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(71) Applicant (for all designated States except US): **DSTL**
[GB/GB]; Secretary of State for Defense, Porton Down,
Salisbury, Wiltshire SP4 0JQ (GB).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **BARBER, Brian,**

Charles [GB/GB]; DSTL, Cody Technology Park, A2
Building, Room G132, Ively Road, Farnborough, Hamp-
shire, GU14 OLX (GB).

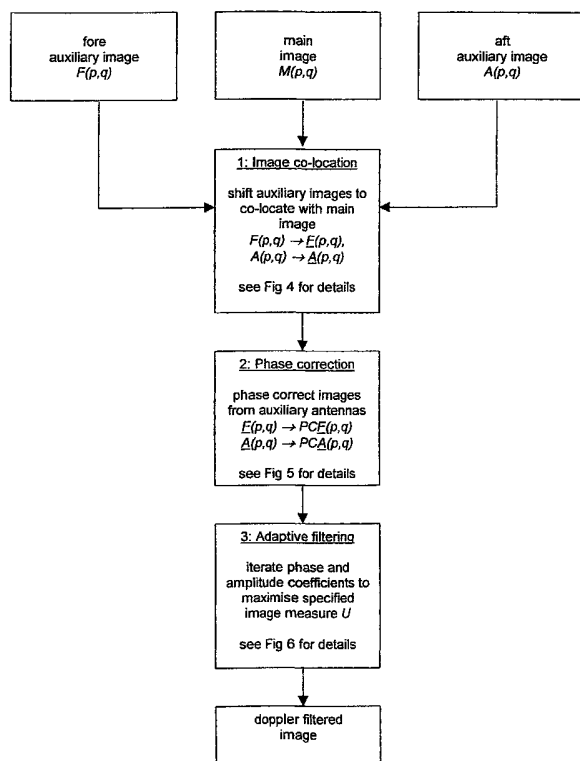
(74) Agents: **GODDARD, David, John** et al.; Harrison God-
dard Foote, Orland House, 11c Compstall Road, Marple
Bridge, Stockport SK6 5HH (GB).

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(54) Title: INTERFEROMETRIC SYNTHETIC APERTURE RADAR FOR IMAGING THE OCEAN SURFACE



(57) Abstract: In a radar imaging arrangement having a platform for movement along a first direction and a plurality of radar receivers mounted on the platform, and image means for providing a respective initial radar image from the output of each said receiver, the receivers being mounted so as to have at least a component of spacing in said first direction so that there are relative phase errors between the different initial radar image signals, pairs of said initial images are combined to produce composite radar images with fringes arising from the relative phase errors, and a respective filter or filter function is developed in response to each composite image which if it is applied to one of the respective pair of initial images serves to remove or substantially reduce the relative phase errors relative to the other image of said pair. The corrected image from the adjusted initial images may be subject to adaptive Doppler filtering to emphasise particular features.



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INTERFEROMETRIC SYNTHETIC APERTURE RADAR FOR IMAGING THE OCEAN SURFACE

The invention relates to improvements in radar imaging.

One application of the invention is to improve the visibility of ocean surface features which appear in synthetic aperture radar images of the ocean surface. The technique involves Doppler filtering radar signals received from a set of two or more radar antennas arranged so that they are separated along the track of a moving platform (aircraft, spacecraft etc). The antennas may additionally be separated across the track of the moving platform. The use of multiple antennas enables the Doppler frequencies generated by the motion of the radar scatterers to be separated from the Doppler frequencies generated by the motion of the platform. This cannot be done in the case of a synthetic aperture radar using a single antenna. In addition, the multiple antennas enable specific frequency bands to be selected from the overall spectrum of Doppler frequencies generated by the motion of sea surface scatterers. Because the desired features have energy which is concentrated in only part of the scatterer Doppler frequency spectrum, it is possible to improve the efficiency of the imaging process by combining the (complex-valued) images generated from the signals from each antenna in such a way as to bandpass filter the radar images and enhance the desired scatterers and attenuate the unwanted ones. The images are combined so that the antennas operate like an interferometer in the time domain. Such an interferometer can be viewed as a bandpass filter and the shape and centre frequency of the filter pass-band can be adjusted by applying amplitude and phase factors to the images generated from each antenna. Furthermore the phase and amplitude factors can be changed adaptively until the visibility of a particular feature is maximised.

Although the invention is more particularly described here in relation to synthetic aperture radar, it is also applicable to other radar systems, for example real aperture radar imaging systems such as ordinary side looking coherent imaging radars. When synthetic aperture processing is employed, the Doppler filtering can be carried out together with the high spatial along track resolution resulting from the synthetic aperture.

In essence, the array of antennas separated along the track of the moving platform can be viewed as an interferometer working in the time domain because of the motion of the platform. The separation along the track leads to a phase difference between the signals received by each antenna from a moving scatterer because the range to the scatterer changes with time and because there is a time-shift between the images generated from each antenna. If phase shifts are applied to each image which exactly cancel those due to the scatterer motion (this could be regarded as application of an appropriate filter - or filter function if performed by software, but for brevity the term filter may be used for both concepts hereafter) then the images of the scatterer add in phase and the intensity of the resulting scatterer image is maximised. Other scatterers which move with a different range velocity have different phase shifts and so do not add in phase. The intensity of their summed image is thus not maximised and in principle could even be zero if the resulting phases are such that destructive interference occurs.

The invention is concerned with the removal or substantial reduction of phase errors from the radar signals (and hence the radar images). These 'phase errors' are actually errors both in the phase difference between corresponding points on the different images processed from the signals from each antenna and also in the phase difference between points on the same images at different positions. Systematic phase errors are caused by antenna separation across the track. Additional phase errors (which vary with time) are a result of platform roll, pitch and yaw motions coupled with the along track and across track antenna separations. There are also further phase errors caused by the radar system, digital data handling system and radar image processor. The rate of change of these phase errors varies slowly in time and space in comparison with the Doppler frequencies associated with scattering from the moving ocean surface. Nevertheless they are very important because they have the effect of changing the centre frequency and shape of the filter response in an unpredictable and non-stationary way over the images. Hence if the errors are not removed a filter response which is optimal in one part of an image may be worst-case in another part. The phase errors need to be removed to a high degree of precision (corresponding to a change in range of a small fraction of a wavelength -- which may well be only a few mm or so at

a wavelength of 3 cm over a range of many km). This high degree of precision is difficult to achieve by measuring the displacements of the platform directly (for example by integrating the output from an inertial navigation system).

The invention is concerned with the provision of a filter or filter function for correcting the phase errors, and as described in relation to the embodiment such is in the form of a two dimensional phase error function, also referred to herein as a phase screen.

The fringe pattern which results from the intensity of an image produced by adding together two partially correlated complex valued synthetic aperture images processed from the signals received by two antennas in an array defines the phase difference between the images. Hence, by measuring the fringes one can determine the phase errors between the images. Specifically, the fringe pattern can be used directly to define the two dimensional phase error function.

However, the fringe pattern cannot be used directly because the fringes are essentially envelope modulated speckle and it is necessary to smooth the speckle first. In many circumstances, difficulties can then arise because the width of the fringes can easily be too small in comparison with the speckle size to achieve effective speckle smoothing without also distorting the fringes. Thus in a preferred form of the invention the total phase error correction is derived in two stages. First, a phase screen is computed on the basis of the phase errors caused by the geometry, that is the differential change in phase between two antennas resulting from their spatial separation resulting in different ranges to a point on the ground; all of the relevant distances are known from the geometry and so the phases may easily be computed. This initial phase screen may also incorporate estimates of the additional phase errors resulting from aircraft roll, pitch and yaw motion by using data from the inertial navigation system.

The resulting phase screen is then used to compensate the phase errors between the images from the two chosen antennas. Because the initial phase screen is only an approximate estimate of the errors there are remaining errors. Hence a second screen is computed. This is done by again forming an interference fringe pattern. However,

this time the partially phase compensated image pair is used. Because most of the phase errors have been compensated the fringes are now much broader and the speckle can now be successfully smoothed without distorting the remaining fringes. Hence a second screen is now computed directly from the second set of fringes after
5 they have been smoothed. This second screen is then added to the first and the composite screen used to phase compensate the image pair.

Preferably, one antenna in the set is taken as the phase reference (such as, for example, a central antenna of the set), and the image processed from that antenna is the taken as the phase reference. The images from the other antennas (the 'auxiliary
10 images') are then all paired with the reference image and phase compensation screens computed for each pair. The auxiliary images are then phase compensated relative to the reference image using the above procedure. This ensures that all the images are compensated relative to each other with the minimum of computing. Once this has been done all phase difference errors have been removed from the image set and they
15 can then be used for Doppler band-pass filtering.

It should be noted that if the initial set of fringes are sufficiently wide relative to the speckle, the speckle can be directly smoothed for directly deriving the two-dimensional phase error function. Although not described in detail herein, this latter process is akin to the derivation of the second phase error correction function which is
20 described herein in detail with reference to Figure 7 (c) to (e) for example. This one-step derivation of the filter or filter function may be useful for example where the phase errors are relatively slowly changing, such as during long range imaging.

Features and advantages of the present invention will become clearer upon a consideration of the appended claims, to which the reader is referred, and also upon a
25 reading of the following more detailed description of the invention and a preferred embodiment thereof, made with reference to the accompanying drawings, in which:

Figure 1 shows an enhanced radar (ESR) system imaging a sandbank;

Figure 2 illustrates typical interference fringes from the fore and main antennas of the system shown in Figure 1;

Figure 3 shows in block diagram form an overall signal processing scheme incorporating the present invention;

Figure 4 is a block diagram illustrating collocation of an auxiliary image with the main image as performed in the scheme of Figure 3;

- 5 Figure 5 is a block diagram showing phase correction of an auxiliary image as performed in the scheme of Figure 3;

Figure 6 is a set of images for explaining how image co-location using fringe visibility may be performed;

Figure 7 illustrates phase screen generation neglecting aircraft attitude angle changes;

- 10 Figure 8 illustrates phase screen generation taking aircraft roll into account;

Figure 9 is a plot of aircraft attitude angles relating to Figure 7;

Figure 10 is a block diagram showing the adaptive filtering process employed in the scheme of Figure 3;

Figure 11 is a conventional ESR image of faintly visible swell waves;

- 15 Figure 12 is an image produced by the scheme of Figure 3 showing swell wave enhancement;

Figure 13 is a diagram showing swell wave visibility as a function of filter phase angles;

Figure 14 illustrates a maximised spike parameter;

- 20 Figure 15 shows the spike parameter as a function of filter phase angles; and

Figure 16 shows filter functions for max (spike parameter) and max (wave visibility).

In the plots of Figures 2, 6, 7, 8, 11, 12 and 14 the vertical axis represents range, e.g. slant range, and the horizontal axis represents along the along track dimension.

Multi-Aperture Along Track Interferometric (MATI) SAR systems are a special case of the general class of multi-aperture coherent imaging radars. These radars can, in principle, reconstruct the three-dimensional range/azimuth/velocity image of any moving object [1]. The ESR (Enhanced Radar) MATI is an example of this type of radar and an ESR experimental airborne three aperture MATI is described together with some of the processing techniques which have been developed to exploit the use of the system in imaging the ocean surface.

The use of ATI systems in imaging the ocean surface goes back at least to the 1980's [2, 3] when it was shown that the range component of surface ocean current velocity can be linearly related to the phase difference between the signals received by two antennas arranged along track provided the phase differences are small [4,5], and provided a number of assumptions are made concerning the sea surface scattering mechanisms. The theory of multi-aperture systems has been much developed and extended recently to the point where it can be demonstrated in principle (using analysis and simulation) that such radars can measure 'velocity maps' of the sea surface [6] and can also measure the coherence time of the scatterers [7,8]. There is, however, another closely related and potentially very useful and interesting application: MATI techniques can be used to Doppler filter radar signals backscattered from the ocean surface acquired from a moving platform (aircraft or spacecraft) using a SAR.

Suppose that a certain class of scatterer is associated with energy located in a particular part of the Doppler spectrum, and that an image feature is the result of the modulation of this class of scatterer. Then it is possible, in principle, to adaptively change the position and/or shape of a Doppler filter pass band to achieve optimum capture of the energy from the required scatterers and rejection of the remainder. Hence it is possible, by using an adaptive Doppler filter technique, to enhance the 'signal to clutter' ratio or 'visibility' of a given image feature. In consequence, Doppler filtering can be used to improve the visibility and clarity of features on SAR images of the sea surface (as well as gathering useful information on the nature of the scattering mechanisms).

