# Exploration of multidimensional Radio Frequency imaging to derive Remote Intelligence of Building Interiors

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***Abstract*—The Remote Intelligence of Building Interiors poses a number of serious challenges to a radio frequency imaging system. The complex nature of the building environment alongside the requirement to attain a sufficient amount of energy on the target necessitates massive measurement diversity to provide useful intelligence. QinetiQ is currently undertaking a research and demonstration project under UK MoD's Chief Scientific Advisor funding that aims to develop and exploit active and passive RF imaging of building interiors as a widely applicable intelligence tool. The objectives of the project are to derive an understanding of RF interactions with the building environment and objects and activities of intelligence interest; develop active and passive imaging techniques exploiting that understanding; evaluate potential intelligence concepts and capabilities; and mature system technology and processing techniques, facilitating rapid development and transition into service. These objectives are being addressed through the development of an experimental sensing and processing system comprising a miniature, coherent, active/passive sensor based on commercial off-the-shelf (COTS) technologies; the use of 20kg class unmanned multi-rotor aircraft as a low-cost sensor platform; the deployment of multiple sensor platforms in a distributed, coherent aperture; and the use of advanced synthetic aperture processing techniques to derive high resolution, multi-dimensional image products. This paper will provide a general review of these activities and the principles behind them.**

***Keywords—SAR; passive radar; bistatic; coherence; image formation***

## I. Introduction

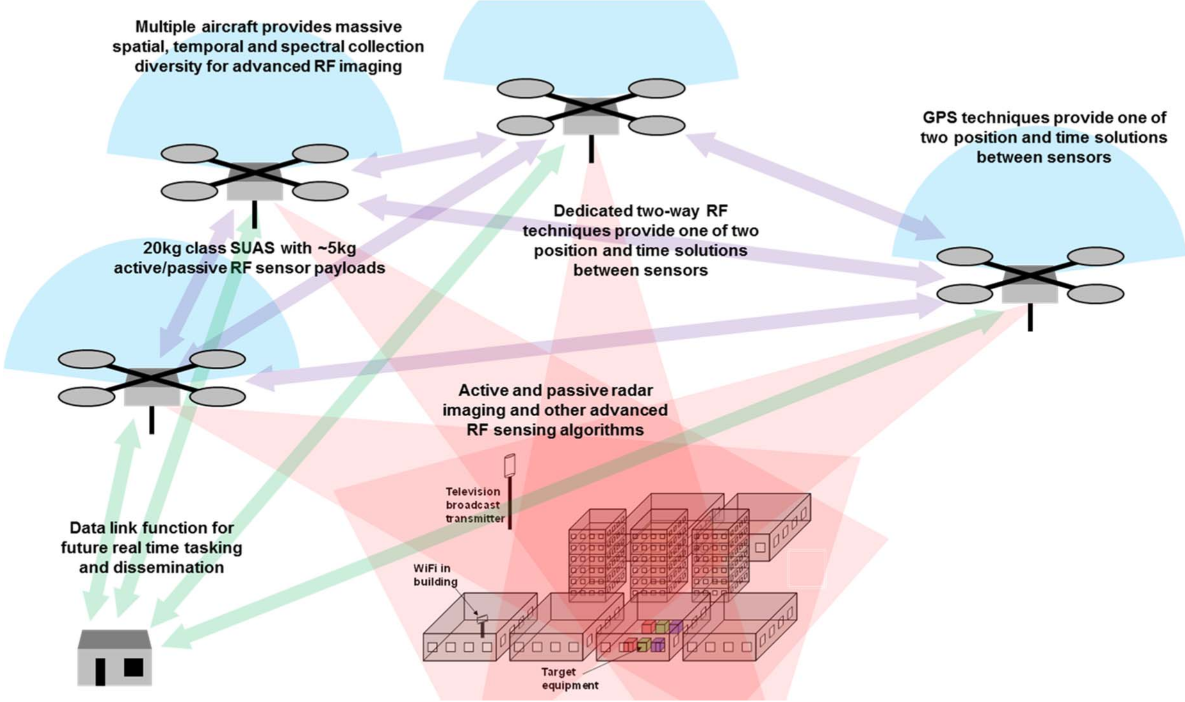
Remote Intelligence of Building Interiors (RIBI) poses a fundamental technical challenge: obtaining a sufficiency of energy and information at a remote sensor to draw inferences concerning a building structure and objects and activities within it.

