BISTATIC SYNTHETIC APERTURE RADAR

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ABSTRACT

Synthetic Aperture Radar (SAR) is becoming increasingly important in many military ground surveillance and targeting roles because of its ability to operate in all weather, day and night, and to detect, classify and geolocate objects at long stand-off ranges. Bistatic SAR, where the transmitter and receiver are on separate platforms, is seen as a potential means of countering vulnerability. This paper provides an overview of QinetiQ's on-going research into the processing techniques for bistatic SAR, the fundamental problems it introduces, and ways to overcome them.

INTRODUCTION

The first radar experiments and operational radar systems were all bistatic – meaning that the transmitter and receiver were located at different sites. In the first instance of radar detection this was inherent in the nature of the experiment, which employed an illuminator of opportunity and an independent receiver. In early operational systems, a short baseline bistatic arrangement overcame the considerable engineering difficulties associated with coupling a high power transmitter and a sensitive receiver into the same antenna. Clever engineering developments then overcame the transmitter/receiver isolation problem. The monostatic radar configuration became established as the most practical system solution for most applications. This was developed, into the high resolution, multi-mode, pulse Doppler radars we see today. In comparison, bistatic system concepts became increasingly unattractive as radar complexity and performance increased.

Bistatic radar represents a class of systems, of which monostatic radar is a special case. As would be expected, this results in limitations in monostatic systems that can be overcome in the more general bistatic configuration. Advances in timekeeping, communications, and navigation in the last two decades have made bistatic radar a practical option again and bistatic systems have started to receive consideration. A typical example of such work was the extensive research and demonstration programme into ground-based air defence radar, centred at what was then RSRE Malvern, and involving many research groups in UK industry, Dunsmore (1).

This paper describes a programme of research into an even more challenging application of bistatic techniques – airborne ground surveillance radar and, in particular, synthetic aperture imaging radar.

Synthetic aperture radar is becoming increasingly important in many military ground surveillance and targeting roles because of its ability to operate in all weather, day and night, and to detect, classify and geolocate objects at long stand-off ranges. SAR in the UK is typified by the forthcoming ASTOR system and a wide range of system concepts work including its use on strike aircraft, Horne and Coe (2). Bistatic SAR is seen as a potential means of countering vulnerability to electronic countermeasures, particularly directional responsive jamming, and avoiding physical attack to the imaging platform, aided by its electronic emissions. Bistatic SAR counters these problems by allowing the receive-platform, with its expensive processor and invaluable exploitation personnel, to remain covert. The transmit platform remains inherently vulnerable but is cheaper and for system reasons we generally have more freedom of deployment than we do for the receiver. We then have scope to counter that vulnerability, for example, by deploying the transmitter further away from defences, or even using multiple expendable transmitters on UAVs. The physics of the interaction of bistatic SAR with a target environment also opens up a number of interesting possibilities. For example, it is likely that, by breaking up strong trihedral responses, bistatic imaging will reduce the dynamic range of difficult imaging environments such as urban ones, making it easier to exploit imagery to detect and classify military activity. Bistatic SAR also has the potential to counter target stealth.

This paper describes a programme of research funded under the MoD Corporate Research Programme, and being undertaken by QinetiQ Malvern. The element of that research described here aims to overcome the fundamental problems of bistatic SAR and develop suitable RF and processing techniques. The programme aims to demonstrate high (sub-metre) resolution bistatic operation to de-risk the technique, understand performance limitations and quantify military utility to inform future concepts and systems development work. We concentrate here on the key spotlight mode of operation, in which a single antenna footprint is imaged with no restrictions on aperture time. This removes the need for pulse chasing techniques, Willis (3), although these and the sophisticated antenna techniques needed to achieve them are addressed elsewhere within our programme. Here we concentrate on the issues specific to bistatic SAR as opposed to other bistatic modes: imaging performance theory; bistatic synchronisation and phase noise; bistatic SAR processing and motion compensation; and the characteristics and utility of bistatic SAR imagery. This paper reviews our research into these topics under our on-going programme of work.

BISTATIC SAR PERFORMANCE THEORY

Understanding the operation of bistatic SAR at a system level is a key aim of our research and also provides a good introduction to many of the issues. We have developed a complete theory of performance. However, the areas in which it is most distinct from monostatic SAR are in the imaging process itself (through the complexity of the bistatic geometry) and in the accuracy of geolocation (through the use of multiple airborne platforms). We limit discussion here to the first of these topics.