When a feature is known to produce a predictable type of pattern in the radar image, it is possible to detect this pattern by the use of known pattern matching techniques, and hence to use adaptive Doppler filtering to maximise the pattern. This can be done irrespective of the scale of the pattern. Thus, for example, a periodic swell wave
5 could be enhanced; or if the shape of a sandbank is already known, e.g. from a chart, this could be employed as a pattern template for detecting and enhancing the sandbank image. Adaptive Doppler filtering to enhance patterns in a radar image is believed to be known, albeit not in connection with MATI systems.

Consider a SAR which images the sea surface. This surface moves in a random
10 manner and the backscattered electromagnetic waves have random Doppler frequencies as a result – frequencies which change in both time and space over the surface. If the radar (the source and receiver of the electromagnetic waves) is stationary and both the amplitude and phase of the waves scattered by the water waves on the sea surface are measured then the Doppler spectrum can be computed by
15 Fourier transforming the measured scattered signal over a long enough time interval. In practice, however, the radar is moving since it is attached to an aircraft or spacecraft. In this case the Doppler spectrum of the object becomes distorted and spread out by the radar motion. This occurs because different points within the illuminated region of the sea surface have different Doppler offsets due to the
20 temporal variations in range caused by the motion of source and receiver and, in addition, these Doppler offsets will vary over the finite time interval required to compute the Doppler spectrum. Clearly, if the scattering object is perfectly coherent in time then the Doppler frequencies are predictable and, of course, this is how a synthetic aperture is constructed.

25 Now consider a situation where a moving radar emits two coherent pulses of waves and these electromagnetic waves are scattered from a water wave on the sea surface. The two scattered pulses are measured, say, for the sake of argument, at the same point in space each time. This can be achieved by having two receiving antennas separated along the velocity vector of the radar platform and using a suitable radar
30 pulse recurrence frequency and platform velocity. If the object (water wave) is perfectly coherent then there is a predictable systematic phase shift between the

measurements of the two scattered pulses. This arises because the pulses are emitted and received at different ranges owing to the motion of the radar. Suppose that this phase offset is removed, then the remaining phase shift is due to the motion of the scatterer. Clearly, if a number of antenna pairs are used, then a sequence of residual
5 phase shifts can be measured [7] and hence the Doppler frequency of the water wave causing the radar scattering can then be measured to within a spectral resolution dependant on the number of antennas, their spacing, and the speed of the aircraft. Alternatively, the signals from the antennas can be combined to form an interferometer working in the time domain so that the signals can be filtered.
10 Furthermore, the signals from each antenna can be relatively phased and amplified (or attenuated) so that the filter pass band and shape can be changed.

Alternatively, the statistical properties of the radar image may be analysed to control how the adaptive Doppler filtering is effected. Thus, for example, a sandbank viewed with horizontally polarised low incident angle (20-30°) radar waves of the frequencies
15 commonly employed in MATI systems will generally produce a radar image which consists of a number of bright points having a significantly non-Gaussian distribution. By controlling the adaptive process to maximise the “spikiness” of the image, the image of the sandbank may be enhanced relative to other features.

It is believed that the statistical analysis of a radar image in order to derive at least one
20 parameter for use in adaptive Doppler filtering is a novel technique. Although specifically described here in relation to the use of a particular phase filter technique in conjunction with radar imaging from a moving platform (whether or not ATI), the adaptive Doppler filtering could be used with other radar systems such as an ordinary static radar imaging system.

25 More details concerning the adaptive Doppler filtering techniques mentioned above will be provided later.

In the next section the ESR system is described and the use of this MATI system in imaging the ocean surface is described in a physical way. Section 3 covers the processing techniques which have been developed to remove phase difference errors
30 (including systematic errors and also those resulting from aircraft motions) between

the signals from the various antennas. Filtering techniques are discussed in section 4 and an example of the optimal imaging of a swell wave is presented.

2. The ESR Interferometer system.

A practical implementation of the ideas discussed in the introduction has been
5 installed on an airborne radar system: the Enhanced Radar (ESR). Figure 1 shows a diagram of this radar system imaging swell waves on the ocean surface.

The aircraft platform (a BAC/BAe 1-11) is equipped with a conventional synthetic aperture radar except that the radar echoes from the target are received by three antennas. The two extra antennas are typically placed about a metre in front and a
10 metre behind the main radar antenna (these antenna spacings are fixed in flight but can be varied on the ground). The footprints of the three beams overlap and so the main antenna is used to transmit and all three antennas are used to receive. The relative sizes of the footprints are indicated only very approximately in Figure 1; the much larger footprints from the auxiliary horn antennas are a result of their much
15 smaller size. This is a practical necessity resulting from the simple aircraft installation. The main antenna is fully stabilised but the auxiliary antennas are attached rigidly to the airframe. The much larger auxiliary antenna footprint has an advantage in that the aircraft attitude angles can change by many degrees while the main antenna footprint remains well within the auxiliary antenna footprints. However,
20 there is a signal to noise ratio penalty resulting from the relatively low auxiliary antenna gain. This restricts the grazing angle to greater than about 30° at low wind speeds and horizontal polarisation using a mean radiated power of around 250 watts divided between four channels. Some radar system parameters are given in Table 1 below.

25 A pulse recurrence frequency of 2 kHz was typically used, the received echoes being multiplexed so each receive channel effectively operated at 500 Hz (and since there were three receiving antennas one of the four channels was unused). The system is capable of considerably better performance than is indicated in table 1 in many respects but the table reflects the typical parameters used in the work described here.
30 The main radar is fully polarimetric but current data handling system limitations only

allow the use of one polarisation for the auxiliary interferometer horns and horizontal polarisation was used throughout for the work presented here.

Wavelength	I Band
Azimuth resolution	1.0 m
Slant range resolution	1.2 m
Main antenna one way beamwidth in azimuth in range	1.32° 7.0°
Auxiliary antenna one way beamwidth in azimuth in range	28.0° 28.0°
Main antenna Stabilisation error	0.1° rms max
Pulse width	5 μ sec
Peak power	15 kw
Typical aircraft speed	128 m/sec

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Table 1: ESR Radar system parameters

Synthetic aperture radar images are formed from the signals from each antenna. Exactly the same processing parameters (and processor) are used in the processing of each image; this ensures that any phase errors introduced by the processor are the same for each image. These images are analytic images in complex form and there is a systematic phase shift between them due to the physical separation between the receiving antennas both along the aircraft track and across track. The across track variation comes about because the main and auxiliary antennas are located at different vertical locations on the airframe (see Figure 1) and because of aircraft yaw, pitch and roll motions. The along track variation also comes from aircraft yaw, pitch and roll motions. The phase changes are first order functions of changes in yaw and roll angle and second order functions of changes in pitch angle. All are functions of time and their effects have to be removed from the data. The phase errors can then be removed in an elegant way by using a phase screen technique. In the case of the ESR system the images from the three antennas are initially formed into two two-beam interferometer images using pairs of images from fore and main and main and aft antennas. Thus the signals from the main antenna are always used as the phase

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reference. The interferometer images from each pair are formed in exactly the same way as in a two beam optical interferometer (see, for example, chapter 7 of [9]). So, if the complex-valued image at pixel location (p,q) resulting from the signals received by the front antenna is $F(p,q)$ and the image at the same location received by the main antenna is $M(p,q)$ then the interferometer image $G(p,q)$ is formed where

$$G(p,q) = |F(p,q) + M(p,q)|^2 \quad (1)$$

The antennas are separated and consequently there is a differential change in range to the antennas resulting in interference fringes. In addition though, because the aircraft's yaw, pitch and roll angles are changing (as well as vertical and transverse velocities), the fringes are distorted due to the additional phase fluctuations which the aircraft motion causes. These phase fluctuations would normally be very difficult to detect and measure from the radar data to the high precision needed for Doppler filtering. However, the presence of the interferometer fringes renders these fluctuations easily measurable through the fringe distortions.

An example of the interferometer image which results from the fore and main antenna pair is shown in Figure 2. It is an image of the sea surface, but of more immediate interest are the fringes. It is possible to construct an algorithm (see the next section for details) which automatically computes the two dimensional phase function or 'phase screen' which the fringes represent. Let this phase function be $\phi(p,q)$. All that now needs to be done to remove the fringes from $G(p,q)$ is to multiply $F(p,q)$ by the conjugate phase screen function $\exp[-i\phi(p,q)]$. The same procedure is carried out for the pair of images from the main and aft antennas, except that the fringes are not exactly the same as those from the fore and main pair and so a different phase screen $\exp[-i\psi(p,q)]$ is computed for them. The three images from the antennas are then combined to form a three beam interferometer, and the resulting image $H(p,q)$ is given by

$$H(p,q) = |F(p,q)\exp[-i\phi(p,q)] + M(p,q) + A(p,q)\exp[-i\psi(p,q)]|^2 \quad (2)$$

As mentioned above such an interferometer can be regarded as a band-pass filter. It is straightforward to work out the frequency response of the filter simply by supposing

that the three antennas receive perfectly coherent plane electromagnetic waves of unit amplitude scattered by a moving object. Take the main antenna to be the phase reference. Phase functions of time due to the radar 'carrier' frequency are the same for all three antennas and are ignored. The fore antenna 'sees' an object before the main
 5 antenna so take the wave at the fore antenna to be $\exp[-i\theta]$ where the phase shift θ is caused by the motion of the scatterer between being imaged by the fore and main antennas. If the Doppler frequency due to the motion of the scatterers is ν and the time interval between the antennas is Δt (which equals the antenna along track separation divided by the aircraft speed) then $\theta = \pi\nu\Delta t$. The reason that there is no
 10 factor of two in the expression for θ is that due to the 'monostatic-bistatic equivalence theorem' (see [10]), Δt has to be halved because, for small angles, the radar views the scattering object as if it was located halfway between the antennas. The phase at the aft antenna is equal and opposite since it is separated from the main antenna by an equal and opposite distance so the wave at the aft antenna is
 15 $\exp[i\pi\nu\Delta t]$. Replacing each of the three terms in the equation (2) by $\exp[-i\pi(\nu - \nu_0)\Delta t]$, and $\exp[i\pi(\nu - \nu_0)\Delta t]$ respectively where ν_0 is an offset frequency and then normalising to give a maximum value of unity gives

$$F(\nu) = | \sin[3\pi(\nu - \nu_0)\Delta t/2] / 3\sin[\pi(\nu - \nu_0)\Delta t/2] |^2 \quad (3)$$

which will be recognised as the usual unweighted 'periodic sinc function' (but for
 20 only three coefficients). It represents the power spectral response of a band-pass filter with centre frequency ν_0 to the Doppler frequencies ν of the scatterers.

In actual practice a more general view of the filter is adopted and both the phase and amplitude of the filter coefficients are changed adaptively in order to enhance the images of certain sea surface scatterers. For example the backscattered
 25 electromagnetic waves responsible for images of swell waves may have Doppler shifts contained within a well defined band. The filter centre frequency and the shape can then be changed adaptively in order to reject the clutter outside of this band and hence maximise the visibility of the swell waves. An example of this is presented later in section 4. This type of adaptive processing has received considerable attention

in the radar processing community during the past decade in relation to interference suppression and clutter cancellation [11,12]. Here, however, the adaptive processing is used to enhance one part of the *clutter* spectrum relative to the rest of the clutter. The processing methods used in the multichannel interferometer are presented in
5 detail in the next section.

The range of grazing angles typically used in the work presented here covered about 33° to 43°. Measurements of the Doppler spectrum of scattering from the ocean surface at 3 cm radar wavelength and for relevant windspeeds are presented in [13] at a grazing angle of 35° for a range of angles relative to the wind vector. The data
10 presented in [13] were used to set the antenna spacing (1m) and aircraft speed (typically 125-130 m/sec) so that the Doppler spectrum was well sampled by the interferometer.