Of the sensing modalities currently available, radio frequency (RF) imaging probably has the best prospect of providing a widely applicable solution to RIBI. RF signals of appropriate frequencies are known to propagate into and out of buildings, for example television, radio, WiFi and mobile phones [1]. RF imaging, in the form of synthetic aperture radar (SAR), is well established as a high spatial resolution sensor, used in a wide range of intelligence tasks with appropriate exploitation. However, this imposes a number of serious and related challenges in the RIBI role: opposing requirements from energy and information considerations on choice of frequency; conflict with other users of the RF spectrum at the frequencies of choice; and the more fundamental question as to how RF signals interact with a complex building environment and objects and activities within it.

The level of information delivered by a radio frequency sensing system, 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 [2]. 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.

QinetiQ is currently undertaking a research and demonstration project under UK MoD's Chief Scientific Advisor funding that aims to develop and exploit active and passive RF imaging of building interiors as a widely applicable intelligence tool. These objectives are being addressed through the development of an experimental sensing and processing system comprising a miniature, coherent, active/passive sensor based on commercial off-the-shelf (COTS) technologies; the use of 20kg class unmanned multi-rotor aircraft as a low-cost sensor platform; the deployment of multiple sensor platforms in

Figure 1. Research and demonstration system concept




a distributed, coherent aperture; and the use of advanced synthetic aperture processing techniques to derive high resolution, multi-dimensional image products.

This paper examines the system concepts and engineering challenges of realising coherent sensors in a small form-factor, at low cost. Initial work investigating performance prediction, RF imaging techniques and sensor technology for RIBI is addressed followed by an early understanding of the phenomenology of RF interactions with the building environment and its contents, based on computer modelling. We conclude with a summary of our findings so far and a description of the forthcoming experimental phase of the programme.

## II. System Concepts

The research and demonstration system concept is shown in Fig. 1. It sets out to achieve a step-change in capability and represents a possible transition route to an end-application, but constructed as a tool to advance our understanding of the RIBI problem. It is based on a generalisation of RF imaging, a ‘distributed active/passive coherent synthetic aperture’. Sensors operate together coherently, meaning that data is combined at the signal level, between sensors and over time, to realise specific active or passive imaging techniques, or to extend the measurements to increase spatial resolution [3]. Utilising combined measurements over space, time, frequency, and potentially polarisation is described as ‘high measurement diversity’ and at a fundamental level is the means of extending the information obtained to a level that may allow RIBI problems to be tackled.

Distributed coherent sensing requires that the position and time of all sensors in the array is known very accurately as a function of time [4, 5] – the goals for this system are 5mm for position and 15ps for time. This is achieved using multiple facilities within the system including GPS carrier phase methods, inertial measurement, an atomic clock on each sensor, and dedicated two-way broadcasts between all sensors in the array. This last measure could be thought of as a private GPS network but, by operating it at a much higher frequency, has a much higher measurement precision than GPS.

The coherent sensors are implemented in miniature form using COTS technologies that have become available in the last few years. Hitherto, coherent sensors could only be implemented in large, heavy (order 100kg) and expensive installations to be flown on large, manned aircraft. Utilising advanced COTS technologies and more sophisticated processing to counter their limitations allows a sensor to be realised that, in some respects, is more capable than previous sensors, but with a mass of around 5kg. This, in turn, allows the use of a much smaller and cheaper aircraft, in this case a 20kg class Small Unmanned Aircraft System (SUAS), in other words, a large quadcopter. The use of much lower size, weight, power and cost (SWAP-C) sensors and aircraft makes a distributed aperture system practical and affordable for both research and potentially operational purposes, although the quadcopter is not necessarily the aircraft of choice for operational use. The research/demonstration system is currently in the testing and characterisation stage with some preliminary experimentation having been carried out against building environments.

## III. RF IMAGING TECHNIQUES

One of the advances we are seeking to make in applying RF imaging to RIBI is a substantial increase in information through increased measurement diversity. This exploits the distributed coherent aperture sensing concept employed in the experimental system by extending measurements in space, time, frequency, polarisation etc. to produce a multidimensional dataset.

For practical reasons, our experimental RIBI system operates bistatically, meaning that transmission and reception is accomplished from different sensors [2]. An active SAR in a RIBI role will typically operate at lower frequencies than a system designed to operate in free space, as attenuation through the building structure is lower, although coupling through apertures such as windows reduces at very low frequencies. From a propagation perspective, frequencies as low as 100MHz might be desirable; however spatial resolution and thus information scales with frequency, and frequencies in the range 300MHz to 3GHz probably represent the best compromise for RIBI. Thus medium to low frequency SAR is one of the primary RF imaging modalities for RIBI. Our experimental system covers a frequency range of 500MHz to 6GHz, and down to 100MHz with an alternative antenna, allowing the utility of different frequencies against different building structures to be investigated.