SAR employs a focussed form of range-Doppler imaging to resolve objects in two dimensions. As such one would expect image characteristic orientations to be determined by lines of constant Doppler frequency and range, and this is indeed the case. Figure 1 shows a simplified (two dimensional) bistatic geometry (not to scale). We define a Cartesian frame centred at scene centre with axes (termed u and v) orientated perpendicular to iso-dops and iso-ranges respectively.

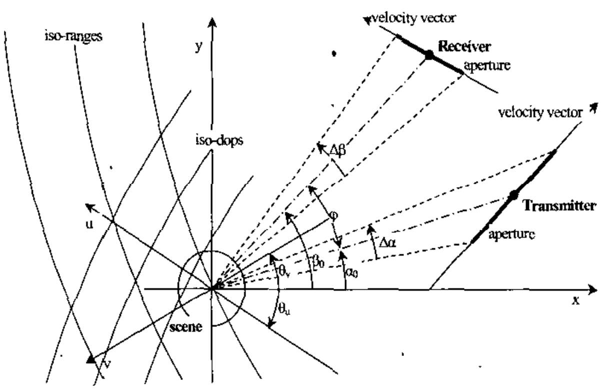


Figure 1 bistatic SAR imaging geometry

We can show that the orientations of these axes are given by:

$$\tan\theta_u = -\frac{\Delta\alpha\cos\alpha_0 + \Delta\beta\cos\beta_0}{\Delta\alpha\sin\alpha_0 + \Delta\beta\sin\beta_0},\ \theta_v = \frac{\alpha_0+\beta_0}{2} \quad (1)$$

where $\Delta\alpha$ and $\Delta\beta$ are the angular rates of transmitter and receiver about the scene, and α_0 and β_0 are their orientations with respect to the scene at aperture centre. Spatial resolutions in the u and v dimensions are given by

$$\rho_u = \frac{c}{f_0 K},\quad \rho_v = \frac{c}{2\Delta f\cos(\varphi/2)} \quad (2)$$

where $K^2 = (\Delta\alpha)^2 + (\Delta\beta)^2 + 2\Delta\alpha\Delta\beta\cos\varphi$, φ is the bistatic angle, f_0 is the radar centre frequency and Δf is the bandwidth. These results represent a reduction in resolution compared to a monostatic system with the same bandwidth and synthetic aperture time, and a non-orthogonal point spread function that may affect image interpretability. These effects are shown in Figures 2I and 2ii as four plots: orthogonality, u-axis resolution, v-axis resolution and a single overall measure. In each case the x-axes show relative angular motion of transmitter and receiver with equal angular motion at the axis centre and opposite angular motion at the edges, the y-axis represents the bistatic angle.

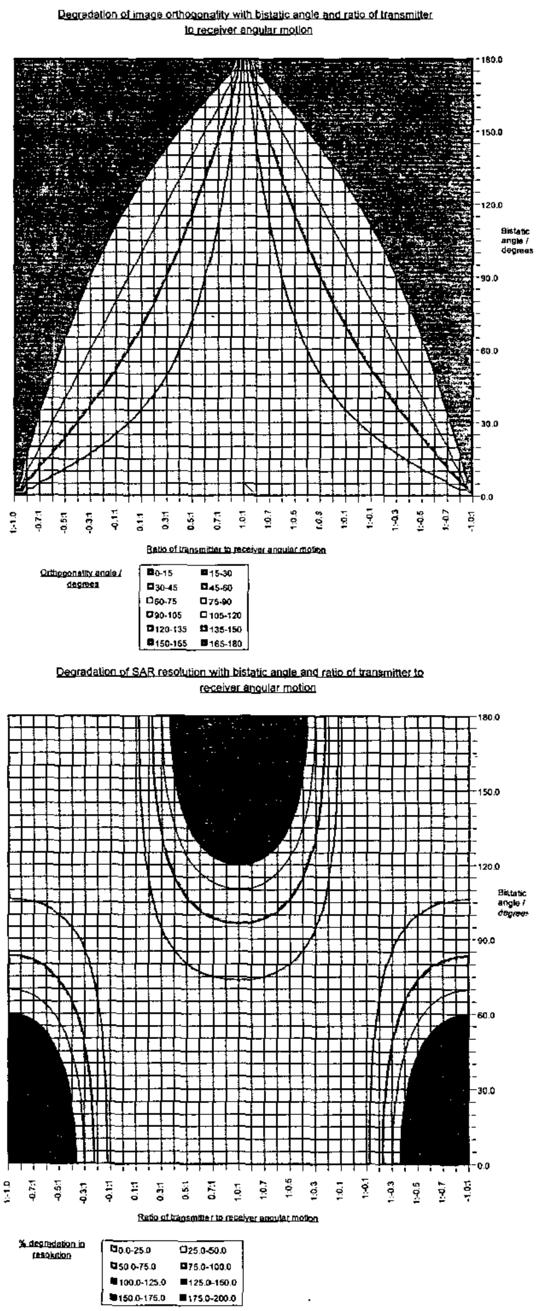
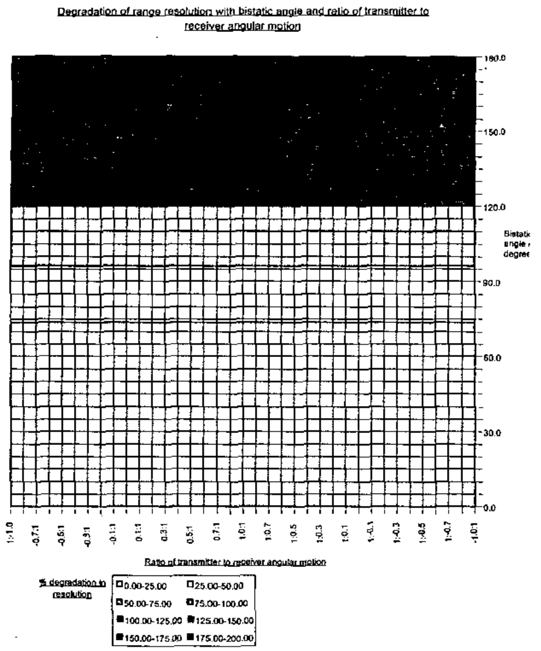


