

## ORIGINAL RESEARCH

# Bistatic multi-polarimetric synthetic aperture radar coherence investigation using spatially variant incoherence trimming

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## Abstract

Synthetic Aperture Radar (SAR) Coherent Change Detection allows for the detection of very small scene changes. This is particularly useful for Intelligence, Surveillance and Reconnaissance as small changes such as vehicle tracks can be identified. Rapidly collecting repeat pass SAR imagery is important in these applications. For space-borne platforms, such repeat passes may however have significant differences, or baselines. Coherent Change Detection products are reliant on high coherence for good interpretability. This work investigates the sources and levels of incoherence associated with bistatic SAR imagery for a variety of baselines using simulations and measured laboratory data for two ground types. Additionally, spatially variant incoherence trimming is implemented. The paper shows the importance of angle-dependant backscatter on the coherence of sub-resolution cell scatterers.

## KEYWORDS

decorrelation, electromagnetic wave scattering, frequency-domain analysis, multistatic radar, polarimetric radar, radar clutter, radar interferometry, remote sensing by radar, synthetic aperture radar, ultra wideband radar

## 1 | INTRODUCTION

High resolution Synthetic Aperture Radar (SAR) images enable detailed reconnaissance and surveillance of the Earth's surface for all weather, during the day and night. Synthetic Aperture Radar interferometry can be used to determine a Digital Elevation Maps [1, 2] and can be used for the detection of very small scene changes, such as vehicle tracks, using Coherent Change Detection (CCD) [3–6].

For high quality CCD results, typically two radar platform trajectories are closely repeated, with a low baseline, [7–9]. For satellites, this may necessitate long revisit times which may for example, lead to decorrelation due to natural processes such as wind and rain [8], which would reduce CCD interpretability.

The research presented here is applicable to multistatic/bistatic satellite constellations, such as that being developed by the UK MOD under the name Project Oberon [10]. For such constellations, the ability to utilise trajectories with greater baselines and differing bistatic geometries could help reduce revisit times. However, such image pairs may potentially have low SAR coherence. This work is also relevant to multistatic

Uncrewed Air System swarms with either a transmitter [11–13] as part of the swarm or with a stand-off large illuminator [11, 14].

Forming good quality high contrast CCD results is reliant on high coherence between SAR images [7, 15]. This coherence can be reduced by natural processes such as wind and rain [15–18]. Thus, conducting rapid repeated passes would help mitigate this effect and allow for monitoring developing situations in a timely manner.

Bistatic (and multistatic) radar geometries involve having the transmitter and receiver(s) substantially separated, with multistatic geometries being comprised of multiple simultaneous bistatic collections. Multistatic SAR can have several advantages, such as providing improved cross-range resolution [19, 20] and Signal to Noise Ratio (SNR) [21], although the choice of which SAR trajectories to combine significantly affects these [22].

Multistatic SAR satellite constellations may allow the collection of more timely change detection images to be formed using SAR image collections from differing trajectories, thus reducing the repeat pass time [23, 24]. However,

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the CCD's may be subject to varying degrees of coherence due to differing baselines and other effects such as different radar scattering due to a change in geometry, such as due to varying multipath or shadowing [25].

For high coherence and an improved change detection capability over nominally horizontal ground, the repeat pass geometries should be chosen to provide a high degree of spatial frequency (K-space) support vertical projection overlap [7, 9, 26], though it has been found that this alone is insufficient to guaranty high coherence and good CCD contrast [25].

This paper investigates the sources and levels of incoherence between Ultra-Wideband SAR [27] with different bistatic geometries, through both simulation and laboratory radar measurements. The bistatic radar trajectories were chosen to maintain a high K-space overlap with increasing bistatic angles. This allowed for the investigation into a new decorrelation parameter,  $\gamma_{\text{Scat}}$ . Synthetic Aperture Radar measurements of two ground types were conducted, to show variability due to different terrain.

This research is supported by measurements at the Cranfield University Ground-Based Synthetic Aperture Radar (GBSAR) laboratory [25, 28, 29], where antennas are scanned within two vertical rectangular apertures, which allow a great deal of flexibility and fine control of SAR geometries for the scene.

In Section 2, a background discussion of CCD and the spatial frequency domain is provided. Methodology is described in Section 3, covering the GBSAR laboratory, SAR and CCD processing and the estimation of the scattering factor. Results are presented in Section 4. Discussion and conclusions are provided in Section 5. References are provided in Reference section and SAR geometry information is provided in the appendices Section.

## 2 | BACKGROUND

### 2.1 | Coherent Change Detection

Coherence between SAR images can be provided by a measure of the similarity between the two images, ranging from 0 to 1. It can be calculated via a normalised cross correlation [7, 17, 30] over corresponding samples of the images to provide a CCD image product,

$$\hat{\gamma} = \frac{\left| \sum_{k=1}^N S_1(k) S_2^*(k) \right|}{\sqrt{\sum_{k=1}^N |S_1(k)|^2 \sum_{k=1}^N |S_2(k)|^2}} \quad (1)$$

where the magnitude,  $\hat{\gamma}$ , is referred to as the sample (estimated) coherence,  $S_1$  and  $S_2$  are the two complex images being compared,  $N$  is the number of pixels within a window sampled over the two images and  $k$  is the pixel index.

A value approaching zero indicates low coherence, for example, from a scene change, whereas values approaching 1 indicate areas of no change. An example CCD image is shown

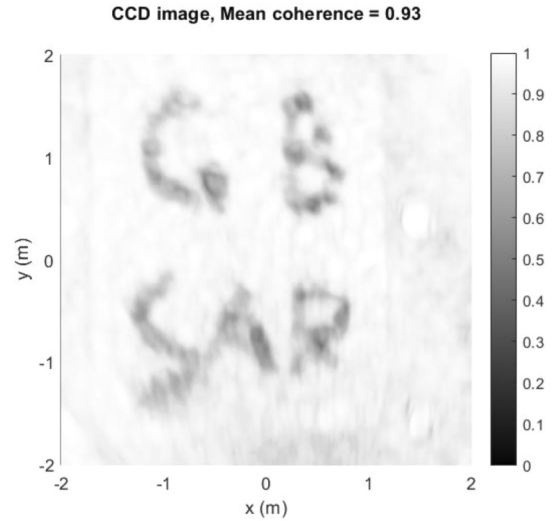


**FIGURE 1** An example Synthetic Aperture Radar (SAR) laboratory Coherent Change Detection (CCD) image.

in Figure 1. The image was produced using exactly repeated SAR trajectories of a gravel rectangle. The letters 'GBSAR' were traced on the gravel, leaving legible incoherence tracks.

### 2.2 | Spatial frequency domain

Synthetic Aperture Radar image information can be represented in the spatial frequency domain, also known as K-space, where it is given the name "image support" [7, 26, 31]. The extent of the image support is a composite of incident minus scattered wave vectors from transceivers,  $\vec{K} = \vec{k}_i - \vec{k}_s$ , to the different scene positions, where  $\vec{k}_i = \frac{2\pi}{\lambda} \hat{i}$  and  $\vec{k}_s = \frac{2\pi}{\lambda} \hat{s}$ , and  $\hat{i}$  and  $\hat{s}$  are normalised incident and scattered directions. The length of  $\vec{K}$  is proportional to frequency, and to the cosine of the bistatic angle,  $\beta$  [7]. These vectors can be plotted to trace out annulus segments within the K-space. An example is shown in Figure 2, for two different trajectories. The vertically projected areas corresponding to each collection are referred to as Projected Fourier Supports (PFS), and the PFS's corresponding to the collections in Figure 2 can be seen in Figure 3.

In the context of coherence between SAR images of horizontal rough terrain, the proportion of the overlapping PFS areas to the square rooted product of the total PFS areas [17, 26] can be used to predict coherence (see section 2.3). In Figure 3, the overlapping area  $A_c$  is defined as  $A_c = A_1 \cap A_2$ , where  $A_1$  and  $A_2$  are the PFS areas of the two radar collections.

In the SAR far-field it is straightforward to calculate K-space overlap as the PFS areas are constant over the scene. However, in the SAR near-field, the PFS areas and their overlap varies significantly across the scene, complicating the estimation of coherence [7, 26]. The SAR near-field is defined as the regime where the range  $d < 2L_{cr}^2/\lambda_c$  for centre wavelength  $\lambda_c$  and for a scene with cross-range extent  $L_{cr}$ . For the

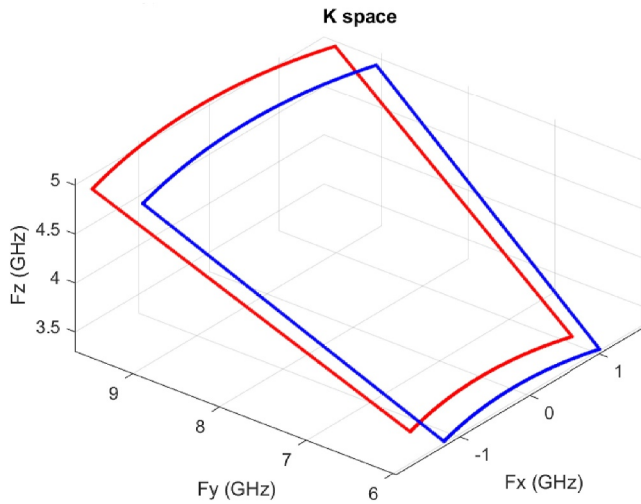


**FIGURE 2** Spatial frequency plot showing the outline of two spatial frequency domain image supports.

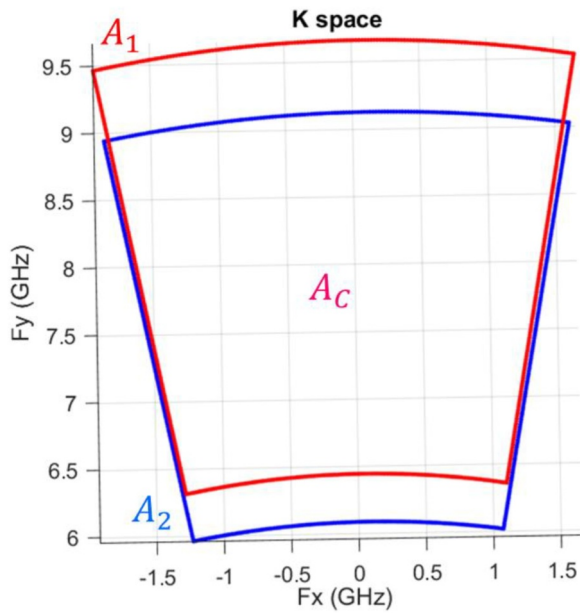


**FIGURE 3** Projected Fourier Supports (PFS) of two radar collections. The two PFS areas are labelled  $A_1$  and  $A_2$ , and have the intersecting area  $A_C$ .