The use of active SAR in the 300MHz to 3GHz frequency range pre-supposes that free spectrum is available. This may be true in some scenarios but is generally not the case as broadcast radio and television, cellular communications and wireless networks occupy all available spectrum [6]. An active SAR would cause unacceptable interference to these systems and would itself be degraded by interference, precluding the use of active techniques in most scenarios. An alternative approach is to use these interfering signals as illuminators of opportunity in a passive SAR concept [7, 8].

While an active SAR is based on matched filtering with the known transmitted waveform, a passive SAR is based, in principle, on correlative processing between a direct-path reference signal and signals reflected from the scene being imaged. In some scenarios, for example the case of a broadcast radio illuminator, the illuminator is located outside of the scene and a clean direct path reference signal may be obtained using angular discrimination. This concept requires a single sensor platform with two antennas (beams). A more interesting scenario from a RIBI perspective is that of an illumination source, such as a WiFi transmitter, operating inside the building. This has performance (sensitivity) advantages as the signals only need to penetrate the building structure in one direction. However, this is more challenging from a techniques perspective as a clean reference signal cannot be obtained. Multiple receivers must now be used in a bistatic configuration, and more sophisticated processing is required to form an image.

a)

b)

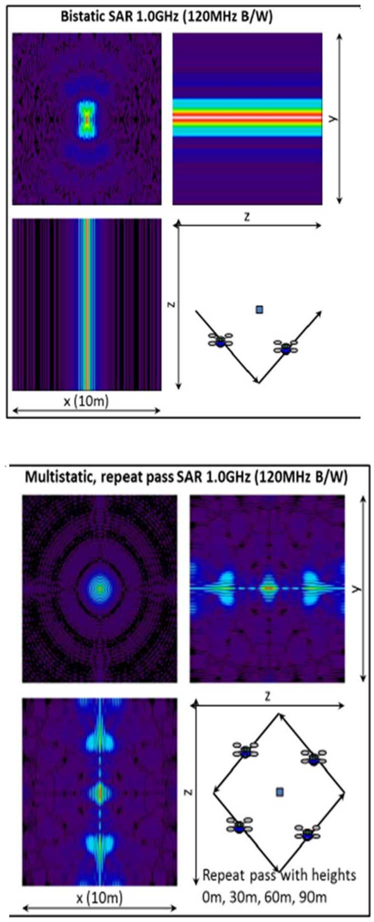



Figure 2. Transition from 0.1x0.6,m 2-D to 0.1x0.1x0.6m 3-D resolution through measurement diversity (2-D principal axis slices through 3-D image impulse responses)

Conventional active and passive SAR images are generated from one imaging leg undertaken by a single sensor. Employing additional sensors at different collection geometries and/or combining data from multiple imaging legs over time (repeat pass imaging) substantially increases measurement support and thus spatial resolution. An example of the predicted improvement in resolution from such measures is given in Fig. 2. This case is based on the use of additional sensors and repeat pass imaging at different platform heights, and shows how spatial resolution may be improved and resolution in a third dimension obtained. This last aspect is particularly important for RIBI as a building is a three dimensional structure and resolving in all three dimensions is essential if results are to be interpretable. Simulated 3-D imagery of a simple building is shown later in Fig. 4.

Increased measurement diversity can be employed to achieve increased information in forms other than spatial resolution. For example, measurement diversity in time can be used to detect movement (moving target imaging) or wavelength scale changes within the scene over timescales up to days (coherent change detection). These are all examples of ways in which the information available from RF imaging may be enhanced to address the complexity of the building environment. At this stage, it is not clear which techniques will be most effective and the experimental system supports all of these options and will allow different RF imaging modalities and forms of extended measurement support to be evaluated.

## IV. Compact Coherence Sensor Technology for RIBI

In the traditional radar context, a coherent sensor is one that achieves coherence (sub-wavelength stability) between transmit and receive functions on a timescale of the propagation time from transmitter to receiver via the target, typically a few milliseconds. In the case of a conventional monostatic SAR, there is also a requirement that platform position is known to sub-wavelength accuracy in a time-relative sense, on the timescale of the synthetic aperture which is typically of order ten seconds. Coherence in the context of a distributed coherent aperture system is substantially more demanding. Achieving full performance potential requires that position of sensors is known in an absolute sense (i.e. on an indefinite timescale) to sub-wavelength level, in this case assuming operation at 3GHz a tolerance of 5mm. The phase of transmitter and receiver local oscillators and the timing of direct digital synthesis (transmit) and receiver digitiser functions must be related across the sensors making up the system to a relative accuracy of 15ps, also on an indefinite timescale. These numbers represent the ultimate performance goals for the system and useful partial capabilities are still achievable with various degrees of compromise.