3. Phase correction techniques

Figure 3 shows a block diagram of the overall interferometer and adaptive filtering
15 processing scheme. First, as a result of using the same range history in the processing of the images, the auxiliary images have to be co-located with the main antenna image and this is shown in the block at the top of Figure 3. A block diagram for this process is shown in Figure 4 and the process is described in subsection 3.1 below. Next, the auxiliary images have to be phase corrected relative to the main antenna image as
20 explained in section 2, and this is shown in the next block down in Figure 3. A block diagram for this process is shown in Figure 5 and it is described in detail in subsections 3.2 to 3.4 below. The third block in Figure 3 shows the adaptive filtering and this process is summarised by the block diagram in Figure 10 and is described in detail below in section 4.

25 3.1 Auxiliary image collocation

The main image and auxiliary images are displaced from each other both along track and across track. It would, of course, be possible to remove this displacement by using appropriate range history functions in the processing of each image. However, for the images used in the work described here exactly the same processing

parameters (and processor) were used in processing the synthetic aperture images from each antenna in order to ensure that any processor generated phase errors were identical for each image. A consequence of this is that because the antennas are physically displaced, so are the images. It is then necessary to shift the images relative to each other in order to collocate them. If this is not carried out then the cross-correlation can be very small (because the displacement can easily be much greater than the point spread function width either in range or azimuth) so that no fringes are visible. Fortunately, there is a straightforward way to attack this problem because the cross-correlation coefficient is maximised when the fringe visibility is maximised - see [9]. Hence the auxiliary antenna images are shifted in range and azimuth relative to the main antenna image until the fringe visibility is maximised. The fringes are warped in an arbitrary way (but nevertheless slowly varying) and under this circumstance the best way of measuring the visibility is to Fourier transform the intensity image. The fringe spectral energy is concentrated on a localised domain in the transform and the visibility is maximised when this local domain has maximum peak amplitude. This procedure is illustrated in Figure 6. Figure 6 shows nine sets of fringes generated from the fore and main images of the ESR system described above. The (x,y) coordinates give the relative shift in image pixels in azimuth (the x axis) and in range (the y axis). The image set is centred on (0,-2) because in the ESR radar system there is a constant offset of typically nearly two range samples due to the installation of the antennas on the aircraft. The 'max' values listed in Figure 6 refer to the maximum values of the peaks of the power spectra of the fringes. There is an obvious correlation in Figure 6 between fringe visibility and the peak values of the power spectra. It is also obvious from Figure 6 that the true maximum lies somewhere in the interval with corners at (-1,-1), (0,-1), (0,-2) and (-1,-2).

In order to determine the position of the correlation maximum more accurately an interpolation technique is required. The method which has been used in the work described here is to increase the number of image pixels by an integer multiple and then choose the nearest neighbour. This is a fast technique which also has reasonably quantifiable errors. The technique consists of performing a 2-D FFT followed by re-indexing the spectrum and then an inverse FFT with the number of samples

multiplied by an integer. Typically, multipliers of 4 or 8 were used in the work described here. Only the images processed from the auxiliary antenna data need to be interpolated. The interpolated auxiliary antenna image is shifted one (interpolated) pixel at a time in range and azimuth, subsampled to reinstate the original size, and the fringes are formed with the main antenna image. The fringe visibility is then measured. The interpolated image is then shifted again and the procedure repeated until a fringe visibility maximum is achieved. The auxiliary image is then taken to be properly collocated with the main image and is input to the phase screen construction process. The whole image collocation process is repeated for all the auxiliary images.

10 **3.2 Construction of the first phase screen**

The interferometer fringes are a consequence of phase variations only, and image intensity modulations caused by spatial variations in scatterer cross-section are a nuisance in measuring the phase variations from the interference fringes. Hence the first step in constructing a conjugate phase screen is to normalise all the images (auxiliary antenna and main antenna) in order to remove any image modulations which may be present. This is easily accomplished by normalising each complex valued pixel so that the phase is preserved, but the modulus is set to some convenient constant value. The resulting interferometer fringes are then free from any scatterer amplitude effects, to first order.

20 The fringes are essentially envelope modulated intensity speckle patterns and in using fringe patterns such as those in Figure 6 to define a phase screen the speckle has to be smoothed to leave only the envelope. This comes about because only the systematic phase errors due to the antenna separation and aircraft motion should be removed. Phase fluctuations due to scatterer effects need to be retained otherwise the whole object of the exercise is nullified! Clearly, in smoothing the speckle the fringes should be as broad as possible so that the scale lengths of speckle modulation and scale lengths of the fringes are as widely separated as possible. The phase shifts leading to the fringes are a result of the physical antenna separation, the imaging geometry and the linear and rotational velocities of the aircraft. The phase shifts resulting from the antenna separation and imaging geometry are easily predictable. An approximate

initial phase screen can therefore be constructed which can be used to remove this component of the phase shifts. In most cases the aircraft is flown in a uniform way with a nearly constant velocity vector and small rotational velocities. Under these circumstances the approximate phase screen will remove the majority of the phase differences between the main image and auxiliary images. The result of applying the screen is that the fringes formed from the residual phase differences are much broader so that speckle smoothing can be done using a wider smoothing kernel and in consequence is more effective. The same initial phase screen is used for all the auxiliary images as a matter of convenience; any residual errors are taken out by the second phase screen.

In the case of the imaging system described here (which typically flies at an altitude of a few thousand feet at grazing angles of 20°-50°) a simple linear initial screen is used when the flying conditions are good in calm weather. In such conditions the quadratic range components are typically of the same order of magnitude as the along track phase variations due to aircraft attitude angle changes and so in this case there is little point in estimating either of them initially.

The two auxiliary antennas were arranged symmetrically either side of the main antenna, and the aircraft installation required that the auxiliary antennas were situated above the main antenna. Consider a vertical plane containing the main antenna focus, the plane being orthogonal to the longitudinal axis through the airframe, and let the distance between the focus of the main antenna and the foci of the auxiliary antennas projected on to the plane, measured in the plane, be l . Let the angle between the line connecting the main antenna focus and auxiliary antenna foci in the plane and the vertical be ϕ . Let the incidence angle of the radar beam centre at the target at the minimum range be θ . A linear approximation for the change in phase across the interferometer image at constant azimuth time is thus

$$\text{Phase} = \text{constant} + 2\pi \frac{l}{\lambda} \frac{\sin(\theta + \phi)}{\tan \theta} \left(\frac{r}{r_0} - 1 \right) \quad (4)$$

Where r_o is the range at the near edge of the image (or any suitable reference point), r is the range across the image and λ is the radar wavelength. The electromagnetic waves transverse one path difference between the main antenna and auxiliary antennas, hence the factor of 2π .

- 5 The initial phase screen is then

$$P(r) = \exp \left[i 2\pi \frac{l}{\lambda} \frac{\sin(\theta + \phi)}{\tan \theta} \frac{r}{r_o} \right] \quad (5)$$

and the image is multiplied by the complex conjugate of (5) to produce a set of broadened fringes.

The process described above is illustrated by the images in the top line of Figure 7.

- 10 The left hand image (labelled 'a') shows the fringes obtained from the fore and main antennas in this instance. The fringe distortion is caused by an aircraft roll angle variation. The Center image 'b' shows the (unwrapped) initial screen defined by equation (4) and the right hand image 'c' shows the resultant fringes after applying the initial phase screen.

15 3.3 The second phase screen

The speckled fringes resulting from the first phase screen have to be smoothed and this is accomplished by convolving the real and imaginary points of the image separately with a smoothing function. The function used here was a raised cosine (a 'Tukey' kernel). This coherent averaging is quite powerful in smoothing out the local

- 20 phase variations to give the local mean phase. This process amounts to constructing a random walk which is naturally biased due to the correlation which leads to the fringes. The size of the kernel to the zero points was about 10% of the size of the image in each direction. The phase defined by the argument of the smoothed real and imaginary points gives the second phase screen. This is shown at the bottom left of
- 25 Figure 7 at 'd'. Note that although this image appears to be the same size as the previous images it is in fact smaller by the width of the smoothing kernel because the partially smoothed edges have been deleted. This is also true of the remaining images.

The residual phase function is then combined with the initial phase screen (which is clipped to make it the same size) to produce the final screen shown in the bottom Center of Figure 7 at 'e'. The raw interferometer image is then operated on by the complex conjugate of the final screen to produce the final corrected image, the
5 residual phase of which is shown at bottom right in Figure 7 at 'f'. There are some slight patterns in the residual phase and those are a result of phase modulations resulting from ocean swell waves present in the images from which the fringes were formed. These phase modulations are, of course, exactly the information which is needed in order to use the interferometer to either enhance or suppress the swell
10 images as is demonstrated in the next section.

3.4 Non-negligible aircraft motion

In the construction of the first phase screen the aircraft roll, pitch and yaw motions are not always negligible especially in flying conditions which are less than ideal. Even when an attempt is made to fly straight and level at constant speed, gusts and
15 turbulence can perturb the platform and significantly affect the utility of the simple phase screen technique described above. In this case the rate of phase change along track at constant range can be much higher than the rate of change across track at constant along track time. In this case the initial phase screen must incorporate phase data relating to the aircraft motion. Because any residual errors are removed by the
20 second screen the estimates of aircraft motion do not need to be of high precision. These estimates can conveniently come from the aircraft inertial navigation system. The interferometer phase shifts are first order functions of aircraft yaw angle changes because of the along track antenna separation and first order function of the roll angle changes because of the vertical separation of the antennas. Pitch angle changes only
25 have a second order effect on the phase shifts however, so only the roll and yaw angles are of primary importance. Furthermore, the rate of change of yaw is usually much less than the rate of change of roll for typical aircraft (and this is certainly true of the aircraft used for the ESR) so usually the roll angle changes are of more importance than the yaw changes in this context.

Figure 8 illustrates the modifications to the phase screen technique for a situation where the aircraft motions have to be accounted for. The purpose of applying an initial screen is to broaden the fringes sufficiently to enable a smoothing kernel to filter out the phase fluctuations. A rapid change in phase in the along track direction is not compensated by a simple range based screen and the remaining along track fringes can be too fine to successfully smooth. In the case of the fringes shown in Figure 8a the initial phase screen (at 'b' in Figure 8) included phase changes based on the attitude angles of the aircraft, and as an additional refinement the change in range across track in equation 4 was taken into account (i.e. r was not assumed constant = r_0). It will be seen from the residual phase shown at Figure 8c that the initial phase screen is quite successful in removing most of the phase fluctuations. Figure 9 shows the aircraft roll, pitch and yaw angles for the data set from which the fringes in Figure 8a resulted. Compare the shape of the roll angle function in Figure 9 with the shape of the fringes in Figure 8 and it is at once qualitatively apparent that the roll in this case is largely responsible for the phase changes.

Using the same definitions and coordinates as described in 3.2 above it is straightforward to show that a linear approximation for a small change in roll angle $\Delta\psi$ gives a corresponding range change of Δr_{roll} where

$$\Delta r_{roll} = \Delta\psi l \sin(\phi + \theta) \quad (6)$$

There is one path length change for the electromagnetic waves to traverse so the phase change is $2\pi\Delta r_{roll} / \lambda$, λ being the radar wavelength. It is supposed that there is no permanent roll offset for simplicity (but within this approximation this would amount to only an extra cosine term).

Now consider yaw angle changes and consider a horizontal plane containing the main antenna focus. Let the separation between the focus of each auxiliary antenna projected on the plane be $2s$. Then if there is a change $\Delta\eta$ in yaw angle the corresponding range change Δr_{yaw} is

$$\Delta r_{yaw} = \Delta\eta s \sin\theta. \quad (7)$$

Again, there is one path length change so the corresponding phase change is $2\pi\Delta r_{yaw} / \lambda$.

For the data considered here, $l = 3.60\text{m}$, $s = 1.00\text{m}$, $\phi = 27^\circ$ and $\theta = 48^\circ$. Referring to Figure 8 the total change in roll angle over the data set is 10.47° and the total change in yaw angle is 1.91° leading to total range changes of 21.2 and 0.8 wavelengths respectively. It is clear that changes in roll angle dominate changes in yaw angle and this is typical for this particular radar system. The total number of cycles through 2π radians along a line of constant range can be easily counted from the fringes in Figure 8 and is approximately 21 at near range, agreeing with the above calculations within the errors inherent in the approximation used.

As in the previous example, the residual phase is smoothed (shown at 8d), and then added to the first screen to produce the second screen shown at 8e. The residual phase at 8f demonstrates that the processing has again successfully removed the fringes.