GBSAR system the far-field distance  $d \approx 150$  m. The ranges in the laboratory are in the range of 4–10 m.

This can be further complicated by undulating or non-flat terrain, where the PFS projection directions are to the local terrain normal [32, 33].

The impact of the SAR near-field on the K-space is demonstrated in Figure 4. Here the K-space segments are plotted for the four corners of the scene as well as for the scene centre. It can be seen that in the SAR near-field, the PFS is spatially variant over the scene.

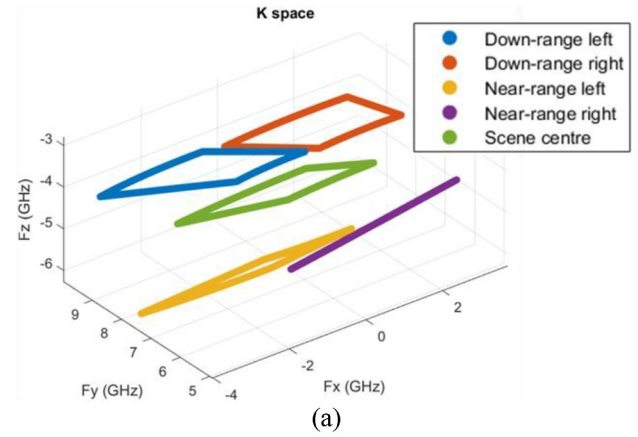
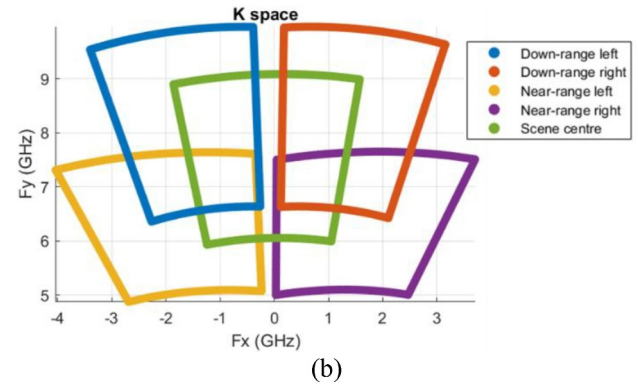


**FIGURE 4** Spatial frequency plots showing the outline of five spatial frequency domain segments in the Synthetic Aperture Radar (SAR) near-field regime, corresponding to the four corners and centre of the measured scene. A three-dimensional view is shown in (a) and ground plane projection in (b).

### 2.3 | Factors affecting coherence

The formula for calculating the sample (estimated) coherence,  $\hat{\gamma}$ , was presented in (1) Section 2.1. It is referred to as the estimated coherence because it differs from the *true* coherence. The estimated coherence,  $\hat{\gamma}$ , is biased dependent on calculation features such as the CCD estimation window size [17, 34].  $\gamma_{\text{true}}$  can be decomposed into factors which are also in the range 0–1 [7, 8, 17, 18, 35]:

$$\gamma_{\text{true}} = \gamma_{\text{temp}} \gamma_{\text{SNR}} \gamma_{\text{proc}} \gamma_{\text{geom}} \quad (2)$$

$$\gamma_{\text{geom}} = \gamma_{\text{baseline}} \gamma_{\text{Scat}} \gamma_{\text{reg}} \quad (3)$$

Temporal decorrelation,  $\gamma_{\text{temp}}$ , refers to the change in the scene between the two SAR collection times. This may be the changes we wish to detect such as vehicle tracks or objects being placed in or removed from the scene.  $\gamma_{\text{temp}}$  can also be reduced by natural processes such as wind and rain [15–18].

The SNR coherence factor  $\gamma_{\text{SNR}}$  also affects coherence [8, 17] and is given as follows:

$$\gamma_{\text{SNR}} = \frac{1}{1 + \text{SNR}^{-1}} \quad (4)$$

$\gamma_{\text{proc}}$  and  $\gamma_{\text{geom}}$  represent the decorrelations due to the processing and imaging geometries respectively.  $\gamma_{\text{proc}}$  accounts for decorrelations due to the image formation algorithm accuracy and assumptions, and the geometry term includes terms which are a function of the SAR imaging geometries. This includes  $\gamma_{\text{baseline}}$  which accounts for K-space overlap [7, 9, 17, 26] and  $\gamma_{\text{Scat}}$  which accounts for differences in electromagnetic backscatter, which would include shadowing and multipath effects [28, 36].  $\gamma_{\text{reg}}$  refers to the image registration decorrelations due to differential layover [17].

The baseline correlation factor is as follows [17, 18]:

$$\gamma_{\text{baseline}} = \frac{A_c}{\sqrt{A_1 A_2}} \quad (5)$$

where  $A_1$  and  $A_2$  are the PFS areas corresponding to the two radar collections and  $A_c = A_1 \cap A_2$  is the area of their intersection (see Figure 3). For the near-field the  $\gamma_{\text{baseline}}$  must be evaluated on a per pixel basis, and then the values are averaged.  $\gamma_{\text{baseline}}$  is sometimes referred to as the *spatial* correlation term. Alternative formulae for the spatial term in the monostatic far-field case are found in refs. [8, 18], though these are not applicable to the SAR near-field data examined in this paper.

The Scattering term  $\gamma_{\text{scat}}$  was introduced in ref. [28] and discussed further in ref. [25], though originally referred to as the radar cross section (RCS) term. It accounts for a difference in backscattering dependent on imaging geometry, and includes effects such as variation in shadowing, multipath and scattering due to polarisation. The temporal and baseline correlation terms are typically of most interest for imaged scenes with developed speckle and low baseline [15, 35], however at least for bistatic geometries with either high baseline or significantly different bistatic angles, the scattering term is hypothesised to play a significant role.

The misregistration term,  $\gamma_{\text{reg}}$  corresponds to the decorrelation due to a difference in layover [17],

$$\gamma_{\text{reg}} = \text{sinc}\left(\frac{h_s(\tan \psi_1 - \tan \psi_2)}{\rho_{\text{res}}}\right) \quad (6)$$

where  $h_s$  corresponds to the scatterer height,  $\psi$  the grazing angle and  $\rho_{\text{res}}$  is the resolution cell size.

### 3 | METHODOLOGY

The laboratory SAR geometries available resulted in substantially curved wavefronts over the scene Region Of Interest (ROI). For this SAR near-field scenario, the Back Projection Algorithm (BPA) [37, 38] was extended to the bistatic case to generate well-focused SAR imagery. Bistatic versions of the Range-Migration Algorithm [39, 40] or of a curved wavefront corrected Polar Format Algorithm (PFA), [1, 7, 38, 39, 41]

would also have provided focussed image results in the near-field, though would be less straight forward to implement than the bistatic-BPA. For the less stringent case of far-field SAR geometries where wavefronts are approximated as planar over the ROI, one may instead choose more computationally efficient image formation algorithms, such as the standard (bistatic) PFA [1].

### 3.1 | Ground-Based Synthetic Aperture Radar laboratory

Bistatic SAR measurements were conducted at the Cranfield University Ground Based SAR laboratory (GBSAR lab) [25, 42] (see Figure 5).

The measurements were conducted with a Vector Network Analyser (VNA), with centre frequency of 10 GHz and bandwidth of 4 GHz. Due to the use of a single VNA, there were no signal synchronisation issues associated with the bistatic measurements – often a significant issue for practical remote bistatic SAR sensing.

#### 3.1.1 | Scene ground types

Two scenes were used. Each was surrounded by spheres and top hat scatterers, used to verify the alignment of the SAR images.

The first measured scene is shown in Figure 6 and was a rectangle of gravel (2.7 m × 1.5 m). The gravel consisted of approximately 1 cm-sized pieces of gravel, significantly smaller



**FIGURE 5** The Ground Based Synthetic Aperture Radar (GBSAR) laboratory in a bistatic configuration. The transmitter is circled in red and labelled Tx; the receiver is circled in blue and labelled Rx.



**FIGURE 6** Image showing the gravel rectangle, together with spheres and top hat scatterers used to ensure image alignment.

than the resolution cell size. A smaller rectangular area ( $1.5 \text{ m} \times 1.4 \text{ m}$ ) was used for the calculation of coherence and will be referred to as the ROI.

The second scene was a rectangle ( $1.6 \text{ m} \times 1.5 \text{ m}$ ) of densely packed stones, seen in Figure 7. This scene was less wide than the gravel scene, but encompassed the ROI used for this investigation.

### 3.2 | Synthetic Aperture Radar images and background subtraction

Example SAR images of the two scenes are shown in Figures 8 and 9. To increase the Signal to Clutter Ratio (SCR) and to better estimate the SNR, Radar Absorbent Material (RAM) panels were employed, and background scans, free of gravel



**FIGURE 7** Image showing the stone rectangle. The spheres and top hat scatterers shown in Figure 6 are also present.

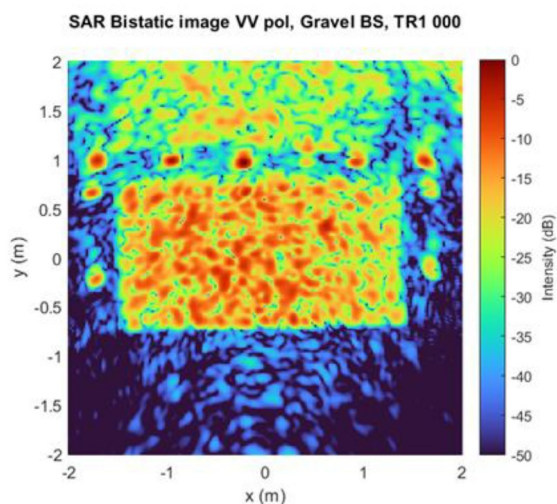


**FIGURE 8** Synthetic Aperture Radar (SAR) image (VV, TR1 000) of the gravel scene with background subtraction.

and stones, were carried out. The background scans were subtracted from the scene measurement data. In the region of the floor on which the gravel was placed, the floor itself was smooth and highly reflective for the frequency range measured, so that there was little scattering response from the ROI in the background scan. This helped ensure that the background subtraction was effective here.

From these SAR images the SCR was estimated as 21 dB for the gravel measurements and 25 dB for the stones measurement. This clutter represents scattering from the laboratory itself and some multipath, and most of it was removed by the background subtraction. Some multipath signature remained visible after the subtraction, and because it was associated with the stones and gravel, it could not be removed with a background subtraction. However, the SAR geometry and the arrangement of the gravel and stones was designed such that the multipath appeared down-range of the ROI, so that it did not affect the coherence results.