Figure 2i Imaging "efficiency" as a function of bistatic geometry



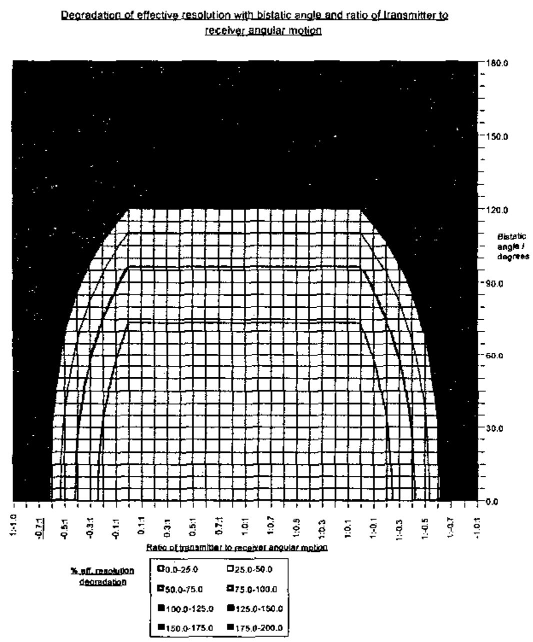


Figure 2ii Imaging "efficiency" as a function of bistatic geometry

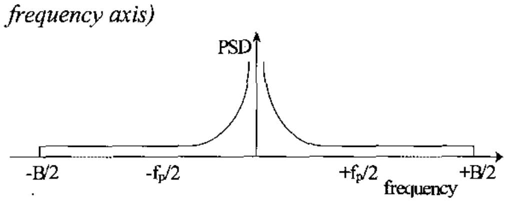
BISTATIC SYNCHRONISATION AND PHASE NOISE

The synchronisation of transmitter and receiver is a fundamental part of any bistatic system and is very demanding in bistatic SAR because of the long integration times and wide signal bandwidths involved. Any pulse Doppler radar measures two quantities: time delay and Doppler shift. There are two corresponding aspects to bistatic synchronisation: time *synchronisation* and frequency *syntonisation*. Time synchronisation accuracy is driven by required geolocation performance and will typically be less then 100ns. Frequency syntonisation accuracy is driven by aperture time (and, thus, range and resolution) requirements, *u*-axis sidelobe requirements and geolocation performance. Syntonisation accuracy is best characterised by oscillator phase noise and is very demanding.

There are two fundamental approaches to achieving bistatic synchronisation: provision of extremely accurate independent time and frequency standards on each platform, or the continuous transfer of time and frequency standards between platforms. The first method requires something like an atomic clock. The second can be achieved through direct path reception of the transmitted waveform at the receiver, a dedicated RF link, or a broadcast link such as that provided by the GPS system. We will use the atomic clock method, but the analysis that follows is universally applicable.