4. Filtering techniques

The use of adaptive processing for along track SAR interferometry has been discussed in, for example, [12]. The methods described there were developed primarily for the detection of moving 'hard targets' (such as vehicles) moving within a stationary clutter background. The Doppler spectrum associated with a compact perfectly coherent scatterer (vehicle) is well defined, unlike the spectrum from a sea surface scatterer. Clearly, the situation here, where both the 'target' (which is a sea surface clutter intensity modulation corresponding to a desired feature such as a swell wave) and the 'clutter' (everything else) is more general in that both 'target' and 'clutter' are both only partially coherent in time and space. Very few assumptions can be made. One assumption which has to be made is that the Doppler spectrum associated with the 'target' is sufficiently different in some sense to the spectrum associated with the 'clutter' so that the adaptive bandpass technique can enhance the spectral energy of one relative to the other. A stronger assumption concerns the azimuth image shift and smearing associated with a moving scatterer. It is necessary for the shift and smearing to be sufficiently similar for each image in the interferometer set so that the Doppler

spectrum measured at a particular image location on each image is generated by the same physical scatterer. This is really just an assumption that the cross correlation between the images in an interferometer set is 'sufficiently high' in some sense.

Following the removal of the phase errors, the residual phase differences contained in the images represent the Doppler information which the interferometer technique uses to band pass filter the Doppler spectrum. Equation 2 gives the image function $H(p,q)$ for uniformly weighted images from the three antennas. In general, if the fore and aft antennas are weighted by $C \exp(i\alpha)$ and $D \exp(i\beta)$ respectively, then the image function is

$$H(p,q) = |C \exp(i\alpha) F(p,q) \exp[-i\phi(p,q)] + M(p,q) + D \exp(i\beta) A(p,q) \exp[-i\psi(p,q)]|^2 \quad (8)$$

The basic idea is then to combine the images, and systematically change the complex weighting factors until a given image measure contained in $H(p,q)$ is maximised (or minimised). The phase screen technique sets the mean phase difference between antenna pairs to zero and so the mean Doppler frequency in a given image is also zero: the Doppler spectrum is essentially shifted to zero baseband. The must always be borne in mind when interpreting the Doppler spectra.

This multidimensional process is clearly very slow if there are a large number of auxiliary antennas and there is a scope here for the design of optimal algorithms and systems which will achieve a minimal number of arithmetic operations. Even for the relatively simple case of two auxiliary antennas a four dimensional (two phase and two amplitude) search is required. Even then the process is not strictly optimal because antenna spacing and/or aircraft speed could in principle be varied as well as polarisation vector, grazing angle etc.

Practical experience of using this technique for sea surface images of swell waves and sandbank modulations has shown that the optimal values of (α, β, C, D) are near to the diagonal plane where $\alpha = \beta$ and $C = D$. Very little performance is then lost by reducing the dimensionality of the search space by a factor of 2, and this may well be generally true.

The filtering process is shown in block diagram form in Figure 10. It is understood in Figure 10 that there is a finite set of parameters (α, β, C, D) corresponding to integer indices (a, b, c, d) . In addition, the phase function $\exp[-i\psi(p, q)]$ is identical to the final phase screen $P_1^*(p, q) P_2^*(p, q)$ function of Figure 5 for the aft antenna and $\exp[-i\phi(p, q)]$ is the corresponding phase screen for the fore antenna. The filtering process is best described through an example and this section is a discussion of the methods which have been developed for adaptive filtering and the various wider issues which arise in the design of the algorithm shown in Figure 10.

4.1 Image measure

The optimisation is based on the search for an extremum of some image measure. For example one may wish to suppress swell waves if they are interfering with some other image feature, or one may wish to maximise the swell wave modulations. This is used as an example below. In this case the visibility of the waves can be defined so the ratio of the peak in the 'power spectrum' of $H(p, q)$ to the average of the 'power' in the image at the relevant wavevector. This is a particularly simple example because the image feature can be readily localised in the Fourier domain. In general, some sort of detection process is required ('pattern matching'). For example, if the image of a sandbank which has an irregular shape can be predicted in advance then pattern matching can be used. Otherwise, a different technique has to be employed. Ideally, if it could be demonstrated that the maximisation of the visibility of image modulations is accompanied by a maximisation or minimisation of some statistical property of the image speckle, then this property could be used instead of direct detection of the image modulation pattern, thus avoiding problems in trying to predict irregular shapes. A suitable statistical property would have to be determined on the basis of the physics and statistics of the scattering and modulation processes.

4.2 Filtering a swell wave example

Figure 11 shows a slant range image, 384 pixels square, of a small area of sea about 25 km east of Ramsgate in the southern North Sea. The radar grazing angle was about 43° at the image Center, the range to the image Center is about 1270m and the aircraft

speed was 128 m/sec. The image is an ordinary intensity SAR image from the main antenna of the ESR. Field observations taken at the time of the image showed that the wind was blowing towards the radar with a speed of 6-7 m/sec and that there were swell waves travelling towards the radar. The swell (which has a wavelength of approximately 26 m, or 30 range samples) is only just visible on Figure 11. The wave-crests are not quite parallel with the along track direction, the direction of travel being about 12° anticlockwise from the direction of decreasing range. In fact there are a number of different swell waves present in the data set (one of which has a wavelength of about 120-130 m and is travelling at about 60° to the short 26 m swell).

The short wave swell is, however, the largest component in the spectrum and so was chosen for enhancement. The intensity images from the fore and aft auxiliary antennas were well correlated with the main antenna image so that an incoherent sum of the three images only improved the wave visibility (which is the ratio of the peak of the power spectrum at the swell wavevector to the mean power less the dc component) by about 2%, which is insignificant.

Figure 12 shows the same image with adaptive bandpass filtering applied using the scheme shown in Figure 10 in which both gain and phase factors have been varied until the visibility of the short wave swell is maximised. The wave visibility in Figure 12 is improved over Figure 11 by a factor of 5.8 (7.6 db). This has been measured from the ratio of the peak in the power spectrum of the modulus (i.e. amplitude image) to the mean spectral 'power' minus the dc component.

Figure 13 is a plot of the fore and aft phase angles (α, β) for the values of antenna amplitude weighting (gain) for which the swell wave visibility is a maximum. This occurred at fore amplitude = 0.95, main amplitude = 1.0 and aft amplitude = 0.85 for this image. Figure 13 is therefore a two dimensional slice through the four dimensional (α, β, C, D) space at $(C, D) = (0.95, 0.85)$. The maximum is well defined, but the minimum is flat and not so well defined. Notice that Figure 13 has approximate symmetry properties. In particular Figure 13 is nearly anti-symmetric about the main diagonal and symmetric about the secondary diagonal. The fore and aft antennas undoubtedly have slightly different antenna patterns (as installed on the

aircraft), the receiver channels have slightly different noise factors, and the antennas are not perfectly symmetrical about the main antenna. All of the imperfections (and also asymmetry in the Doppler spectrum of the radar signals) will lead to asymmetry in the processing.

5 Figure 12 results from maximising the ratio of the peak in the power spectrum at the wavevector of the swell to the average spectral power. However, as discussed above, there are other measures which can, in principle, be used, especially the normalised standard deviation of the speckle, called the 'spike parameter' here. A region of the image with no modulation of the speckle is used to do this and in Figure 12 there are
10 two bands, at the top and bottom of the image about 50 pixels broad where there are no swell waves. These bands were used to measure the spike parameter. Processing the image set maximising the spike parameter produces Figure 14. The waves have completely disappeared and the power spectrum fails to show any peak at all above the background at the expected wavevector. In this case the optimum gains for the
15 fore and aft channels were equal to 0.90 and 1.15 with a maximum value of speckle standard deviation normalised by the mean of 1.99. This spike parameter is not sensitive to the channel gains and altering the gains to the optimal values appropriate to the spectral visibility maximum (0.95 and 0.85 for the fore and aft channels) reduced the spike parameter to 1.98, which is an insignificant change. The phase
20 versus spike parameter plot is shown in Figure 15 for the optimised amplitude case. Comparing Figures 13 and 15 shows that at first sight they appear to be approximate 'complementary pairs' or inverses of each other.

This, however, is somewhat fortuitous. If another swell wavevector is chosen for the optimisation then the filter peak moves to a new Doppler frequency and the phase
25 peak in Figure 13 moves. Nevertheless one solid conclusion can be drawn from this: a comparison of Figures 13 and 15 shows that the ratio of the standard deviation to mean of the speckle intensity in the interferometer image at the spectral visibility maximum is not far from unity. It is then reasonable to deduce from this that 'spiky behaviour' in the interferometer images has nothing to do with the swell wave
30 imaging process. Before concluding that this is also true for ordinary SAR images a careful comparison of spike behaviour in interferometer images and ordinary SAR

images would be required. Existing work [5] does not take into account the correlation between the interferometer images formed from the various pairs of antennas (because it was developed for the coherent addition of statistically uncorrelated adjacent pixels in interferometer images) and needs to be developed
5 further.

The power spectral filter responses resulting from the amplitude and phase factors used in Figure 12 (maximising the swell visibility) and Figure 14 (maximising the spike parameter) are shown in Figure 16 and again it is clear that for the swell waves imaged here, the circumstances which lead to the spiky returns in the interferometer
10 image play no role at all in the imaging process of the waves. The circumstances which are important for swell imaging in the interferometer images produce (nearly) Gaussian first order statistics because the standard deviation/mean is close to unity resulting from an approximately negative exponential distribution for the image intensity. Also, the Doppler spectrum of the swell wave modulated scatterers is one
15 sided. One might imagine that if the radar scatterers are uniformly distributed on the surface and are simply riding up and down on an underlying swell wave then both positive and negative frequencies would be present in the signal.

It is clear from the results presented here that when the swell wave is travelling towards the radar, and the radar is looking into the wind, only those scatterers which
20 are moving towards the radar and are therefore located on the parts of the wave for which the range to the radar is reducing contribute towards the image of the wave. This strongly suggests that the scatterers are located near the wave crests and moreover result in approximately Gaussian scattering statistics at a grazing angle of 43° and horizontal polarisation.

25 Although a system has been described which uses three antennas, it would be equally possible to use just two, or more than three. Although the term "image" has been used in the appended claims, the reader will appreciate that where appropriate reference is being made to the signal providing that image. The invention is not limited to SAR but may be used with other radars, such as real aperture radars.

5. Summary

As particularly described an 'Enhanced Radar' (ESR) is equipped with a three beam along track interferometer. This interferometer consists of a main antenna plus two auxiliary horn antennas fixed on the airframe of a BAC/BAe 1-11 aircraft. The main antenna is fully steerable. The two auxiliary antennas are located in front of and behind the main antenna on the side of the aircraft. It is shown that the interferometer can be viewed as a Doppler filter. Flying at a speed of 128 m/sec and with a 1 metre spacing along track between the antennas the interferometer can sample a Doppler spectrum of ± 128 Hz. Special purpose processing techniques have been developed for the interferometer for phase compensation and phase error removal. Synthetic aperture images processed from the three receiving antennas are taken in pairs (fore-main and aft-main), the main antenna signals always being taken as the phase reference. Initial phase screens are set up for each pair to remove most of the systematic phase differences resulting from across track antenna separation and aircraft attitude angle changes. The remaining phase differences are smoothed and a second phase screen constructed for each antenna pair. This final screen then removes the remaining phase errors. This double phase screen technique is shown to work well and does not require high precision measurements of the aircraft motion.

An adaptive processing technique is described which enhances the visibility of swell wave image features. Image modulation optimisation depends on the definition of suitable image measures and two are described. These are swell wave visibility (the ratio of the peak in the power spectrum of the swell wake modulus image at the required wavenumber and direction to the mean spectral power minus the dc component), and a 'spike' parameter (the ratio of the standard deviation to mean of image modulations). It is demonstrated that, for the presented example, the swell wave visibility is improved by a factor of 5.8 (7.6 db) using an algorithm based on maximising the wave visibility.