The SNR was estimated as 30 dB for the gravel and 38 dB for the stones. The difference in the SNR and SCR between the gravel and stones is due to the stones reflecting more strongly than the gravel.

### 3.3 | Synthetic Aperture Radar geometries

The SAR geometries used were constrained by transmitter and receiver vertical rectangular scanning apertures  $0.4 \text{ m}$  high by  $2.4 \text{ m}$  wide, seen in the SAR geometry overview in Figure 10. The red lines correspond to the transmitter positions used, and the blue to receiver positions.

Fifteen bistatic SAR geometries were measured, and in each of them the transceiver heights were kept the same. For each of them, a  $1.6 \text{ m}$  horizontal aperture was scanned by both the transmitter and the receiver, and with five different horizontal positions labelled TR1 to TR5, and with three vertical positions, labelled 000, 200, 400, corresponding to vertical

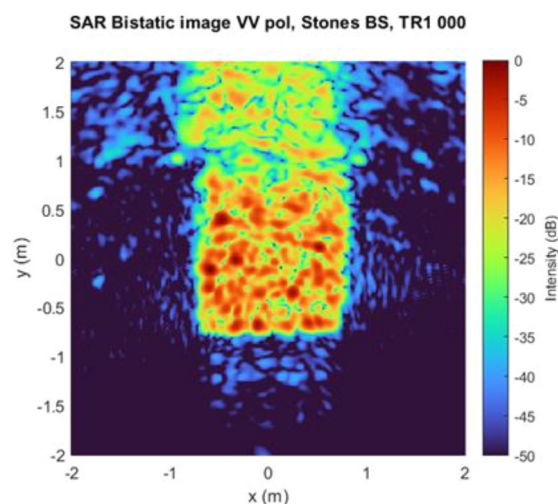


**FIGURE 9** Synthetic Aperture Radar (SAR) image (VV, TR1 000) of the stone scene after background subtraction.

distances in millimetres to the scanner origin, with “000” corresponding to the highest trajectories and 400 corresponding to the lowest. The individual transmitter apertures are shown in Figure 11 and the corresponding receiver apertures in Figure 12, with local scanner axis coordinates – in these, the “X” marker colours denote the scanned aperture

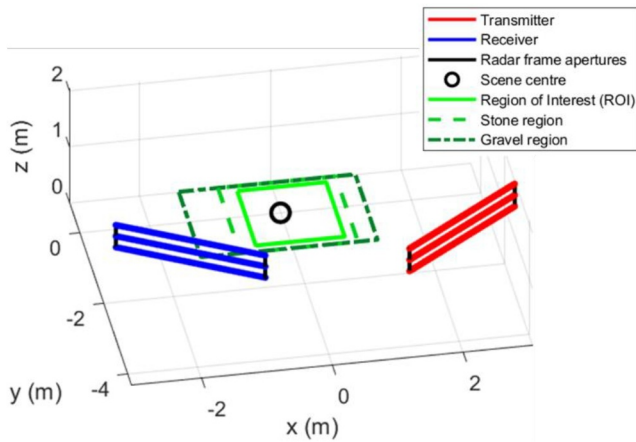


**FIGURE 10** Diagram showing the radar geometries used. The transmitter and receiver geometries are shown in red and blue respectively. The scene centre is marked by the black circle. The stone and gravel regions are outlined with dashed green lines. The Region Of Interest (ROI) is outlined by the solid green line.

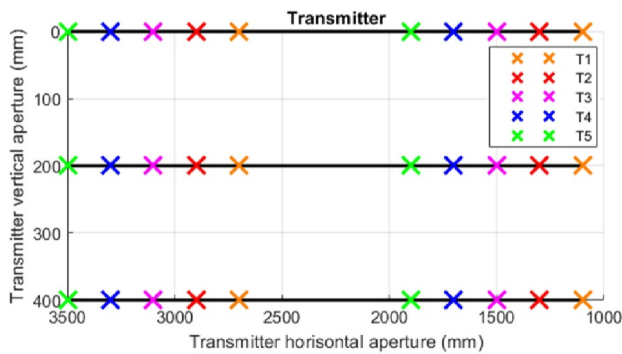


**FIGURE 11** Diagram showing the horizontal extent of the transmitter apertures for each height, in the local axis coordinate system.

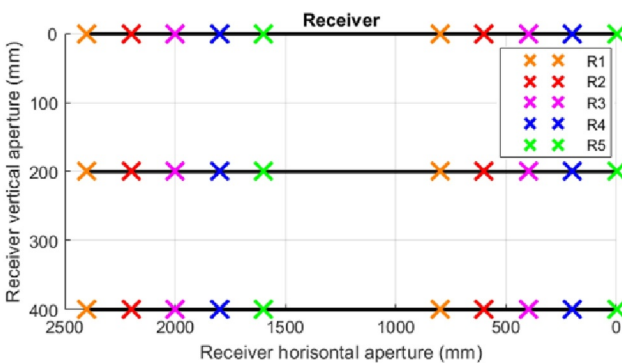


**FIGURE 12** Diagram showing the horizontal extent of the receiver apertures for each height, in the local axis coordinate system.

extents for each geometry, where TR1 form the outer pair of transceiver positions and TR5 form the inner pair.

The chosen SAR geometries allow the bistatic angle to be progressively increased, whilst maintaining a substantial K-space overlap between them. The K-space overlap between the six SAR geometries was high, with  $\gamma_{\text{baseline}}$  ranging from 0.7 to 0.96 for non-repeating trajectories.

Transceiver scan geometry parameters are listed in the appendices section. It is noted that the grazing and bistatic angles are spatially variant over the scene, and the values provided in the tables are calculated to the centre of the scene and gravel region. The SAR resolutions were estimated using the Bistatic Equivalent Monostatic (BEM) antenna positions, calculated along the antenna bisecting direction to the scene centre [43, 44].

The bistatic angle difference between the different trajectories and the grazing angle differences are shown in Figures 13 and 14.

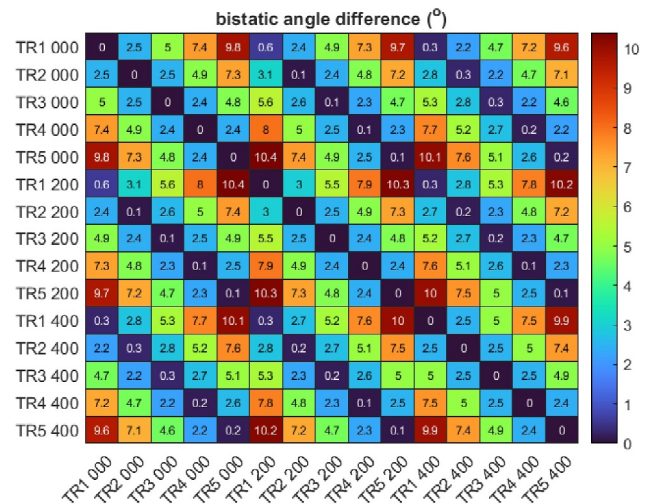


**FIGURE 13** Heatmap and table showing the bistatic angle difference between the Synthetic Aperture Radar (SAR) geometries measured.

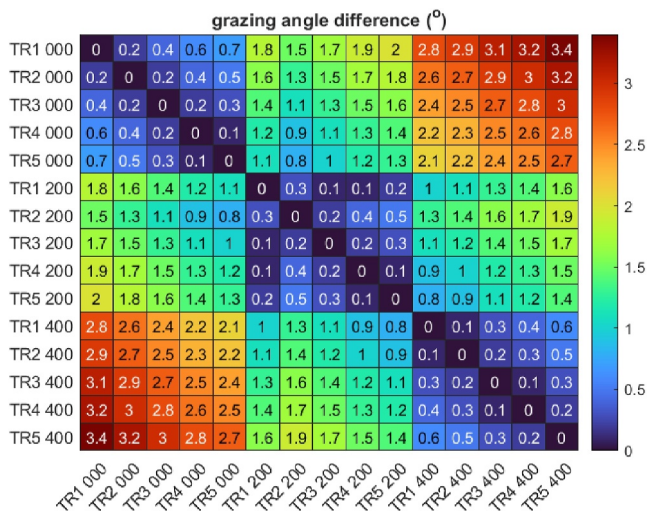


**FIGURE 14** Heatmap and table showing the grazing angle difference between the Synthetic Aperture Radar (SAR) geometries measured.

### 3.4 | Spatially variant processing

As discussed in section 2.2, spatial frequency domain projections of the radar collection data vary substantially across the scene when in the SAR near-field. Hence the calculation of  $\gamma_{\text{baseline}}$  should be performed in a spatially variant manner. Additionally, Spatially Variant Incoherence Trimming (SVIT) can be implemented for increased coherence between images [26, 32, 33, 36, 45, 46].

The SVIT process omits/removes incoherent energy from the non-overlapping PFS data for each SAR image pixel for both SAR collections, during the image formation stage, resulting in two SAR images with greater coherence between them. The PFS areas alone are used to calculate  $\gamma_{\text{baseline}}$ .

Figures 15 and 16 are outputs from the SVIT algorithm corresponding to the laboratory measurements undertaken, and are used to illustrate the need for a spatially variant approach to the near-field regime. The PFS outline for a single point in the scene (or SAR image co-ordinate) is plotted as a characteristic K-space annulus segment. For a particular scene point, the PFS outlines of a master and reference SAR collection are plotted in red and blue respectively. The grey-scale figure backgrounds show a running sum of the intersecting PFS regions, in Figure 15, and non-intersecting, in Figure 16, where each PFS region contributes unit values to the summation K-space image (which is normalised in intensity at the end). These images compare the K-space overlap of SAR geometries TR1 000 and TR4 000. The figures show significant variation in K-space of overlapping and non-overlapping regions as a function of scene position (or SAR image pixel position).

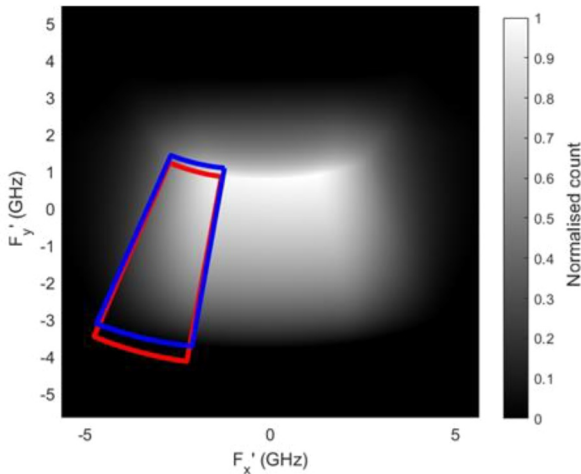


**FIGURE 15** Spatially Variant Incoherence Trimming (SVIT) algorithm output for TR1 000 and TR4 000. The red and blue lines show the Projected Fourier Supports (PFS) for the reference and mission collections for a single scene position and collection pair. The grayscale background shows the sum over the scene of all intersecting PFS regions.