Coherence is realised through a number of measures in the sensor and across the system:

- provision of a stable transducer (radio transmitter and receiver);
- provision of instrumentation – GPS, inertial measurement unit and a chip-scale atomic clock;
- the use of dedicated timing and phase referencing circuitry interconnecting the transducer and instrumentation, and the precise manner of their interconnection;
- the use of dedicated two-way broadcast of timing waveforms between sensors, and algorithms to determine time and position, similar to those used in carrier phase GPS processing.

The top level functional and physical designs of the sensor are shown in Fig. 3. It is centred on a dual channel RF system, instrumentation and a control processor and data storage system.

In more detail, the main components of the system are:

- wide band spiral sensor antenna (intended to be exchangeable for other antennas in different roles, e.g. polarimetric patch antennas) usable from 500MHz to 6GHz;
- omni-directional 5.8GHz dipole antenna for coherent positioning;
- flexible RF system including switches and filters; space to upgrade with power amplifier, LNA, fast frequency agile pre-tranceiver etc;
- dual channel, full duplex software defined radio, tuneable from 10MHz to 6GHz, transmit and receive bandwidths up to 160MHz;
- low noise chip-scale atomic clock, high grade MEMS inertial sensor and commercial multi-band GPS receiver with survey grade antenna;
- multi-core processor for control, diagnostics and data recording on hardware-encrypted solid state disk RAID;
- light-weight carbon fibre and alloy construction, extensive use of 3-D printing, external and internal RF screening.

While performance of the sensor was specified at a high level, design decisions were based primarily on the availability of key COTS components, and the performance of the sensor is determined largely by the performance of those components, many of which are being used outside of their intended application area. A key aspect of the development process is thus characterisation of performance, particularly with regard to timing performance and coherence. This work is currently in progress.

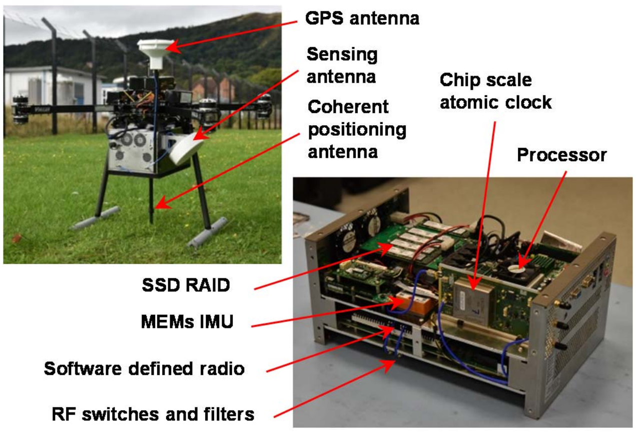



Figure 3. Functional and physical design of the sensor payload alongside the sensor integrated onto the aircraft

Fig. 3 also shows the physical realisation of the sensor installed on the aircraft. The aircraft itself is a Vulcan Raven X8 sub-20kg class SUAS. This is used with a SkyCircuits SC2E autopilot, modified by the manufacturer for this project to provide antenna stabilisation on a specified ground location (by changing the orientation of the aircraft), and automatic, multi-aircraft, waypoint flying using linear trajectories suitable for RF imaging.

The coherent sensor technology developed is believed to be unique, both in terms of performance and form factor. It is seen as a key enabler for the RF imaging approach to RIBI, in supporting the necessary distributed coherent aperture imaging concepts and in allowing this to be realised on small, low cost aircraft. This last factor is critical to a viable multi-aircraft experimentation programme and potentially also to future operational concepts.

## V. PHENOMENOLOGY OF RF IMAGING IN A BUILDING ENVIRONMENT

The interaction of RF signals with a building environment has been investigated by other organisations, primarily for the purpose of predicting performance of wireless networks and cellular communications systems. The experimental work undertaken as part of this programme is focussed heavily on the RIBI application and will investigate the manifestation of objects and activities of potential intelligence interest in RF imaging products. The following list of phenomena is to be investigated: general propagation, attenuation and scattering properties as a function of frequency; general structural layout of building – locations of internal walls and doors; hidden structural elements – cavities, reinforcement, access routes; presence, number and location of people – in concealment, motionless; signatures of specific objects – spatial, polarimetric, micro-Doppler; anomalies between similar buildings; gross (incoherent) changes over time; fine (coherent) changes over time; instantaneous movement; accurate location of all of the above within the 3-D building environment.