Doppler filtering results can give insight into the physics of the imaging process for ocean features. For the presented example the imaging mechanism appears to be associated with scattering near the wave crests. Furthermore, the use of the 'spike

parameter' for swell wave optimisation shows that the visibility of swell waves is minimised when the spike function is maximised for the given example. Hence optimal swell wave imaging is obtained when the spike parameter is minimised (close to unity), and is thus associated with 'smooth' Gaussian statistics. This is consistent
5 with Gaussian scatterers located near the crests of the swell waves.

In conclusion, the Multibeam ATI (MATI) technique appears to be a promising tool for ocean imaging now that a practical technique has been devised for removing phase errors from the multiple image data sets to the precision needed for Doppler filtering.

References

1. Friedlander B, and Porat B: 'VSAR: a high resolution radar system for detection of moving targets', *IEE Proc-Radar, Sonar, Navig.*, 1997, **144** (4) pp. 205-218
2. Goldstein R M, and Zebker H A: 'Interferometric radar measurements of ocean surface currents', *Nature*, 1987, **328** pp. 707-709
3. Goldstein R M, Barnett T P, and Zebker H A: 'Remote sensing of ocean currents', *Science*, 1989, **246** pp. 1282-1285
4. Thompson D R, and Jensen J R: 'Synthetic aperture radar interferometry applied to ship generated internal waves in the 1989 Loch Linnhe experiment', *J Geophys. Res.*, 1993, **98** (C6) pp. 10259-10269
5. Barber B C: 'The phase statistics of a multichannel radar interferometer', *Waves in Random Media*, 1993, **3** pp. 257-266
6. Friedlander B, and Porat B: 'VSAR: a high resolution radar system for ocean imaging', *IEEE trans aerospace and electronic systems*, 1998, **34** (3) pp. 755-776
7. Griffin M F, Bornan E.C, Metal I, and Orwig L P: 'Estimating ocean-scene coherence time with a multi-aperture SAR ocean-scene with a multi aperture SAR', *IEE International conference on Acoustics speech and signal processing*, 1993, pp. 461-464
8. Besson O, Gini F, Griffiths H D, and Lombardini F: 'Estimating ocean surface velocity and coherence time using multichannel ATI-SAR systems', *IEE Proc.-Radar, Sonar, Navig.*, 2000, **147** (6) pp. 299-308
9. Born M, and Wolf E: 'Principles of Optics' (CUP, 1999, 7th edn.)
10. Kell R E: 'On the derivation of bistatic RCS from monostatic measurements', *Proc. IEEE*, 1965, **53** pp. 983-988
11. Klemm R.: 'Space-Time Adaptive Processing' (IEE, 1998)

12. Ender J H G: 'Space-time adaptive processing for synthetic aperture radar'. Digest of the IEE Colloquium on Space-Time Adaptive Processing, IEE, April 1998, London, pp. 6/1-6/18
13. Lee P H Y, Barter J D, Beach K L, Hindman C L, Lake B M, Rungaldier H,
5 Shelton J C, Williams A B, Yee R, and Yuen H C: 'X-band microwave backscattering from ocean waves', *J. Geophys.Res.*, 1995, **100** (C2) pp. 2591-2611

Claims

1. A signal processor for use with a radar imaging arrangement which comprises a platform for movement along a first direction and a plurality of radar receivers mounted on the platform, and image means for providing a respective initial radar
5 image from the output of each said receiver, wherein the receivers are mounted so as to have at least a component of spacing in said first direction so that there are relative phase errors between the different initial radar image signals, the signal processing circuitry having inputs for said initial radar images, first signal combining means for combining pairs of said initial images to produce composite radar images which
10 include fringes arising from said relative phase errors, and means for developing in response to each said composite image a respective filter or filter function which if it is applied to one of the respective pair of initial images serves to remove or substantially reduce said relative phase errors relative to the other image of said pair.
2. A signal processor according to claim 1 wherein the other of said initial
15 images is a reference initial image common to all said pairs of images, and has no filter or filter function applied thereto, whereby the phase errors in all other said image signals can be corrected with reference to the reference image.
3. A signal processor according to claim 1 or claim 2 wherein said first combining means is arranged to combine said images in a manner similar to that of a
20 two beam optical interferometer.
4. A signal processor according to any preceding claim and including co-locating means for processing the initial images from individual said receivers prior to combination with other initial image signals so that the initial images appear as if derived from receivers located at a common location.
- 25 5. A signal processor according to any preceding claim and including first phase screen developing means for receiving or storing information regarding the geometry of the radar system, and optionally additional information, and for developing in response to said received information and for each said receiver pair a respective said first said filter or filter function providing a first two-dimensional filter error function

reflecting the differential changes in image signal phase arising from the spatial arrangement of the two receivers and their different ranges to similar imaged points.

6. A signal processor according to claim 5 and including means for receiving or deriving said optional additional information which includes at least one of platform
5 pitch, yaw and roll, or estimates thereof.

7. A signal processor according to claim 5 or claim 6 and including first correcting means for applying the respective first two-dimensional filter error function to the one initial image of each said pair to provide first corrected initial images.

8. A signal processor according to claim 7 and including second signal
10 combining means for combining the first corrected initial image and the other initial image of each said pair to provide first corrected composite images.

9. A signal processor according to claim 8 wherein said second signal combining means is arranged to combine the first corrected initial image and the other initial image of each said pair in a manner similar to that of a two beam optical
15 interferometer.

10. A signal processor according to claim 8 or 9 and comprising a second phase screen developing means for applying a smoothing function to each first corrected composite image to determine a respective second filter or filter function providing a second two-dimensional filter error function for correcting residual phase error in the
20 first corrected composite image.

11. A signal processor according to claim 10 and including phase correcting means for applying the respective said first and second two-dimensional filter error functions to the one of each said initial image signal pair to provide a corrected output image.

25 12. A signal processor according to any one of claims 1 to 4 and comprising a phase screen developing means for applying a smoothing function to each composite image to determine a respective filter or filter function providing a two-dimensional filter error function for correcting said phase errors in the one initial image.

13. A signal processor according to claim 12 and including phase correcting means for applying the respective said filter error function to the one of each said image signal pair to provide a corrected output image.
14. Radar imaging apparatus comprising a platform for movement along a first
5 direction and a plurality of radar receivers mounted on the platform, and image means for providing a respective radar initial image from the output of each said receiver, wherein the receivers are mounted so as to have at least a component of spacing in said first direction so that there are relative phase errors between the different initial images, and a signal processor according to any preceding claim for receiving said
10 initial images for reducing or removing said relative phase errors to provide corrected images.
15. Apparatus according to claim 14 wherein said image means is arranged for coherent radar imaging.
16. Apparatus according to claim 14 wherein said image means is arranged for
15 synthetic aperture radar imaging.
17. Apparatus according to claim 15 or claim 16 wherein said image means implements a Doppler filter for Doppler band-pass filtering of the corrected images.
18. Apparatus according to claim 17 wherein said Doppler filter is an adaptive filter.
- 20 19. Apparatus according to claim 18 wherein said adaptive filter is arranged for optimising image features which produce a radar response within said Doppler pass band.
20. Apparatus according claim 18 or claim 19 wherein the adaptive filter is responsive to predictable patterns in the radar image.
- 25 21. Apparatus according to claim 18 or claim 19 wherein the adaptive filter is responsive to the statistical properties of the radar image.

22. Radar imaging apparatus comprising an adaptive Doppler filter, and means for analysing the statistical properties of the radar image to derive at least one parameter for use in controlling the adaptive filter.
23. Apparatus according to any one of claims 18 to 22 wherein the adaptive filter
5 is arranged to control the Doppler bandpass position and/or shape.
24. A method of processing images from a radar imaging arrangement which comprises a platform for movement along a first direction and a plurality of radar receivers mounted on the platform, and image means for providing a respective radar initial image from the output of each said receiver, wherein the receivers are mounted
10 so as to have at least a component of spacing in said first direction so that there are relative phase errors between the different initial images, the method the steps of combining pairs of said initial images to produce composite images including fringes; and developing for each said composite image a respective filter or filter function for removing or substantially reducing said fringes when applied to one of the respective
15 pair of initial images before they are combined.
25. The method according to claim 24 wherein the image pairs are selected so that the other of said images is a reference image common to all said pairs.
26. The method according to claim 24 or claim 25 wherein said pairs of images are combined in a manner similar to that of a two beam optical interferometer.
- 20 27. The method according to any one of claims 24 to 26 wherein the initial images are initially processed before combination so that they appear as if the receivers were located at a common location.
28. The method according to any one of claims 24 to 27 wherein for each said receiver pair a respective first said filter or filter function is developed in response to
25 information regarding the geometry of the radar system, and optionally also in response to additional information, the said first filter or filter function providing a first two-dimensional filter error function reflecting the differential change in signal

phase between the two receivers arising from their spatial arrangement and their different ranges to similar imaged points.

29. The method according to claim 28 and wherein said optional additional information includes at least one of platform pitch, yaw and roll, or estimates thereof.

5 30. The method according to claim 28 or claim 29 wherein at least part of said additional information is derived from an inertial navigation system associated with the platform.

31. The method according to any one of claims 28 to 30 and including the step of applying the respective first two-dimensional filter error function to the one of the
10 images of each said pair to provide first corrected initial images.

32. The method according to claim 31 and including the step of combining the first corrected initial image and the other initial image of each said pair to provide first corrected composite images.

33. The method according to claim 32 wherein the first corrected initial image and
15 the other initial image of each said pair are combined in a manner similar to that of a two beam optical interferometer.

34. The method according to claim 32 or 33 and comprising the further step of applying a smoothing function to each first corrected composite image to determine a respective second filter or filter function providing a second two-dimensional filter
20 error function for correcting residual phase error in the first corrected composite image.

35. The method according to claim 34 and including the step of applying the respective said first and second two-dimensional filter error functions to the one initial image of each said receiver pair to provide a corrected output image.

25 36. The method according to any one of claims 24 to 33 and including the step of applying a smoothing function to each said composite image for determining a respective filter or filter function providing a two-dimensional filter error function.

37. The method according to claim 36 and including the step of applying the two-dimensional filter error function to the one initial image of each said receiver pair to provide a corrected output image.

38. A method of radar imaging comprising providing a platform moving along a first direction and a plurality of radar receivers mounted on the platform, and producing respective radar initial images from the outputs of each of said receivers, wherein the receivers are mounted so as to have at least a component of spacing in said first direction so that there are relative phase errors between the different initial images, and performing the method of processing signals according to any one of claims 23 to 36 on the initial images for reducing or removing said phase errors.

39. The method according to claim 38 wherein the initial images are produced by a coherent radar imaging technique.

40. The method according to claim 38 wherein the initial images are produced by a synthetic aperture radar imaging technique.

41. The method according to claim 39 or claim 40 wherein an image developing step implements a Doppler filter for Doppler band-pass filtering of the corrected outputs.

42. The method according to claim 41 wherein said filtering is an adaptive filtering.

43. The method according to claim 42 wherein the image is analysed for a predictable pattern for use in controlling the adaptive filtering.

44. The method according to claim 42 wherein the statistical properties of the image are analysed to derive at least one parameter for controlling the adaptive filtering.

45. A radar imaging method wherein an adaptive Doppler filter is used in producing the radar image, the method including analysing the statistical properties of

the radar image to derive at least one parameter for use in controlling the adaptive filter.

46. The method according to any one of claims 42 to 45 wherein said adaptive filtering comprises adjusting the Doppler band-pass position and/or shape.

