.0 RF IMAGING SENSOR TECHNOLOGY FOR SUAS SWARMS

So far, this paper has considered RF imaging against challenging environments in the abstract. It has been shown that a swarm of miniature sensors on SUAS platforms should be able to realise the necessary information to interpret a complex environment while operating at a sufficiently low frequency to penetrate natural and man-made infrastructure. Even five years ago, if would have been impossible to develop such a system. However, the development of multi-rotor aircraft and certain COTS electronics components – wide band software defined radio modules, powerful single board computers, solid state storage, MEMs inertial measurement units, and chip scale atomic clocks – now make such a system challenging but conceivable. QinetiQ, working with Dstl, is now developing such a system with which to undertake an experimentation and demonstration programme later this year under UK MoD's Disruptive Capabilities research programme.

The system being developed is intended to realise distributed, fully coherent RF sensing across a multi-platform array – the first realisation of this concept of which we are aware. A single sensor design can be flown on a multi-rotor aircraft or operated on the ground. The initial development includes a total of seven sensor units and six aircraft, allowing great flexibility of experimental configuration. The sensor includes facilities for both active and passive RF sensing, and also the means of broadcasting dedicated timing and positioning waveforms between sensors to establish coherence across the array.

The sensor is based around a wide band software defined radio, stabilised using a chip scale atomic clock, and connected through RF signal conditioning circuits to separate antennas for sensing and coherent positioning. A single board computer, equipped with a large solid state storage array, controls the operation of the system and records data from the software defined radio. It also records data from a precision navigation system based on a high grade commercial GPS and MEMs inertial measurement unit. The GPS antenna is shared with the aircraft autopilot. The sensor is housed in a purpose-built carbon fibre and aluminium chassis and is hung on mounting rails under the aircraft. The aircraft provides prime power and also a command and telemetry facility to the ground through which the sensor can be commanded.

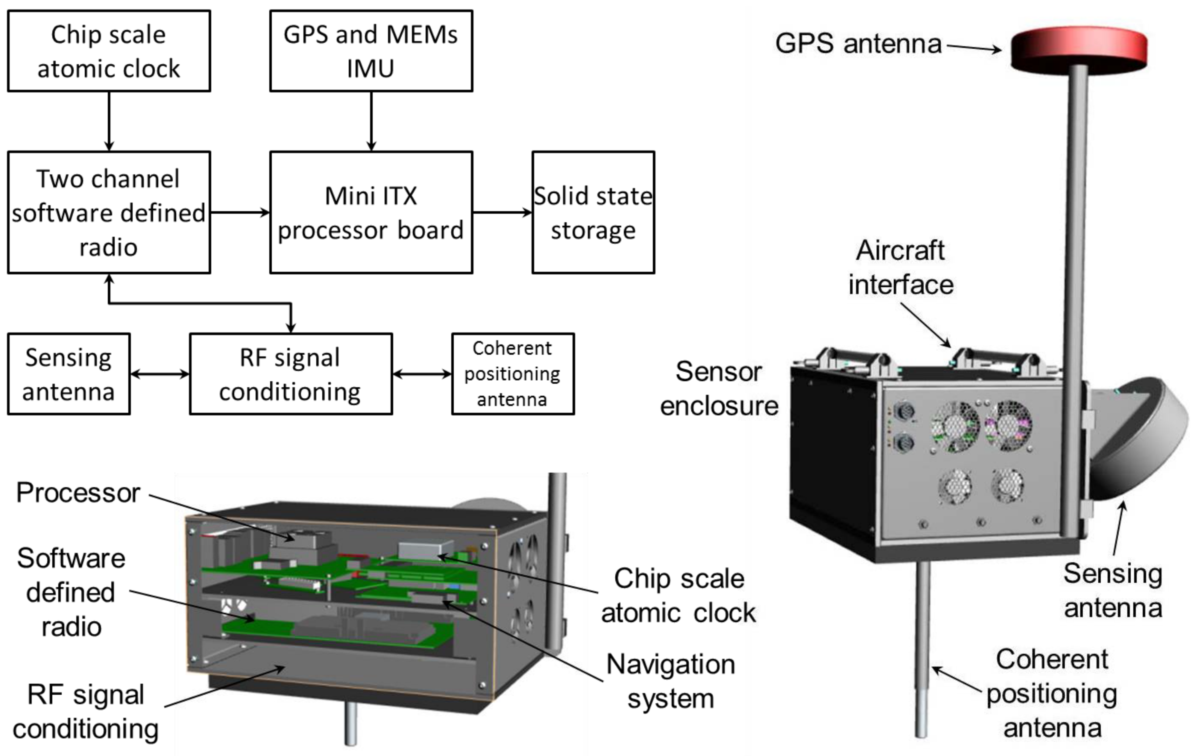

Figure 11: Sensor functional and physical design

Figure 12: Sensor enclosure mounted on Raven X8 multi-rotor aircraft

The entire experimentation and demonstration system comprises:

- seven sensors distributed between aircraft and static ground installations;
- six Vulcan UAV Raven X8 multirotor aircraft with sensors and one smaller test aircraft;
- individual autopilot, flight control and command/telemetry systems for each aircraft;
- central ground segment to command and monitor all sensor and aircraft activities;
- lab-based off-line processing using active and passive aperture synthesis techniques.