### 3.5 | Simulation

Two types of SAR image simulation were used. Both simulations used isotropic point scatterers with a density of approximately 14.3 scatterers per resolution cell, and 30,000 in total. All the scatterers had a consistent brightness. This provided fully developed SAR speckle (see section 3.6). The simulations were run multiple times with randomized scatterer positions and coherence results were found to be stable. Thus, to save time, it was then deemed acceptable to only use a single simulated scene realisation to generate results.

For the purposes of modelling bistatic decoherence for rough ground [17], the second set of simulations added a random phase contribution to the  $n$ th scatterer as follows:

$$\theta_{\text{decorr},n} = C_{\text{sim}}\beta_n A_n \quad (7)$$

The phase is dependent on three components:  $C_{\text{sim}}$  is a coefficient to be determined empirically to fit the measured characteristics of the scene;  $\beta_n$  is the bistatic angle in radians at the location of scatterer  $n$ ;  $A_n$  is a uniformly distributed random real number assigned to scatterer  $n$  such that  $-1 \leq A_n < 1$  [7].

The values  $A_n$  were fixed across the simulations. The result of the application of the decoherence phase in (7), is that a decorrelation between SAR images is imposed which increases with their bistatic angle difference.

The chosen values of  $C_{\text{sim}}$  corresponded to a minimum Root Mean Squared Error (RMSE) between the simulation coherence and the measured data coherence.

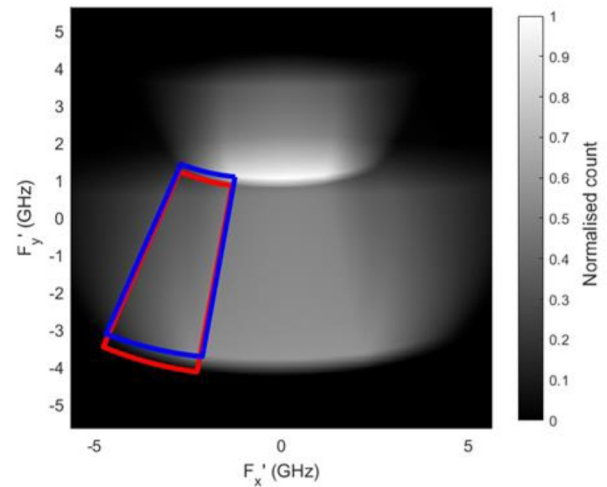


**FIGURE 16** Spatially Variant Incoherence Trimming (SVIT) algorithm output for TR1 000 and TR4 000. The red and blue lines show the Projected Fourier Supports (PFS) for the reference and mission collections for a single scene position and collection pair. The grayscale background shows the sum over the non-intersecting PFS regions.

It is noted that the SAR and CCD processing undertaken was the same for both simulated and measured data.

A 3<sup>rd</sup> order polynomial,  $\gamma_{\text{Scat-fit}}$ , function of the difference in bistatic angle,  $\Delta\beta$ , was used to fit  $\gamma_{\text{Scat}}$  coherence curves as follows:

$$\gamma_{\text{fit}} = \gamma_{\text{Scat-fit}} \left( \gamma_{\text{baseline}} \gamma_{\text{SNR}} \gamma_{\text{proc}} \gamma_{\text{reg}} \right) \quad (8)$$

where

$$\gamma_{\text{Scat-fit}} = 1 + C_{f1}\Delta\beta + C_{f2}\Delta\beta^2 + C_{f3}\Delta\beta^3$$

Whilst  $\gamma_{\text{Scat-fit}}$  represents the scattering parameter ( $\gamma_{\text{Scat}}$ ),  $\gamma_{\text{fit}}$  represents the fitted curve to the measured overall coherence. The coefficients  $C_f$  were chosen so that they resulted in the lowest RMSE between the average measured coherence (across polarisations) and  $\gamma_{\text{fit}}$ . The chosen values for the two measured scenes are presented in Table 1.

The simulations and curve fitting were used to show that the behaviour of  $\gamma_{\text{Scat}}$  can be characterised and predicted.

### 3.6 | Intensity distribution and surface roughness

A surface is considered rough when the size of the scatterers is small in comparison to the wavelength, and there are a large number of scatterers per resolution cell [47]. Additionally, the following roughness criterion should be met [48, 49]:

$$\Delta b > \frac{\lambda}{8 \cdot \cos \theta} \quad (9)$$

where  $\Delta b$  (cm) is the surface height variation,  $\lambda$  (cm) the wavelength and  $\theta$  the electromagnetic wave incidence angle (it is expected that this formula extends to bistatic back-scattering geometries).

The surface height variation ( $\Delta b$ ) is around 1–2 cm for the gravel and 5–10 cm for the stones. These heights give values larger than the value of the criterion:  $\frac{\lambda}{8 \cdot \cos \theta} = 0.41$  cm so that they are considered to be rough.

The intensity ( $|I|$ ) Probability Density Function of Rayleigh speckle takes the form of the negative exponential [7, 50–52].

$$P(|I|) = \frac{1}{\langle |I| \rangle} \exp \left( -\frac{|I|}{\langle |I| \rangle} \right) \quad (10)$$

where  $|I|$  is the intensity and  $\langle |I| \rangle$  is the mean intensity [7, 50, 51].

The pixel intensity distribution, calculated for all geometries of the isotropic simulation, is plotted in Figure 17 and closely follows the negative exponential distribution (red line), indicating that surface roughness has been well simulated.

Similar distributions can be plotted for the stone and gravel SAR images for all geometries. These distributions are plotted below, with the gravel in Figure 18 and the stones in Figure 19. Intensities were averaged across all geometries for each polarisation.

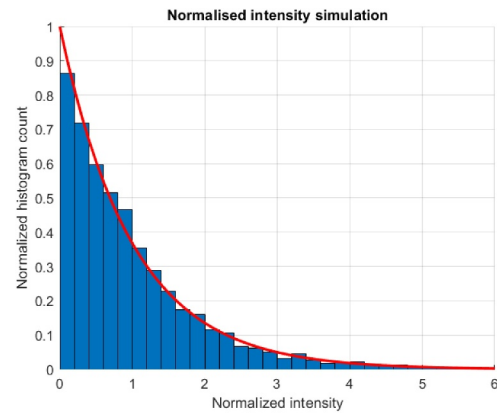


**FIGURE 17** Normalised intensity distribution (histogram) for the isotropic simulations and negative exponential distribution (red).

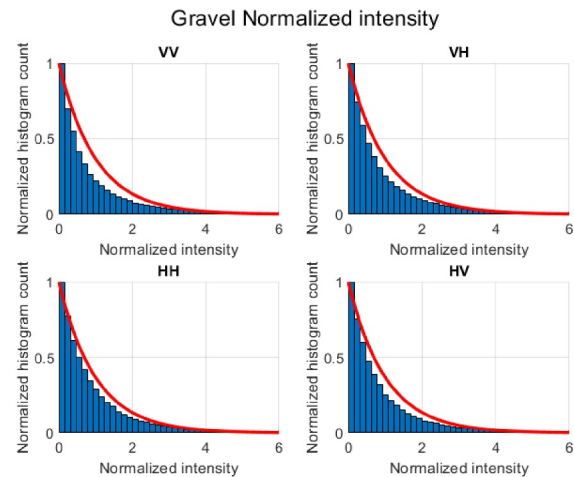


**FIGURE 18** Normalised intensity distribution (histogram) for the gravel Synthetic Aperture Radar (SAR) images and negative exponential distribution (red). Intensities were averaged across all geometries for each polarisation.

|        | Bistatic decoherence simulation parameter<br>$C_{\text{sim}}$ | Coherence fitting coefficients |          |          |
|--------|---------------------------------------------------------------|--------------------------------|----------|----------|
|        |                                                               | $C_{f1}$                       | $C_{f2}$ | $C_{f3}$ |
| Gravel | 5.7                                                           | −0.72                          | −21.87   | 76.19    |
| Stones | 15.1                                                          | −8.23                          | 16.62    | 50.85    |

**TABLE 1** Parameter values used to add a decorrelation factor to the simulation (7), or to fit the overall coherence (8) as a function of bistatic angle difference for the two measured scenes.

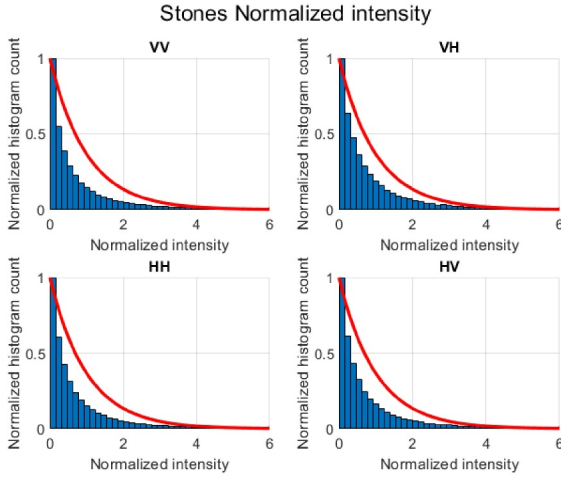


**FIGURE 19** Normalised intensity distribution (histogram) for the stone Synthetic Aperture Radar (SAR) images and negative exponential distribution (red). Intensities were averaged across all geometries for each polarisation.

**TABLE 2** Root Mean Squared Error (RMSE) calculated for the normalised intensity of the measured Synthetic Aperture Radar (SAR) images and the negative exponential distribution.

| RMSE   | Polarisation |      |      |      |
|--------|--------------|------|------|------|
|        | VV           | VH   | HH   | HV   |
| Gravel | 0.33         | 0.23 | 0.19 | 0.25 |
| Stones | 0.61         | 0.43 | 0.55 | 0.52 |

The RMSE can be calculated between the measured intensity values and the negative exponential distribution. These are presented below in Table 2.

The gravel shows a closer alignment than the stones with the negative exponential distribution, as shown in Table 2.

The 1 cm diameter gravel stones give rise to complex scattering, including multipath as well as direct scattering, however the radar wavelength is significantly larger than the scatterers themselves which may change the nature of the scattering away from the simpler and more intuitive Physical Optics regime.