Phase noise requirements for bistatic systems are fundamentally different from those of monostatic radar. The monostatic system uses the same master oscillator to generate the reference frequencies used in both up-conversion and down-conversion. Low frequency components of phase noise have little effect on system performance because they change little from the time of pulse transmission to the time of reception. This time is of the order of the pulse repetition interval for a typical system, thus, the system is not susceptible to phase noise components at frequencies lower than the PRF (f_p). This is shown in Figure 3(b). Thus, The phase noise that the monostatic SAR actually "sees" is the region from the PRF to the bandwidth of the system, aliased back into the region of the spectrum up to the PRF by the Doppler sampling of the system, Figure 3(c).

a) Oscillator phase noise spectrum (note discontinuous frequency axis)



b) Phase noise not cancelled by common transmit/receive oscillator in monostatic SAR

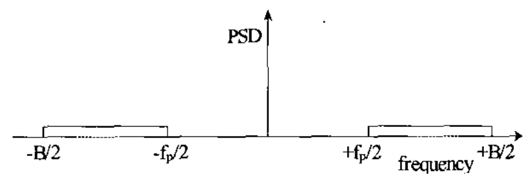
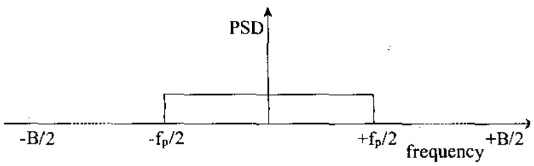


Figure 3i effect of oscillator phase noise in monostatic and bistatic systems *c) Un-cancelled phase noise in monostatic SAR after sampling (aliasing at the PRF)*



d) Un-cancelled phase noise in bistatic SAR after sampling (aliasing at the PRF)

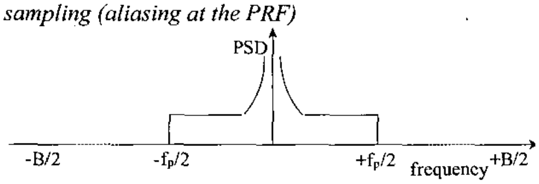


Figure 3ii effect of oscillator phase noise in monostatic and bistatic systems

In the case of a bistatic system, the situation is rather different. Separate oscillators are involved in transmitter and receiver and will exhibit independent realisations of phase noise. Thus the bistatic system is susceptible to the whole phase noise spectrum including the close-to-carrier component, Figure 3(d). In fact the system actually "sees" the sum of the phase noise powers from the two oscillators, i.e. a phase noise spectrum 3dB higher than that from a single oscillator.

We can quantify the phase noise requirements using a relation we have derived for the effect of phase noise on the u-axis point spread function

$$\left\langle |h(u)|^2 \right\rangle \approx |h_i(u)|^2 + \int_0^\infty \frac{\Psi(f)}{2} \left\{ \begin{aligned} &\left| h_i\left(u - \frac{R_0 c}{2 f_0 v} f \right) \right|^2 \\ &+ \left| h_i\left(u + \frac{R_0 c}{2 f_0 v} f \right) \right|^2 \end{aligned} \right\} df \qquad (3)$$

where $h_i(u)$ is the ideal point spread function, $\Psi(f)$ is the single sideband phase noise spectrum, and R_0 and v are a representative range and platform velocity. Substituting the specified phase noise spectrum of a caesium primary frequency standard, Hewlett Packard (4), we can calculate the fidelity of the point spread functions for both monostatic and bistatic systems, Figure 4. It is clear that the performance of both monostatic and bistatic systems are acceptable. However, phase noise effects scale with synthetic aperture length and time, and it is clear that a longer integration time in the bistatic system would result in only a marginal performance improvement.

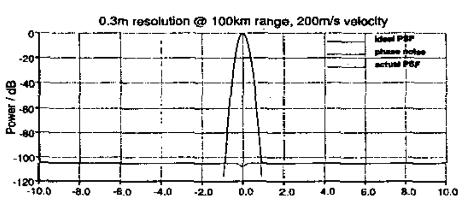


Figure 4a point spread functions for and monostatic SAR.

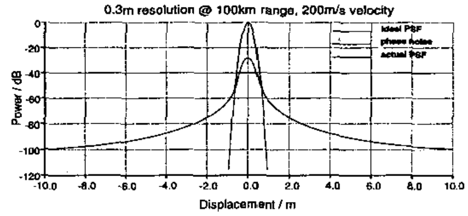


Figure 4b point spread functions for and bistatic SAR.