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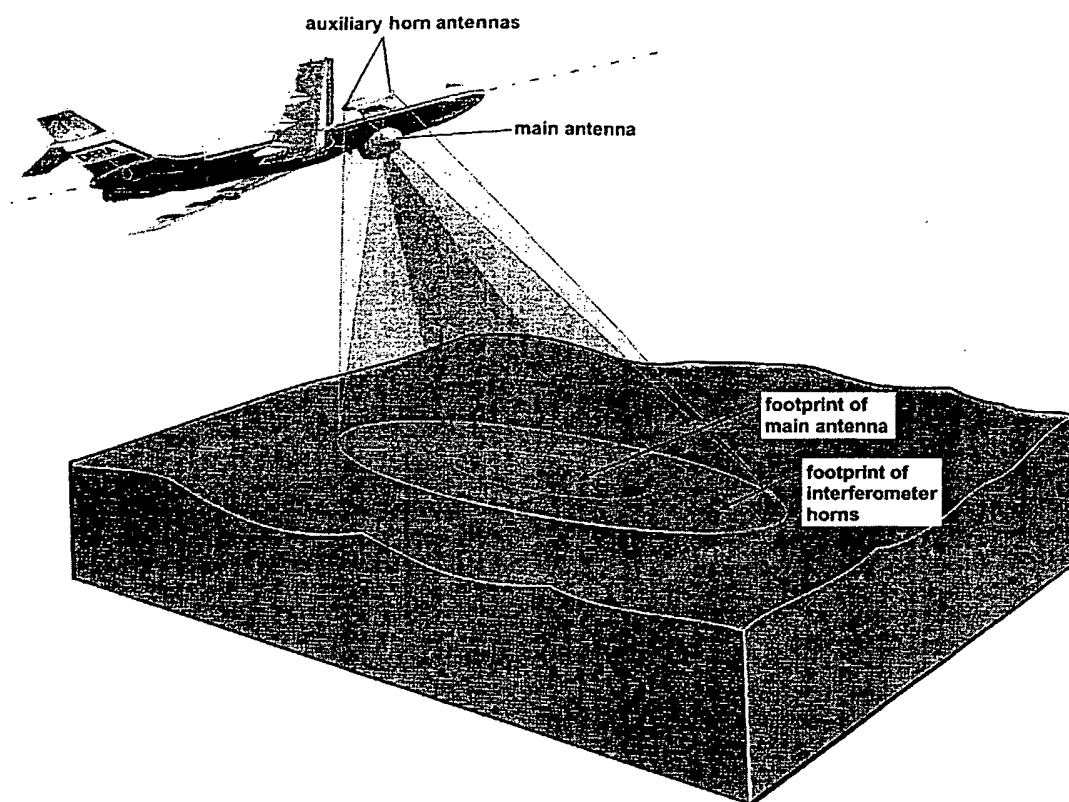


FIG. 1

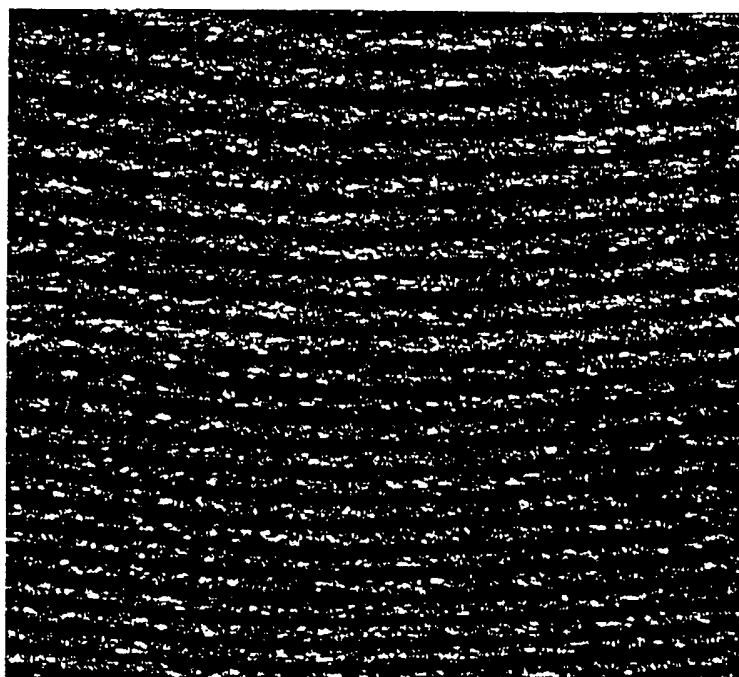
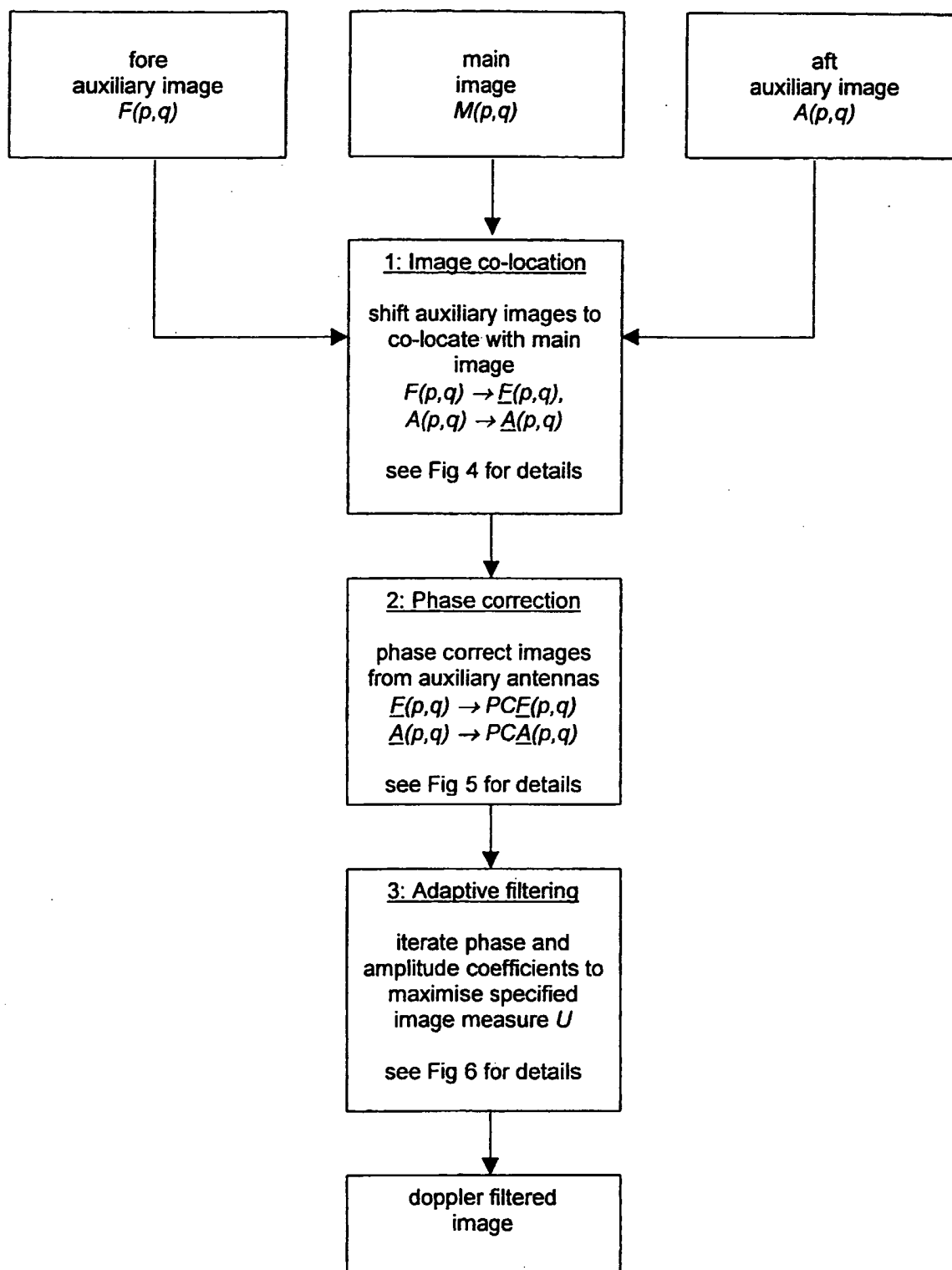
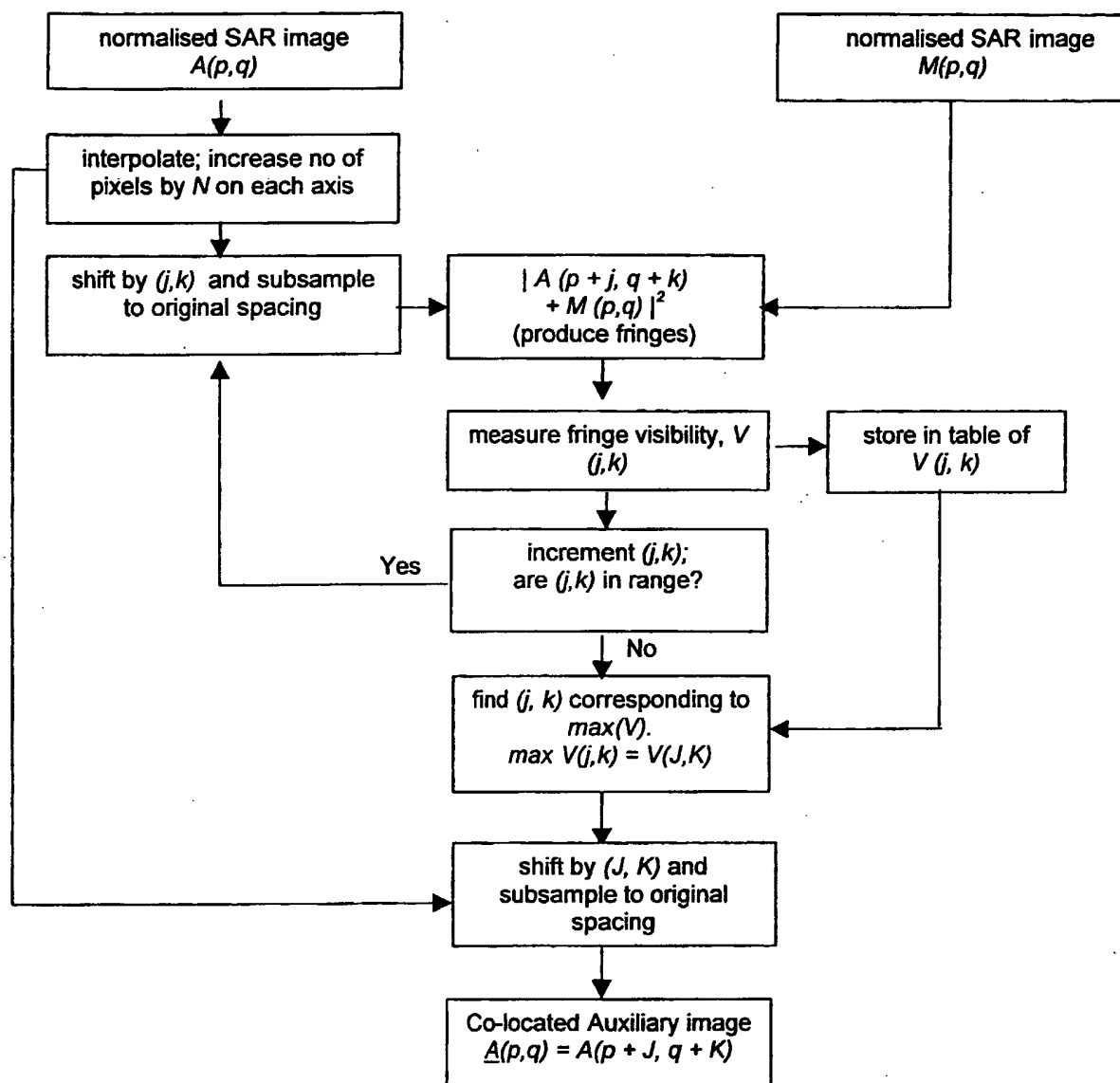