The stones exhibit a greater deviation from the ideal rough (speckle) scattering response than for the gravel scene, which may be due to the presence of fewer scatterers per resolution cell, as the stones are larger. The stones are approximately 10 cm in size, larger than the centre wavelength of 3 cm.

### 3.7 | Estimation of $\gamma_{\text{Scat}}$

Due to the nature of the laboratory environment, Equations (2) and (3) can be simplified and the terms calculated to estimate the scattering component.

No scene changes were present so  $\gamma_{\text{temp}} = 1$ . From the background subtraction images (section 3.2), the SNR was estimated at 35 and 41 dB for the gravel and stones respectively.

Thus, using Equation (4)  $\gamma_{\text{SNR}}$  was estimated at 0.98 and 0.99 for the gravel and stones respectively. The measurement ground truth was accurately known due to the well-controlled antenna positioning and accurate curved wavefront bistatic back-projection image formation used, so  $\gamma_{\text{Proc}} = 1$ . The minimum  $\gamma_{\text{reg}}$  was calculated using Equation (6) as  $0.9968 \approx 1$ .

Hence the following equation is used to give an *estimate* for  $\gamma_{\text{Scat}}$ :

$$\hat{\gamma}_{\text{Scat-baseline}} = \left\langle \frac{\hat{\gamma}_{\text{Meas}}(x, y)}{\gamma_{\text{baseline}}(x, y) \gamma_{\text{SNR}} \gamma_{\text{reg}}} \right\rangle \quad (11)$$

The angled brackets indicate an averaging of the quantities over the scene. It is noted that due to the SAR near-field nature of the measurements, both the  $\gamma_{\text{baseline}}$  and  $\hat{\gamma}_{\text{meas}}$  (evaluated within a square sliding window) vary spatially. Hence, they are functions of image coordinates (x,y). Therefore  $\hat{\gamma}_{\text{Scat}}$  is evaluated as a mean over the spatially varying fraction in Equations (11) and (12). “Meas” denotes that the coherence value is from the measured data.

An alternative method to estimate  $\hat{\gamma}_{\text{Scat}}$  is to use the isotropic simulation. The coherence of the simulation,  $\hat{\gamma}_{\text{Sim-isotropic}}$ , is very similar to  $\gamma_{\text{baseline}}$ , and this is due to the isotropic scatterer assumption in the simulation. With this assumption,  $\gamma_{\text{Scat}}$  for the isotropic simulations is assumed to be unity and,  $\hat{\gamma}_{\text{Sim-isotropic}} \approx \gamma_{\text{baseline}}$ .

Thus, Equation (12) can be used to estimate  $\hat{\gamma}_{\text{Scat}}$  for the measurements. Here “Sim-isotropic” denotes that the isotropic simulation was used.

$$\hat{\gamma}_{\text{Scat-Sim-isotropic}} = \left\langle \frac{\hat{\gamma}_{\text{Meas}}(x, y)}{\hat{\gamma}_{\text{Sim-isotropic}}(x, y) \gamma_{\text{SNR}} \gamma_{\text{reg}}} \right\rangle \quad (12)$$

As in Equation (11), an averaging over the spatially varying fraction is performed in Equation (12) due to the SAR near-field nature of the measurements.

After the spatially variant incoherent trimming process, it is assumed that the resulting coherence between images  $\hat{\gamma}_{\text{Trimmed}}(x, y) = \hat{\gamma}_{\text{Meas}}(x, y) / \gamma_{\text{baseline}}(x, y)$ , hence the following relation is assumed:

$$\hat{\gamma}_{\text{Scat-Trimmed}} = \left\langle \frac{\hat{\gamma}_{\text{Trimmed}}(x, y)}{\gamma_{\text{SNR}} \gamma_{\text{reg}}} \right\rangle \quad (13)$$

Thus, three formulae will be used to calculate  $\gamma_{\text{Scat}}$  Equations (11)–(13) to improve confidence in the results.

## 4 | RESULTS

### 4.1 | Overall coherence results

The coherence between SAR images is evaluated as the mean of the absolute value of  $\hat{\gamma}$  (1), over the ROI. For the

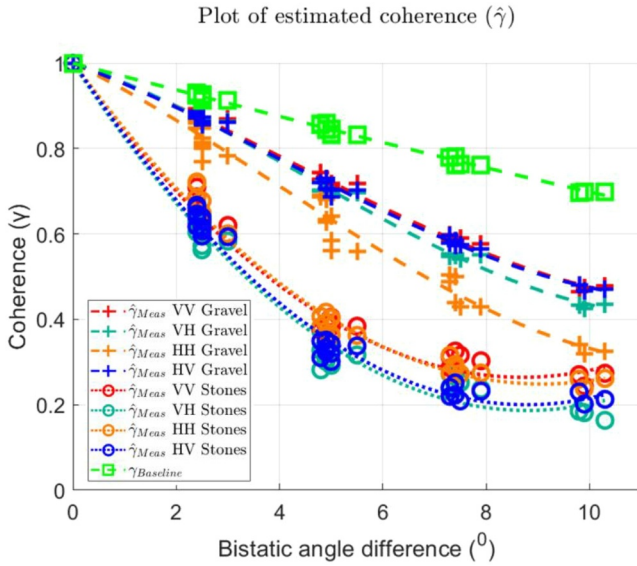


**FIGURE 20** Coherence plotted against bistatic angle difference for the gravel and stone scene datasets, with  $\gamma_{\text{baseline}}$ .

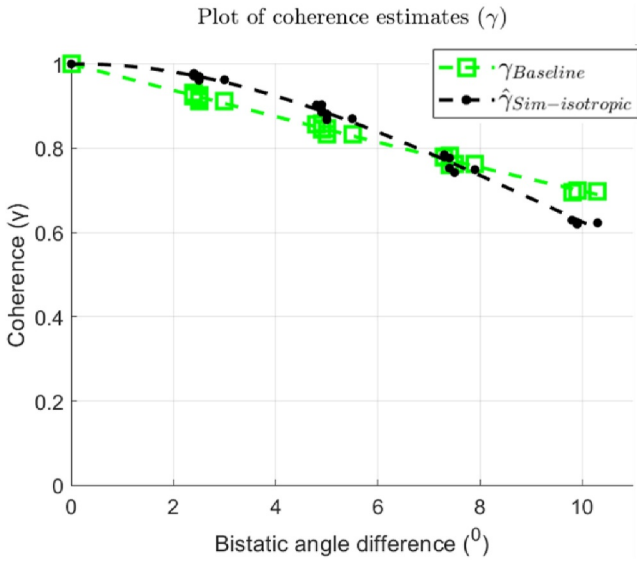


**FIGURE 21** Graph showing the correspondence between  $\gamma_{\text{baseline}}$  and  $\hat{\gamma}_{\text{Sim-isotropic}}$ .

measurements conducted, these are plotted in Figure 20, against the bistatic angle difference. Figures 13 and 14 show that across the SAR geometries measured, the maximum bistatic angle difference is  $10.3^\circ$ , and the maximum grazing angle difference is  $0.7^\circ$ . All four polarisations are plotted, blue and cyan for the cross-polar and red and magenta for the co-polar. Crosses were used to represent the gravel scene data and circles the stone scene data, with curves of best fit added. The  $\gamma_{\text{baseline}}$  values are plotted in green.

For differing bistatic angles, the coherence for SAR images from both measured scenes is less than  $\gamma_{\text{baseline}}$ , with an

increased difference as the bistatic angle difference increases. These results support previous findings [25] and indicate that there is a geometry dependant decorrelation other than that due to PFS overlap.

The coherence for the stones is below that for the gravel scene, indicating that the decoherence is terrain type specific. Reasons for the difference may include a greater variability in bistatic RCS for the larger stones, due to their larger sizes compared to the radar wavelengths (approximately 10 cm compared to a centre wavelength of 3 cm). This would also affect the relative prominence and variability of multipath and shadowing effects. Additionally, the larger stones have a lower number of scatterers per SAR resolution cell, leading to the SAR speckle not being quite as fully developed (see 3.6).

The coherence for the stones plateaus at  $8\text{--}10^\circ$ , this behaviour is attributed to the biasing seen in CCD processing at low coherence levels [17, 53], which increases estimated coherence ( $\hat{\gamma}$ ) above true coherence  $\gamma_{\text{True}}$ , dependant on the CCD window size [17, 53].

Figure 20 shows there is a variation in coherence between the different polarisations, which will be seen in greater detail in Sections 4.2 and 4.3.

It is noted that a simulation using isotropic scatterers  $\hat{\gamma}_{\text{sim-isotropic}}$  provides an overall good match for  $\gamma_{\text{baseline}}$ , seen in Figure 21, as was the case in prior publications [25, 28].

Although there is a good match between the  $\gamma_{\text{baseline}}$  and  $\hat{\gamma}_{\text{sim-isotropic}}$ , there are however some differences.  $\hat{\gamma}_{\text{sim-isotropic}}$  gives coherence values below  $\gamma_{\text{baseline}}$  up to around  $7^\circ$ , after which it gives higher coherence values. This difference may be due to numerical errors and additionally the effects of CCD coherence estimation for the simulation [17, 53]. This results in slightly different corresponding values for  $\hat{\gamma}_{\text{Scat}}$  in the following sections. The results are further described in Section 4.2 for the gravel scene, and Section 4.3 for the stones scene.

## 4.2 | Gravel scene results

This section presents the coherence results for the gravel scene. The measured scene coherence is plotted in Figure 22. It includes measured and simulated coherence as well as  $\gamma_{\text{baseline}}$  and a curve fitted to all of the measured data,  $\gamma_{\text{Curve fit}}$ . The simulated coherence incorporated the bistatic decorrelation model phase in (7) (see Section 3.5) and is referred to as  $\hat{\gamma}_{\text{sim-decorrelation}}$ . The parameters used for the fitted curve and for the decorrelation simulation are provided in Table 1.