BISTATIC SAR PROCESSING

SAR processing performs, what is essentially, a double integral of raw data, along the synthetic aperture and across the bandwidth of the system, for each pixel in the image. Direct implementation of this double integral approach serves to demonstrate the characteristics of the bistatic point spread function to confirm the performance theory presented earlier, but is impractical in any real application. Figure 5 shows images processed from simulated bistatic data using this method. The first simulates a bistatic angle of 60°, the second 90°.

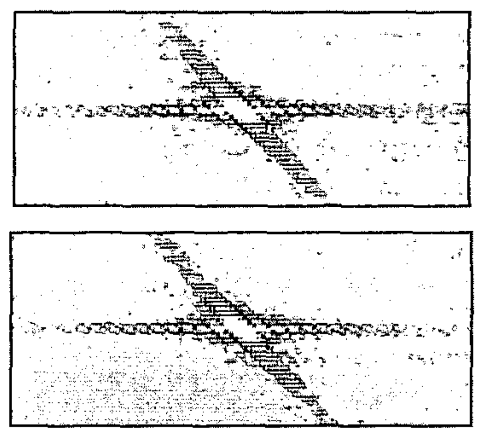
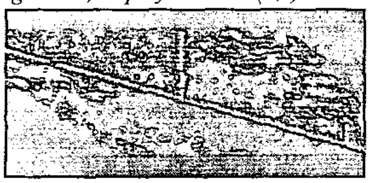


Figure 5 simulated images processed using the double integral method

Practical SAR processing algorithms seek to approximate the double integral using techniques that ultimately link back to fast convolution, i.e. Fourier transforms. While similar types of approximation may be used in bistatic radar as in the monostatic case, a lot of the detail is more complex. We have addressed two algorithmic approaches: a simple approach based on the monostatic polar reformat algorithm (PFA), Carrara et al. (5), and a more sophisticated approach based on the range migration algorithm (RMA), Carrara et al. (6). Monostatic PFA uses three key processing stages: compensation of the raw data for the motion of the imaging platform seen at scene centre, mapping of the resulting (approximate) polar K-space data onto a rectangular K-space representation, and a Fourier transform to the image domain. In the monostatic variant the motion compensation to scene centre has been extended to include the effect of motion of transmit and receive platforms. The second polar reformat stage has been approached using two methods. The first uses the projection of motion compensated data into K-space at an angle bisecting the bistatic angle; the second uses an alternative optimisation that appears to achieve larger scene sizes at severe bistatic geometries. Figure 6 shows an example of processing of simulated bistatic data. Work on the bistatic variant of the RMA algorithm is on-going.

a) monostatic image used as a measure of scene complex reflectivity for bistatic data synthesis

b) bistatic image processed using bistatic PFA algorithm, displayed in the (u,v) domain



c) bistatic image interpolated back to the physically correct (x,y) domain

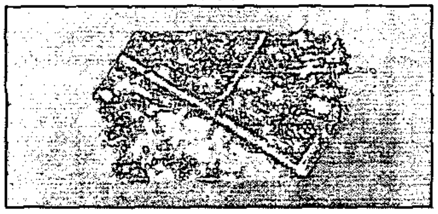


Figure 6 example of processing of simulated bistatic data using the bistatic PFA algorithm

A final aspect of bistatic SAR processing is the compensation of unintended platform motion. In a monostatic system this is achieved using the output of on-board navigation sensors and adaptive processing (autofocus), Oliver (7). Motion can be estimated readily from navigation data in the bistatic case using an integrated navigation solution for each platform. Simple autofocus can also be performed easily, but will not necessarily correct over the entire scene. This is a known problem in the monostatic case also; and the solution we adopt is to use a sophisticated model-based focus method, Oliver (8), that estimates uncompensated platform motion in a number of dimensions, typically two or three. This approach is currently being extended to the bistatic problem using a factorisation to avoid having to estimate the six degrees of freedom present in the bistatic problem.

CONCLUSIONS AND FURTHER WORK

This paper has provided an overview of a programme of research addressing the problems of bistatic SAR imaging. We have shown that imaging is possible over a surprising range of bistatic geometries with reasonable efficiency. The theory of bistatic synchronisation has been set out and the effect of oscillator phase noise considered in detail, showing that caesium atomic clocks provide a viable solution. Finally, we have demonstrated a simple but effective bistatic image formation algorithm, with more sophisticated approaches under development. Our future work will concentrate on putting these components together in a fully synchronised high-resolution bistatic SAR experiment. It is hoped that results will be available by the time of this conference.

ACKNOWLEDGEMENTS

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