FIG. 2

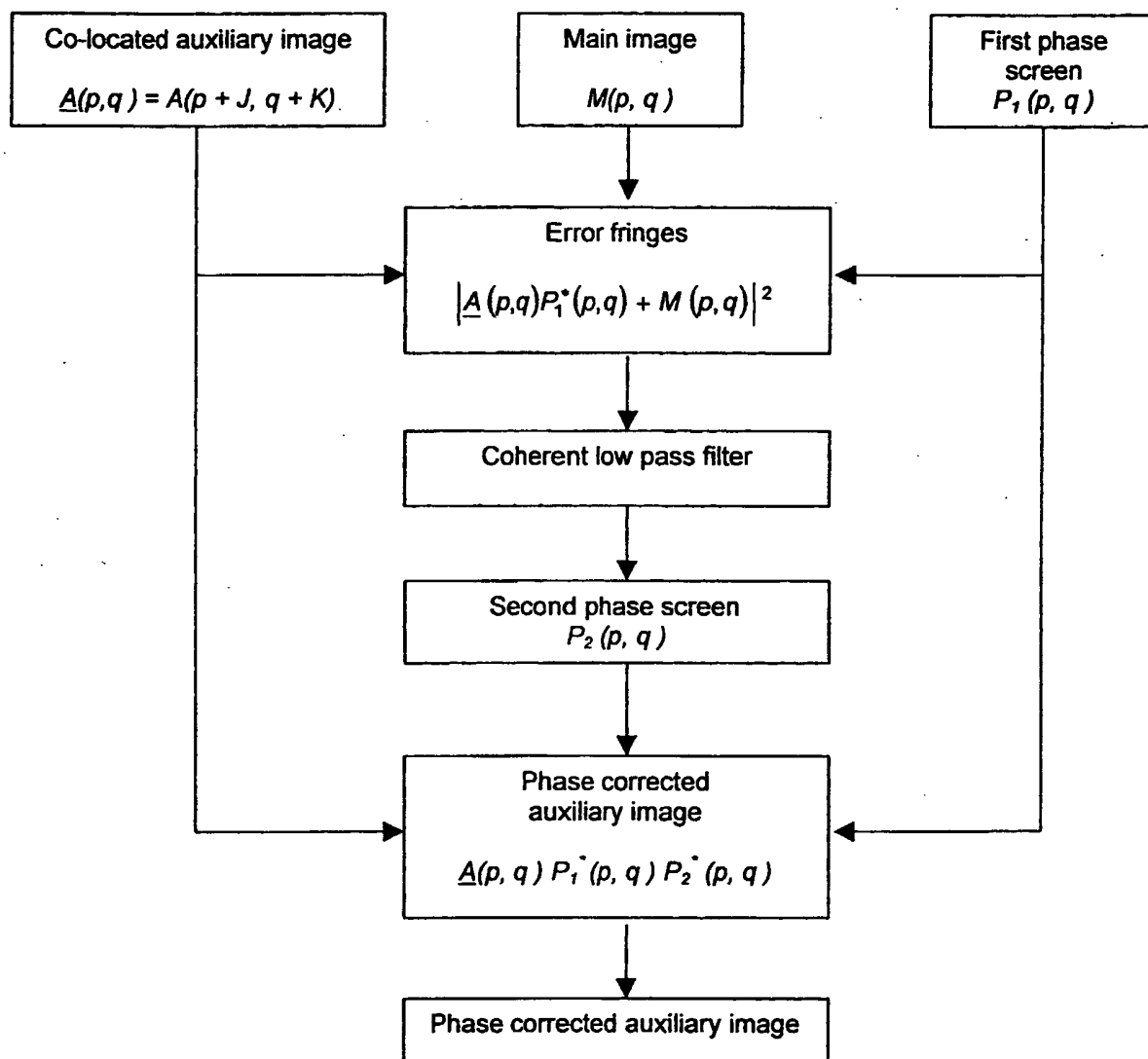
-2/11-

**FIG. 3**

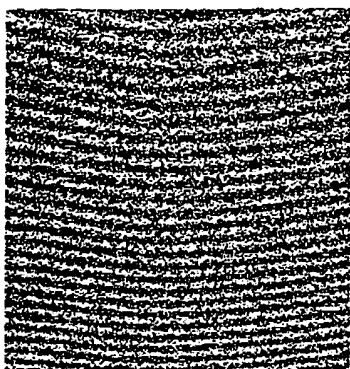
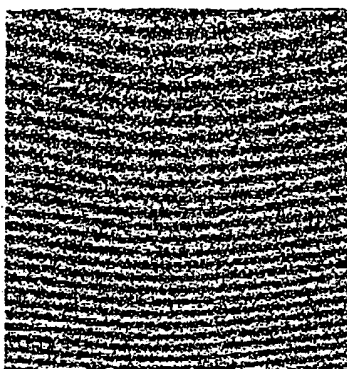
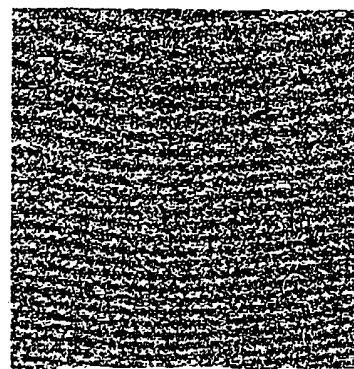
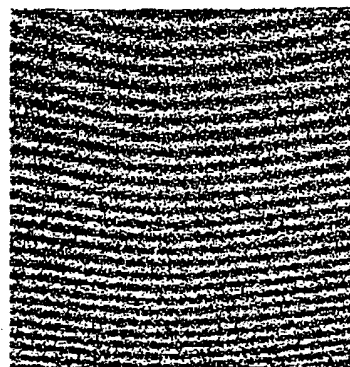
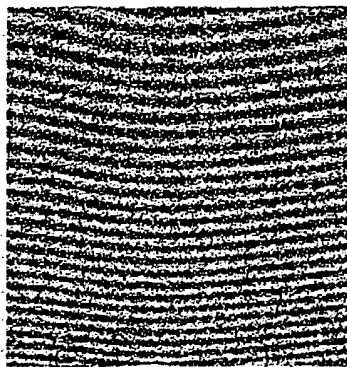
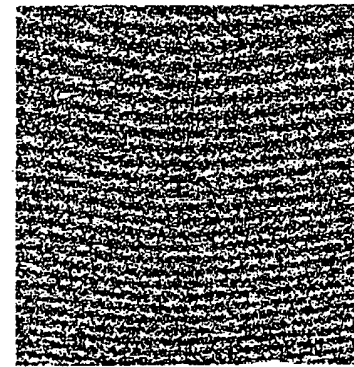
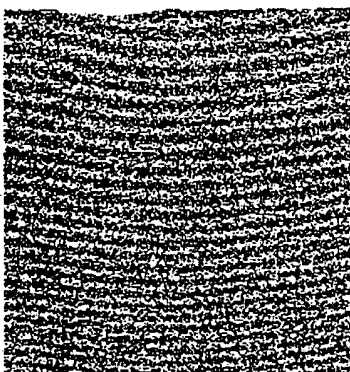
-3/11-

FIG. 4

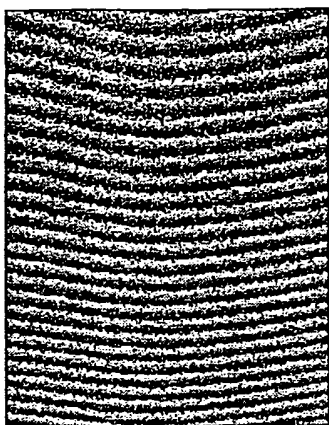
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FIG. 5

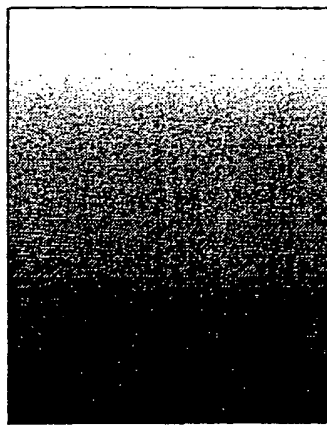
-5/11-

 $(x,y) = (-1,-1)$, Max = 1.76 $(x,y) = (0,-1)$, Max = 1.94 $(x,y) = (1,-1)$, Max = 0.78 $(x,y) = (-1,-2)$, Max = 2.76 $(x,y) = (0,-2)$, Max = 3.06 $(x,y) = (1,-2)$, Max = 1.17 $(x,y) = (-1,-3)$, Max = 1.26 $(x,y) = (0,-3)$, Max = 1.41 $(x,y) = (1,-3)$, Max = 0.58FIG. 6

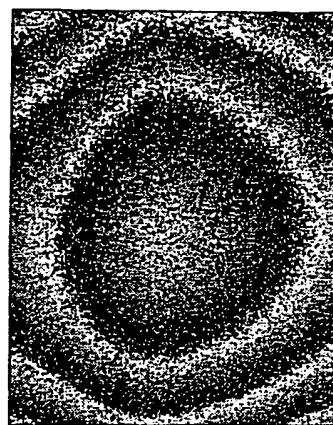
-6/11-



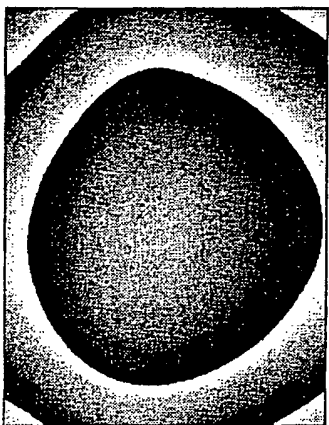
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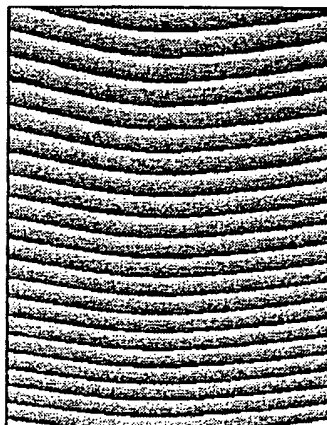
(b)



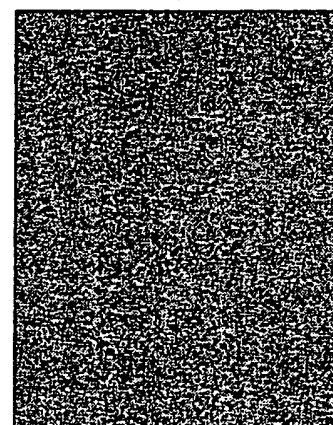
(c)



(d)



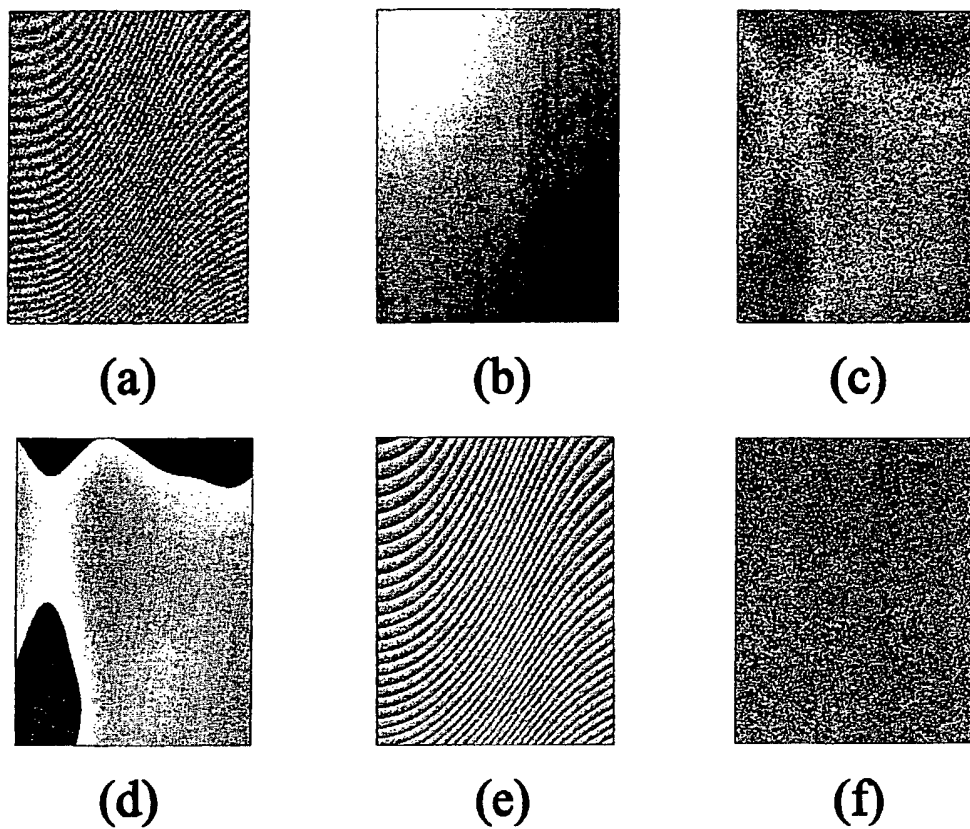
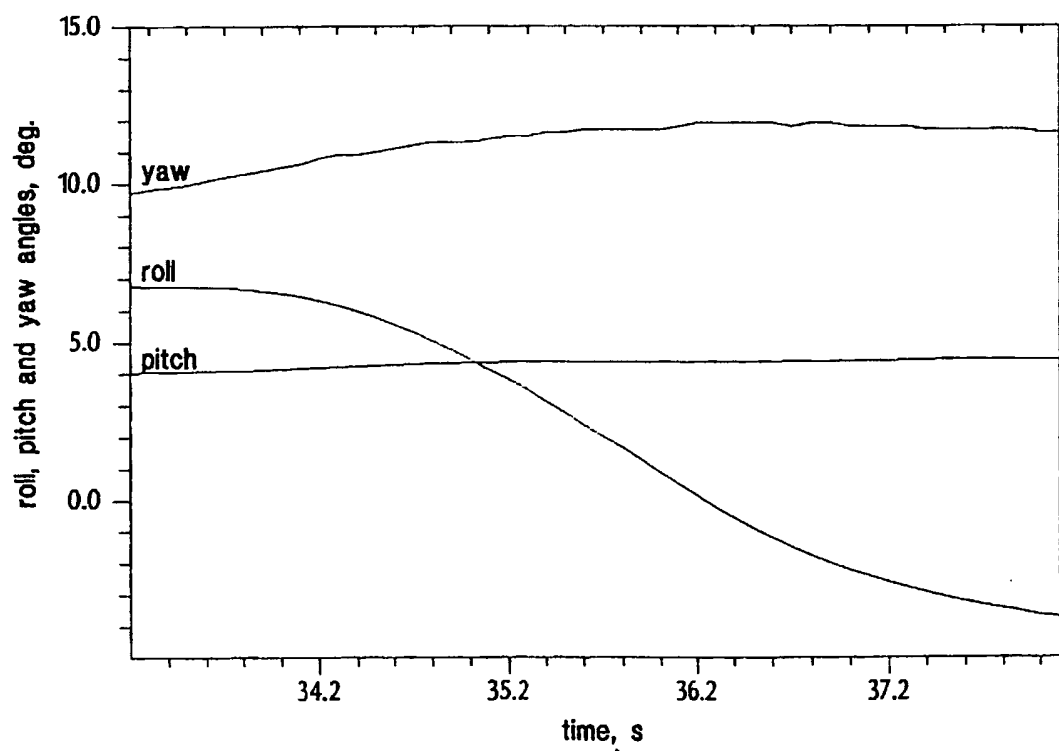
(e)