For differing bistatic angles, the  $\gamma_{\text{baseline}}$  values are significantly higher than for the measured data for all polarisations. The bistatic decorrelation simulation  $\hat{\gamma}_{\text{sim-decorrelation}}$  matches the measured coherence better than the isotropic scatterer simulation  $\hat{\gamma}_{\text{sim-isotropic}}$  (compare with Figure 21). The fit of  $\hat{\gamma}_{\text{sim-decorrelation}}$  could be improved by replacing  $\beta$  with a

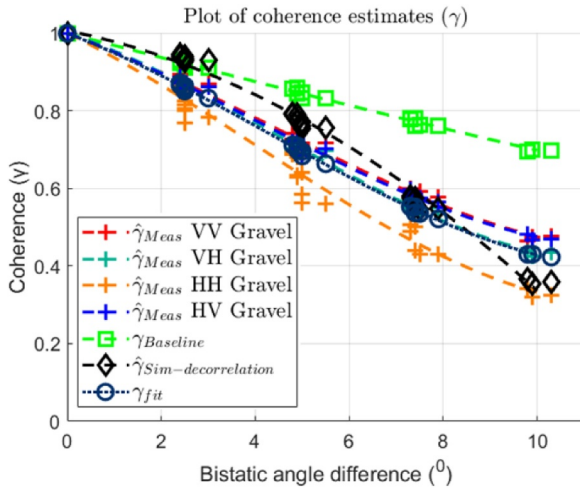


**FIGURE 22** Coherence plots against bistatic angle difference for the gravel scene, including all four polarisations,  $\gamma_{baseline}$ , the bistatic decoherence simulation and the fitted curve, whose parameters are provided in Table 1.

polynomial function of  $\beta$  in Equation (7), however the computationally intensive exercise of finding the optimal coefficient values is beyond the scope of this paper.

Of the four polarisations, HH shows the least coherence, for the gravel scene, and VV the most.

Using Equations (11)–(13) the coherence scattering component associated with a departure from bistatic isotropy,  $\hat{\gamma}_{Scat}$ , can be estimated with three approaches.

Figure 23 shows  $\hat{\gamma}_{Scat}$  for each of the four polarisations. In the case of the gravel scene, polarisation HH exhibits the steepest decrease in  $\hat{\gamma}_{Scat}$  as a function of the bistatic angle difference. The three different methodologies for estimating  $\hat{\gamma}_{Scat}$  result in only slightly different coherence values.

The values for  $\hat{\gamma}_{Scat-baseline}$  (11) and for  $\hat{\gamma}_{Scat-Sim-isotropic}$  (13) are plotted in green and blue respectively.  $\hat{\gamma}_{Scat-Trimmed}$  (13) is shown in red and represents the coherence of the incoherence trimmed image coherence  $\hat{\gamma}_{Trimmed}$  (with compensations for the SNR and registration errors).

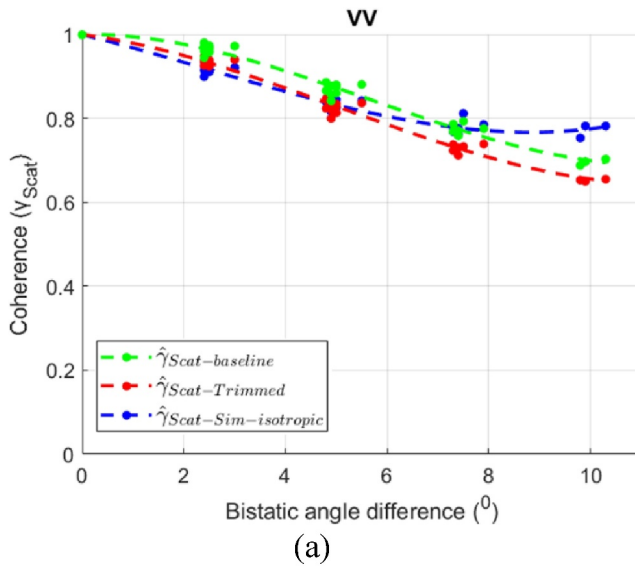
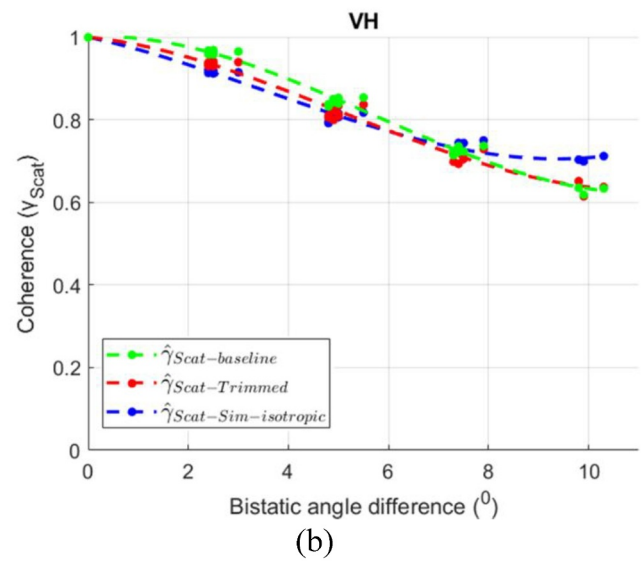
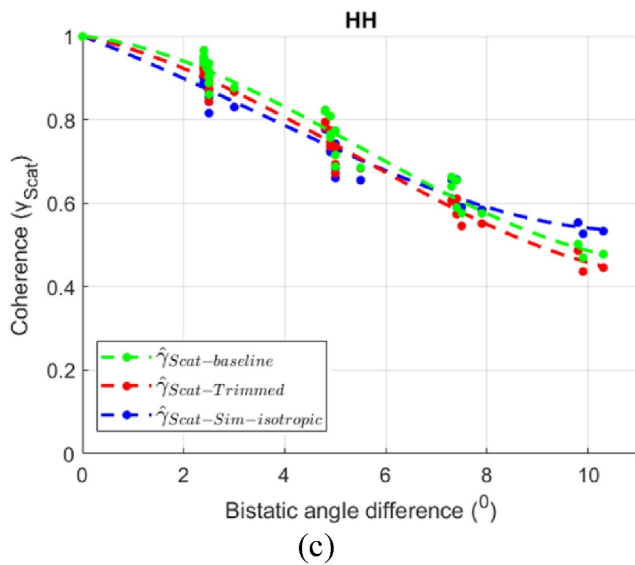
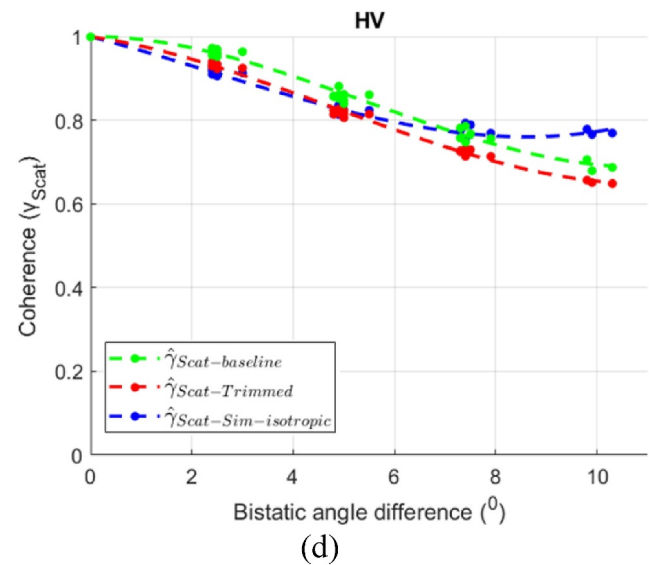


**FIGURE 23** Gravel scene coherence scattering component  $\hat{\gamma}_{Scat}$  against bistatic angle difference, estimated with three methodologies presented in Equations (11)–(13).

The three  $\hat{\gamma}_{\text{Scat}}$  curves mostly show close alignment except for the increased coherence of  $\hat{\gamma}_{\text{Scat-Sim-isotropic}}$  at the most extreme bistatic angle difference of  $10^\circ$ . This is due to the difference between  $\hat{\gamma}_{\text{sim-isotropic}}$  simulated coherence and  $\gamma_{\text{baseline}}$ , seen in Figure 21.

In summarising results, it has been found useful to divide the coherence into three performance bands [36]:

- **Good** CCD performance, occurs where changes are easily detected, and is associated with coherences above 0.8;
- **Moderate** CCD performance, occurs where useful detection information may still be available but is unreliable due to an elevated false alarm rate, and is associated with coherence below 0.8 and above 0.6;
- **Poor** CCD performance, occurs where changes are not discernible due to a very high false alarm rate, and is associated with coherence values below 0.6.

In the summarising of results, the angular differences are rounded here to the nearest  $1^\circ$ .

For the gravel, “good”  $\hat{\gamma}_{\text{Scat}}$  coherence is achieved for bistatic angle differences from  $0^\circ$  up to  $4-6^\circ$ , depending on polarisation. This corresponds to  $0-6^\circ$  for VV and HV,  $0-5^\circ$  for VH and  $0-4^\circ$  for HH.

“Moderate” CCD performance occurred at least for bistatic angle differences of  $6-10^\circ$  for VV and HV,  $5-10^\circ$  for VH and  $4-7^\circ$  for HH. The experimental setup did not allow for angular differences larger than  $10^\circ$ . “Poor” CCD performance occurred beyond these angular values.

The results are listed in the summary Table 3, and presented graphically in section 4.4.

### 4.3 | Stone scene results

This section presents the coherence results for the stones scene. The coherence results are presented in Figure 24. The coherence for the stones is lower than for the gravel, and the difference increases as the bistatic angle difference increases, so that at  $10^\circ$  the difference is around 0.2. There is less variation with polarisation in the measured stones scene than with the gravel and HV is the polarisation in which coherence is least (whereas for the gravel, HH gave the least coherence).

**TABLE 3** Summary of bistatic angular difference extents of coherence ( $\hat{\gamma}_{\text{Scat}}$ ) performance bands for the gravel, where angles are rounded to the nearest  $1^\circ$ .

| Scene  | Polar | $\hat{\gamma}_{\text{Scat}} > 0.8$ | $0.8 \geq \hat{\gamma}_{\text{Scat}} > 0.6$ | $0.6 \geq \hat{\gamma}_{\text{Scat}}$ |
|--------|-------|------------------------------------|---------------------------------------------|---------------------------------------|
| Gravel | VV    | $0-6^\circ$                        | $6-10^\circ$                                | N/A                                   |
|        | VH    | $0-5^\circ$                        | $5-10^\circ$                                | N/A                                   |
|        | HH    | $0-4^\circ$                        | $4-7^\circ$                                 | $7-10^\circ$                          |
|        | HV    | $0-6^\circ$                        | $6-10^\circ$                                | N/A                                   |

The non-isotropic simulation  $\hat{\gamma}_{\text{sim-decorrelation}}$  (see Section 3.5) is plotted in black and the fitted coherence curve  $\gamma_{\text{Curve fit}}$  is dark blue.