We plan to use computer modelling as an aid to understanding the results of experimentation and as a means of extending experimental results. We employ a commercial RF propagation modelling package, WinProp, which takes as its input a CAD model of the building and objects within it. The model predicts possible propagation paths, field strengths and path lengths. We use these with a model of the sensor system to predict measurements over one or more surfaces. RF imaging is emulated by projecting the synthetic aperture of the

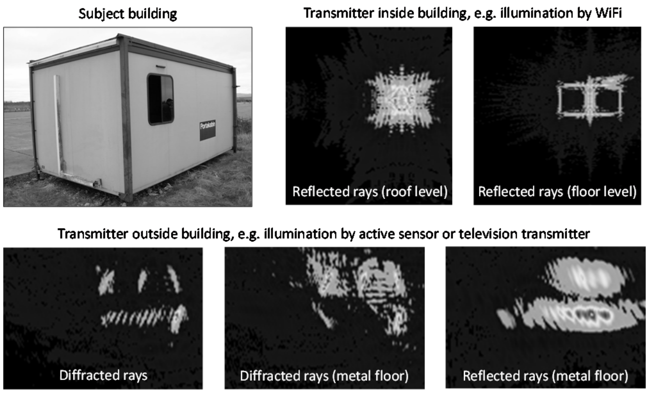



Figure 4. Computer modelling results showing building structure

sensors in the measurement surface, predicting signal data. Example output from the computer modelling for a simple prefabricated building is shown in Fig 4.

Two preliminary experimental campaigns, ground based and airborne, have been undertaken with a spiral development approach being adopted for future collects. Target complexity is planned to increase as the understanding of the system capability increases.

Fig. 5 shows initial results from an airborne collect using two platforms quasi-monostatically at 0.7GHz.

Figure 5. Preliminary results from the active (0.7GHz) airborne collect using two platforms to collect quasi monostatically.

Although Fig. 5 demonstrates successful image formation which corresponds well with the underlying target area, it is evident that interpretation of such data would benefit from increased collection of the available data space, e.g. higher frequency context imagery or exploitation of polarimetry to better understand returns from building internals. Future collections will aim to exploit the full frequency and spatial diversity of the developed system against a range of target structures.

## VI. SUMMARY

The Remote Intelligence of Building Interiors poses a number of serious challenges to a radio frequency imaging system. The complex nature of the building environment alongside the requirement to attain a sufficient amount of energy on the target necessitates massive measurement diversity to provide useful intelligence. QinetiQ is building an experimental sensing and processing system with which to investigate phenomenology, develop techniques, quantify and demonstrate capability, and de-risk key technologies. While it is too early to draw conclusions concerning capability, we have established a number of key findings:

- RF imaging appears to be the sensing modality most likely to result in a widely applicable capability because of the propagation properties of RF signals through building structures and the potential for an imaging process to realise detailed information concerning the building and its contents.
- RF imaging will be required to operate at lower frequencies than conventional imaging radar, probably 0.3-3GHz, to achieve an acceptable balance between energy propagation and information.
- The prevalence of broadcast and communications systems in the relevant band requires that a number of RF sensing modalities are pursued – active imaging,

passive imaging using in-band transmitters as illuminators of opportunity, and electronic surveillance techniques.

- The over-riding need for detailed information to address the complex building environment requires the use of distributed coherent aperture techniques to maximise measurement diversity.
- Distributed coherent processing requires specialised coherent sensors. A unique, low SWAP, high performance coherent sensor has been developed based on COTS technologies and is compatible with sub-20kg class SUAS, making a multi-platform experimental programme viable and potentially facilitating operational applications with this or other small aircraft types.
- Computer modelling has been used to conduct an early investigation of phenomenology and shown the ability to discern internal building structure.
- Preliminary ground and air based data collections have demonstrated promising results in terms of bistatic image formation, showing building penetration and suitable dynamic range.

Further characterisation of the experimental sensing and processing system is currently being completed. This will enable increased exploitation of the frequency and spatial diversity afforded by the system. Further measurement campaigns are planned against a suitable relevant target set.

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