The aircraft are equipped with sophisticated autopilots which allow the aircraft to be flown to specified waypoints and orientated to point sensor antennas at the test target environment. A trained pilot will monitor the activity of each aircraft for safety purposes. The activities of individual aircraft and sensors are to be commanded and monitored from a single ground terminal to coordinate the activities of the swarm. For initial test flying, activities are to be pre-planned, but autonomous activity could be introduced later in the programme. Planned flight test activities include the validation of the system, experimentation against a range of test scenarios to evaluate the sensor concept, and an initial demonstration to UK MoD.

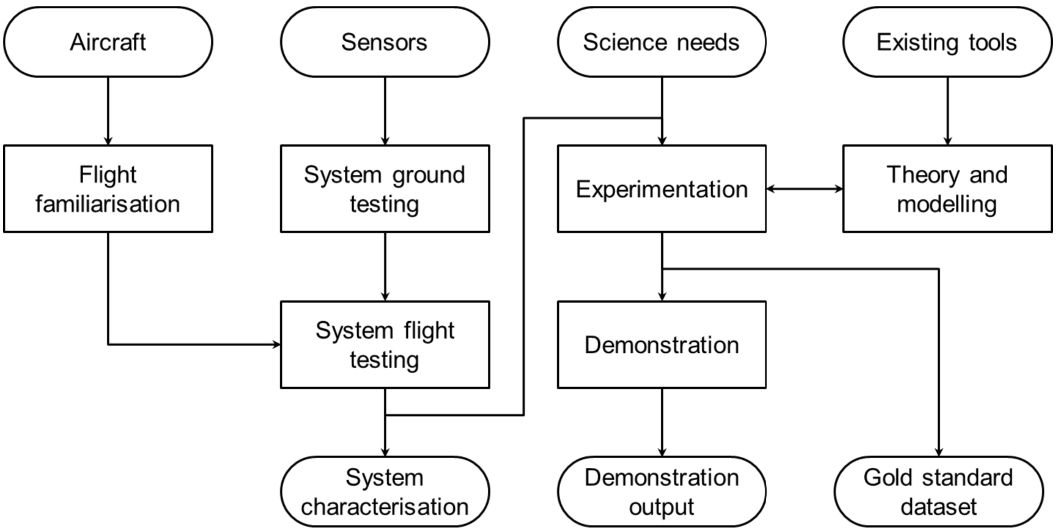

Figure 13: System evaluation, initial experimentation and demonstration programme

6.0 SUMMARY

Radio frequency imaging techniques such as synthetic aperture radar are well established for the purposes of remote intelligence gathering and are deployed in stand-off roles in aircraft such as the UK's Sentinel R1, and for shorter range operation from unmanned aircraft. The change of emphasis of military operations in recent years, towards counter-insurgence, counter-terrorism and smaller scale military activities has raised an additional need for intelligence gathering capabilities in challenging environments such as semi-urban and urban areas, under foliage, into buildings, and even into underground facilities.

RF imaging sensors may address these needs but must operate at lower frequencies than existing systems to achieve sufficient penetration of energy into the environment. Operating at lower frequency generally implies a poorer spatial resolution but, if anything, resolution will need to improve to cope with the extreme complexity of such environments. This will require a sensing system operating with a degree of measurement diversity – the range of spectral, temporal and geometric conditions over which sensing is performed – not achievable with a single, manned aircraft, but potentially achievable with a swarm of small unmanned aircraft, operating at close range. The information generated by the swarm is probably best represented as a volumetric image, potentially with additional sensed dimensions such as frequency, time or aspects of the collection geometry. Numerical methods have been developed to quantify the information-generating capability of the system in these domains, allowing the effect of different swarm configurations and sensor modes to be quantified. These methods are expected to form the basis of algorithms to optimise the configuration of the sensor swarm for a specific task. The radio frequencies able to penetrate man-made and natural structures are precisely those used by modern communications systems and are not generally available for military surveillance purposes. A potential solution is to utilise these communications emissions as non-cooperative illuminators for an alternative passive imaging mode. These ideas lead to the concept of a distributed, coherent, active/passive RF imaging system, hosted on a swarm of unmanned aircraft, adapting the swarm configuration and sensor operation to the prevalent physical and RF environments.

In the last few years, the technologies have become available to realise the distributed, coherent RF sensing concept. QinetiQ is currently developing such a system for UK MoD for experimentation and demonstration of RF imaging concepts, operating against challenging environments. The system is based on a bespoke sensor design, realised using state-of-the-art COTS components – wide band software defined radio, a powerful single board processor, solid state mass storage, a chip scale atomic clock and a navigation system comprising GPS and a MEMs inertial measurement unit. Facilities are provided to achieve coherence between multiple sensors using dedicated timing waveforms broadcast between the sensors. The sensor is to be flown on large multi-rotor aircraft or operated static on the ground in test configurations comprising up to six aircraft and seven sensors. Operation of the swarm of aircraft and sensors in the initial experimentation and demonstration programme is to be pre-planned, but may later be extended to a more sophisticated, self-optimising approach. This programme represents the first attempt, of which we are aware, to develop a distributed RF sensing system of this type. While extremely challenging, the programme is expected to advance military sensing capability at many different levels – sensor technology, distributed sensing techniques, operation and optimisation of sensor swarms, and application to specific military intelligence problems in the challenging environment likely to be encountered in future military operations.

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