The estimates for  $\hat{\gamma}_{\text{Scat}}$  (11)-(13) for the stones are plotted in Figure 25 for the four polarisations. The cross-polarization curves exhibit a steeper decrease in  $\hat{\gamma}_{\text{Scat}}$  with respect to bistatic angle difference. The different methodologies result in only slightly different values.

The slight rise or plateauing of the  $\hat{\gamma}_{\text{Scat}}$  values for the stones seen at  $10^\circ$  is attributed to the biasing seen in CCD processing at low coherence levels [17, 53] and the steeper decrease in coherence of the isotropic simulation ( $\hat{\gamma}_{\text{sim-isotropic}}$ ) compared to the baseline ( $\gamma_{\text{baseline}}$ ) (Figure 21).

In comparison to the gravel results in Figure 23, the values of  $\hat{\gamma}_{\text{Scat}}$  for stones in Figure 25 reduce at a faster rate.

Using the three performance bands defined in Section 4.2: “good”  $\hat{\gamma}_{\text{Scat}}$  coherence is achieved for bistatic angle differences from  $0$  to  $1^\circ$  for VV, VH and HH, and  $0-2^\circ$  for HV; “Moderate” CCD performance occurred for bistatic angle differences in the range  $1-3^\circ$  for VV, VH and HH, and  $2-4^\circ$  for HV; “Poor” CCD performance occurred for angles greater than  $3^\circ$ .

The results are listed in the summary Table 4, and presented graphically in Section 4.4.

### 4.4 | Graphical summary section

The impact of the decorrelation on CCD image interoperability can also be seen by inspecting the CCD images themselves. Two tessellations of CCD images are presented below. The gravel results are shown in Figure 26 and the stones results

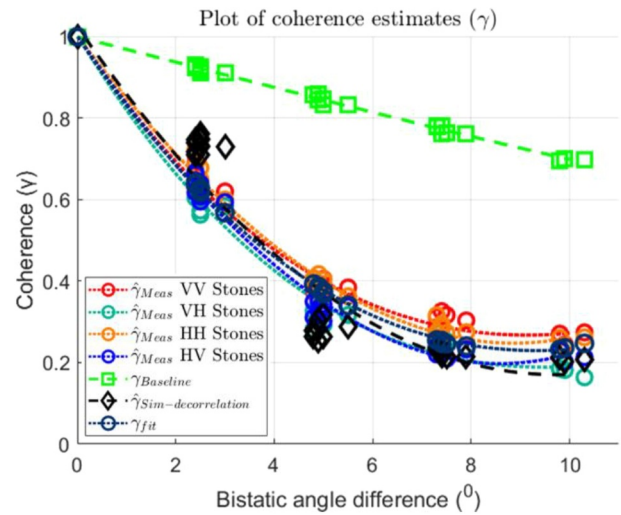


**FIGURE 24** Coherence plots against bistatic angle difference for the stones scene, including all four polarisations,  $\gamma_{\text{baseline}}$ , the bistatic decorrelation simulation and the fitted curve, whose parameters are provided in Table 1.

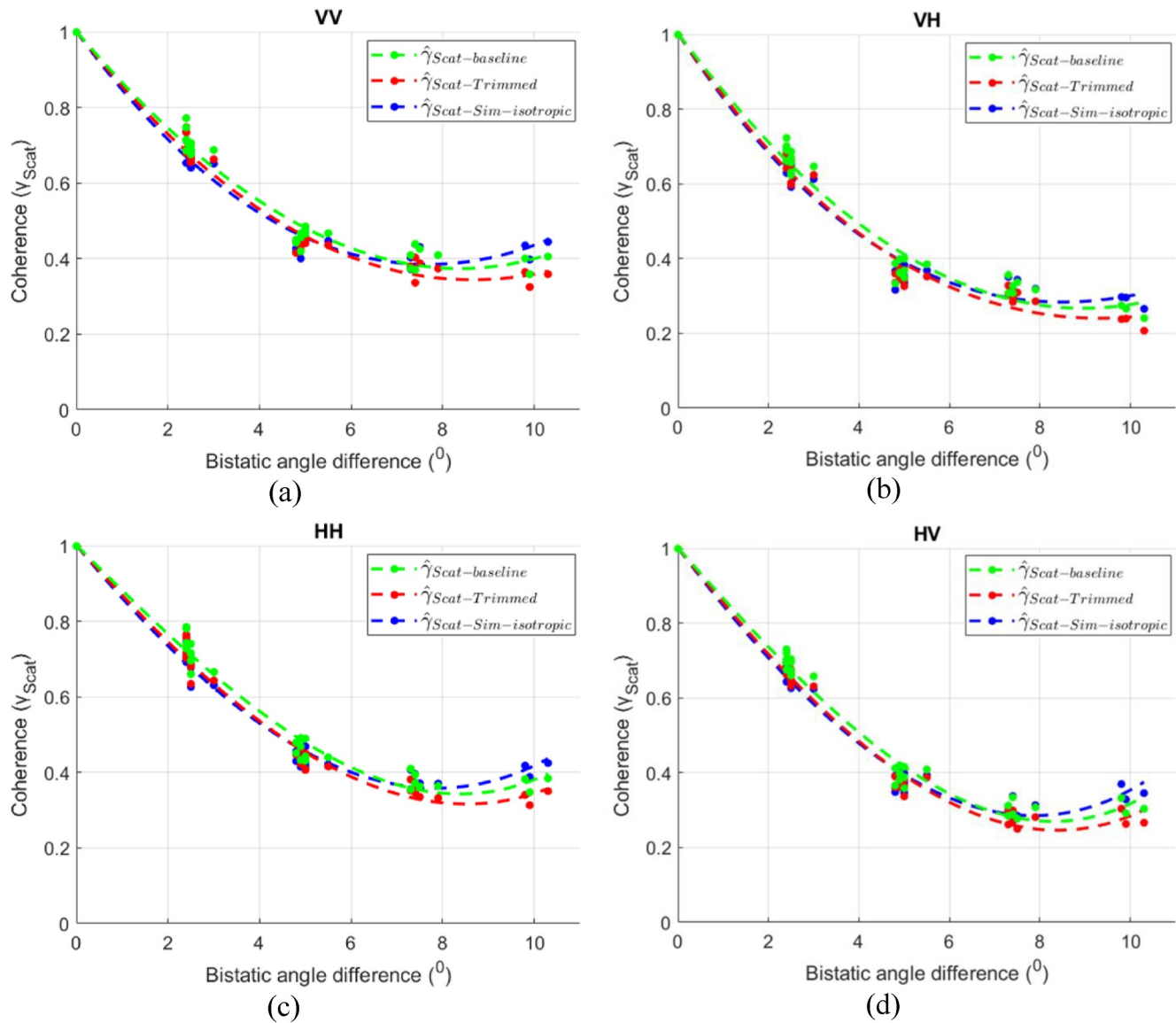


**FIGURE 25** Stone scene coherence scattering component  $\hat{\gamma}_{\text{Scat}}$  against bistatic angle difference, estimated with three methodologies presented in Equations (11)–(13).

**TABLE 4** Summary of bistatic angular difference extents of coherence ( $\hat{\gamma}_{\text{Scat}}$ ) performance bands for the stones, where angles are rounded to the nearest 1°.

| Scene  | Pol | $\hat{\gamma}_{\text{Scat}} > 0.8$ | $0.8 \geq \hat{\gamma}_{\text{Scat}} > 0.6$ | $0.6 \geq \hat{\gamma}_{\text{Scat}}$ |
|--------|-----|------------------------------------|---------------------------------------------|---------------------------------------|
| Stones | VV  | 0–1°                               | 1–3°                                        | 3–10°                                 |
|        | VH  | 0–1°                               | 1–3°                                        | 3–10°                                 |
|        | HH  | 0–1°                               | 1–3°                                        | 3–10°                                 |
|        | HV  | 0–2°                               | 2–4°                                        | 4–10°                                 |

in Figure 27. These images show a marked difference in coherence between the stones and gravel.

The VH polarisation and 000 height were chosen as representative of the CCD images – other heights and

polarisations exhibited similar results (with some variation in coherence as seen in figures Figures 23 and 25).

The results presented in Tables 3 and 4 are presented graphically in Figure 28. The curves of best fit in Figures 23 and 25 were averaged and plotted with a colourmap based on the three performance bands defined in Section 4.2. “Good” CCD performance is represented by green, “Moderate” by yellow and “Poor” by red.

## 5 | DISCUSSION AND CONCLUSION

For two types of terrain, it has been shown that when the difference between bistatic angles is large enough for two bistatic collections, the coherence between the corresponding

SAR images is less than would be expected from the degree of projected Fourier domain support overlap achieved.

It is hypothesised that the observed reduction in coherence is due to differences in the bistatic microwave scattering between the two SAR collections, which would include phenomena such as shadowing and multipath. These effects would be included within the proposed scattering coherence parameter  $\gamma_{\text{Scat}}$ .

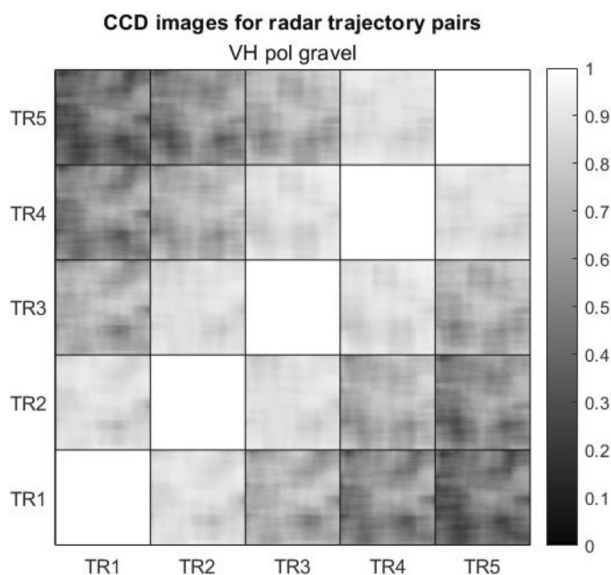


**FIGURE 26** Tessellation of Coherent Change Detection (CCD) images for the gravel. These images are for the 000 height and VH polarisation.

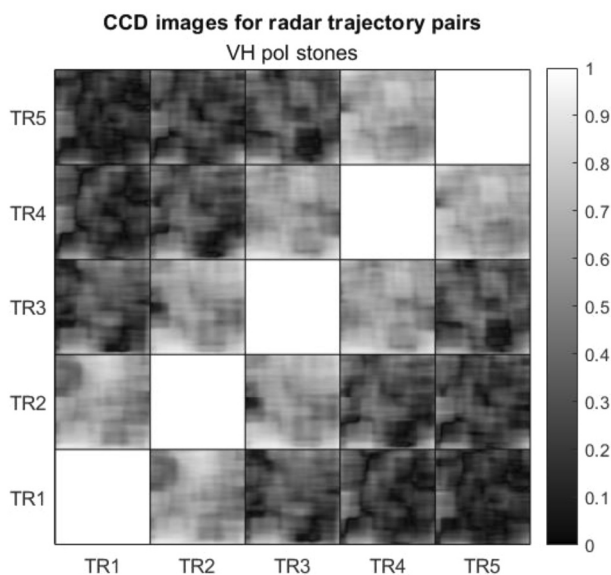


**FIGURE 27** Tessellation of Coherent Change Detection (CCD) images for the stones. These images are for the 000 height and VH polarisation.

The results presented build on those found in [25, 28] and provide improved characterisation of  $\gamma_{\text{Scat}}$ , now for two ground types.  $\gamma_{\text{Scat}}$  was calculated in three ways, which were in good agreement.

A CCD simulation was developed which modelled a decorrelation as a function of bistatic angle difference, implemented via a decorrelation phase controlled by one coefficient. Whilst matching to the experimental results was achieved, it is assumed that the match could be further improved by use of a polynomial function of the bistatic angle. The determination of the polynomial coefficients would be highly computationally intensive and a subject for future research. Additional further work could include the determination of improved curve fitting functions for  $\gamma_{\text{Scat}}$ .

It was shown that for bistatic SAR trajectories where there is a significant bistatic angle difference, the decorrelation due to  $\gamma_{\text{Scat}}$  dominates the coherence and can reduce it to a level where CCD interpretability becomes very poor. This shows that even when terrain has undergone little change, selection of bistatic SAR collections with high spatial frequency domain overlap may not be sufficient for forming good quality CCD images, and that the bistatic angle difference can have a major effect, which is terrain dependent. These considerations would affect the choice of useful interferometric imaging geometries obtained from a multi-static SAR system.

Table 3, Table 4 and Figure 28 summarise the  $\hat{\gamma}_{\text{Scat}}$  coherence results and show that the CCD performance that can be expected depends upon the scene being imaged and the measured polarisation.

The two terrain surfaces investigated can be considered rough, with their surface height variations being above the Rayleigh Roughness Criterion height of 0.41 cm: the gravel with a surface height variation just above the criterion (1–

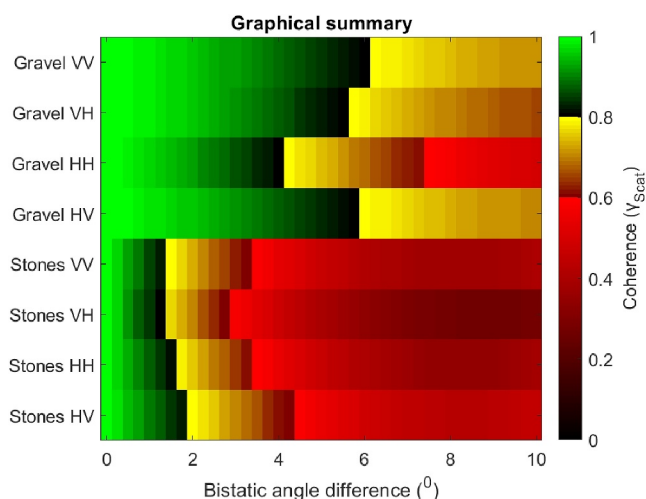


**FIGURE 28** Graphical summary of results showing the bistatic angular difference extents of coherence ( $\hat{\gamma}_{\text{Scat}}$ ) performance bands for the gravel and stone scenes. “Good” Coherent Change Detection (CCD) performance is represented by green, “Moderate” by yellow and “Poor” by red.

2 cm), and the stones about an order of magnitude above it (5–10 cm).

Having investigated only two terrain types, it is difficult to extrapolate the results to general terrain, however the experiments conducted indicate that the bistatic angle difference extent for any particular CCD performance band broadly varies inversely with the terrain height variation (so long as it is above the Rayleigh Roughness Criterion). For example, for “Good” CCD performance, in the gravel case the angular extent reached 6°, whereas for the stones case it reached 2°.

Overall, however, it has been shown that the terrain surface has a significant impact on what different bistatic geometries can be used to form useful CCD images when an exact repeated pass is not possible, for example, due to time or mission constraints.

An approach to simulating the decorrelation has been demonstrated, and matched to two types of terrain, controlled by one empirically determined parameter, however other ground types may respond differently. Future work could investigate additional ground types and how the combination of multistatic collections might be used to reduce the impacts of coherence loss [29]. To improve the understanding of the behaviour of the  $\hat{\gamma}_{\text{Scat}}$  parameter, future experiments could utilise metal spheres or higher fidelity simulations using scene CAD model instead of point scatterers.

## AUTHOR CONTRIBUTIONS

**Alexander Hagelberg:** Conceptualisation; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualisation; Writing - original draft; Writing - review & editing. **Daniel Andre:** Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Writing - review & editing. **Mark Finnis:** Project administration; Resources; Software.

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## CONFLICT OF INTEREST STATEMENT

There is no conflict of interest that we are aware of.

## DATA AVAILABILITY STATEMENT

Radar trajectory co-ordinates will be made available on the Cranfield Online Research Data (CORD) repository: <https://dspace.lib.cranfield.ac.uk/handle/1826/20712>. Synthetic Aperture Radar data is the subject of ongoing research but may be made available on request to the corresponding author or the Cranfield GBSAR group.

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## APPENDICES

The appendices contain information about the antenna SAR trajectories used in this paper. The co-ordinates of the trajectories are available on the CORD repository: <https://dspace.lib.cranfield.ac.uk/handle/1826/20712>.

In Table A1 several angles are presented. The first is the bistatic angle between the mean transmitter and receiver positions. Grazing angles for the mean transmitter, receiver and BEM positions are also presented. The BEM direction is the bisectrix of the vectors joining the antenna positions and the scene centre [43, 44].

The slant ranges to the scene centre, and heights for the mean transmitter, receiver and BEM positions are presented in Table A2. The BEM range is given by the bistatic range.

The ground-range and cross-range resolutions are presented in Table A3.

**TABLE A1** Bistatic and Grazing angles.

| Trajectory | Bistatic angle, $\beta$ (°) | Grazing angle (°) |      |      |
|------------|-----------------------------|-------------------|------|------|
|            |                             | Tx                | Rx   | BEM  |
| TR1 000    | 63.4                        | 25.3              | 26.0 | 30.6 |
| TR2 000    | 58.6                        | 25.2              | 26.1 | 29.8 |
| TR3 000    | 53.8                        | 25.1              | 26.1 | 29.0 |
| TR4 000    | 49.1                        | 24.9              | 26.0 | 28.2 |
| TR5 000    | 44.4                        | 24.7              | 25.9 | 27.5 |
| TR1 200    | 64.7                        | 22.9              | 23.8 | 28.0 |
| TR2 200    | 59.8                        | 22.9              | 23.8 | 27.2 |
| TR3 200    | 54.9                        | 22.8              | 23.8 | 26.5 |
| TR4 200    | 50.0                        | 22.6              | 23.8 | 25.8 |
| TR5 200    | 45.2                        | 22.4              | 23.7 | 25.1 |
| TR1 400    | 65.9                        | 20.5              | 21.4 | 25.3 |
| TR2 400    | 60.9                        | 20.5              | 21.5 | 24.5 |
| TR3 400    | 55.9                        | 20.4              | 21.5 | 23.9 |
| TR4 400    | 50.9                        | 20.2              | 21.4 | 23.2 |
| TR5 400    | 46.0                        | 20.1              | 21.3 | 22.6 |

**TABLE A3** Resolutions.

| Trajectory | Resolution (cm) |             |
|------------|-----------------|-------------|
|            | Ground range    | Cross-range |
| TR1 000    | 5.11            | 5.34        |
| TR2 000    | 4.95            | 5.19        |
| TR3 000    | 4.80            | 5.09        |
| TR4 000    | 4.67            | 5.02        |
| TR5 000    | 4.57            | 4.99        |
| TR1 200    | 5.02            | 5.24        |
| TR2 200    | 4.86            | 5.10        |
| TR3 200    | 4.72            | 4.99        |
| TR4 200    | 4.59            | 4.92        |
| TR5 200    | 4.48            | 4.88        |
| TR1 400    | 4.93            | 5.16        |
| TR2 400    | 4.78            | 5.01        |
| TR3 400    | 4.64            | 4.91        |
| TR4 400    | 4.52            | 4.84        |
| TR5 400    | 4.41            | 4.79        |

**TABLE A2** Ranges and heights.

| Trajectory | Range (m) |      |      | Height (m) |      |      |
|------------|-----------|------|------|------------|------|------|
|            | Tx        | Rx   | BEM  | Tx         | Rx   | BEM  |
| TR1 000    | 4.55      | 4.63 | 4.59 | 1.94       | 2.03 | 2.34 |
| TR2 000    | 4.56      | 4.63 | 4.59 | 1.94       | 2.03 | 2.28 |
| TR3 000    | 4.58      | 4.63 | 4.60 | 1.94       | 2.03 | 2.23 |
| TR4 000    | 4.60      | 4.64 | 4.62 | 1.94       | 2.03 | 2.19 |
| TR5 000    | 4.64      | 4.65 | 4.65 | 1.94       | 2.03 | 2.15 |
| TR1 200    | 4.47      | 4.55 | 4.51 | 1.74       | 1.83 | 2.11 |
| TR2 200    | 4.48      | 4.54 | 4.51 | 1.74       | 1.83 | 2.06 |
| TR3 200    | 4.50      | 4.54 | 4.52 | 1.74       | 1.83 | 2.01 |
| TR4 200    | 4.52      | 4.55 | 4.54 | 1.74       | 1.83 | 1.97 |
| TR5 200    | 4.56      | 4.57 | 4.57 | 1.74       | 1.83 | 1.94 |
| TR1 400    | 4.39      | 4.47 | 4.43 | 1.54       | 1.63 | 1.89 |
| TR2 400    | 4.40      | 4.46 | 4.43 | 1.54       | 1.63 | 1.84 |
| TR3 400    | 4.42      | 4.46 | 4.44 | 1.54       | 1.63 | 1.80 |
| TR4 400    | 4.45      | 4.47 | 4.46 | 1.54       | 1.63 | 1.76 |
| TR5 400    | 4.49      | 4.49 | 4.49 | 1.54       | 1.63 | 1.73 |



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## **Bistatic multipolarimetric synthetic aperture radar coherence investigation using spatially variant incoherence trimming**

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