(f)

FIG. 7

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FIG. 8FIG. 9

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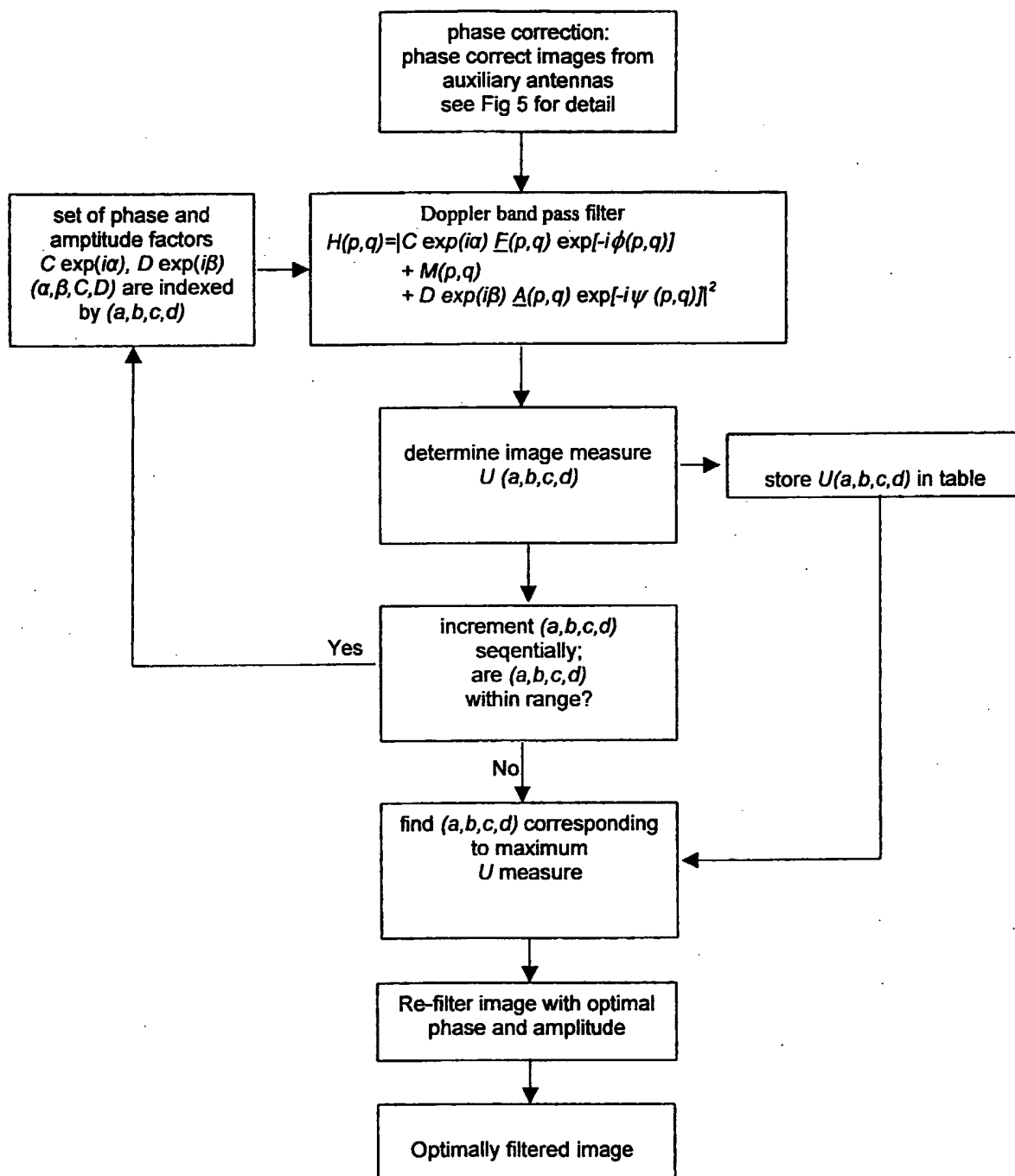


FIG. 10

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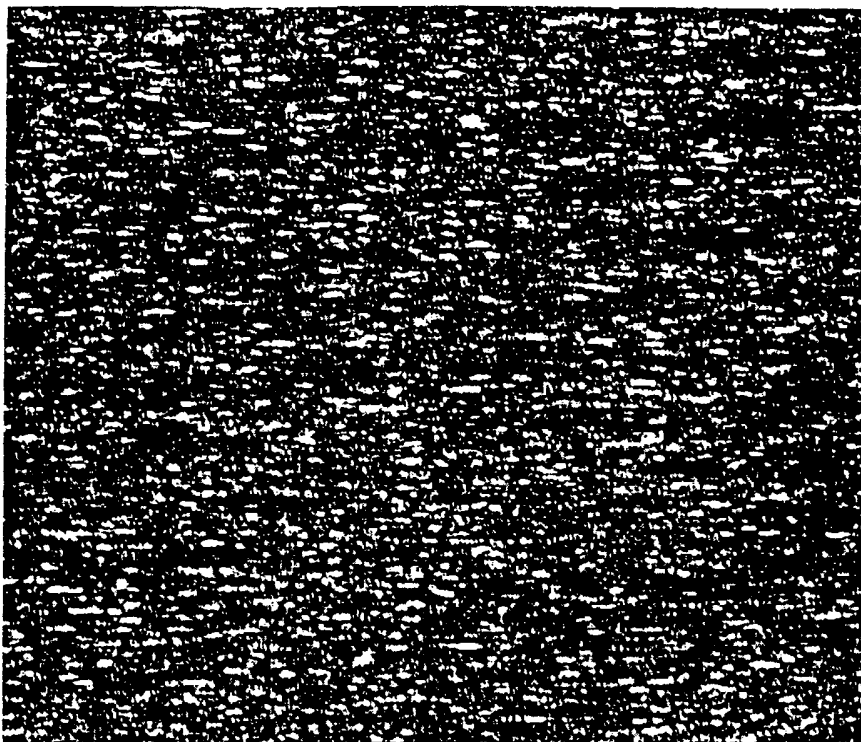


FIG. 11

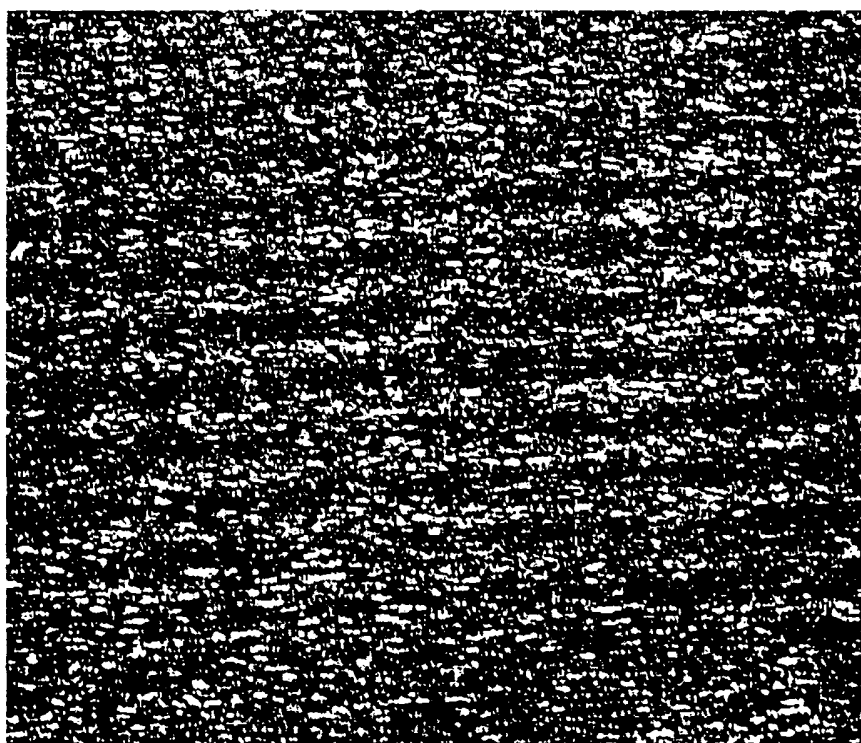
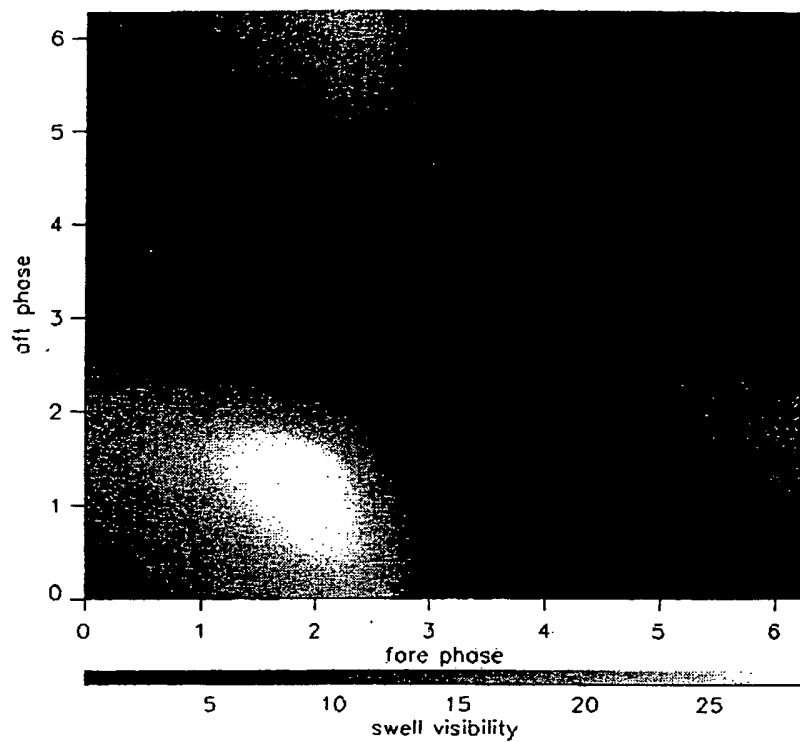
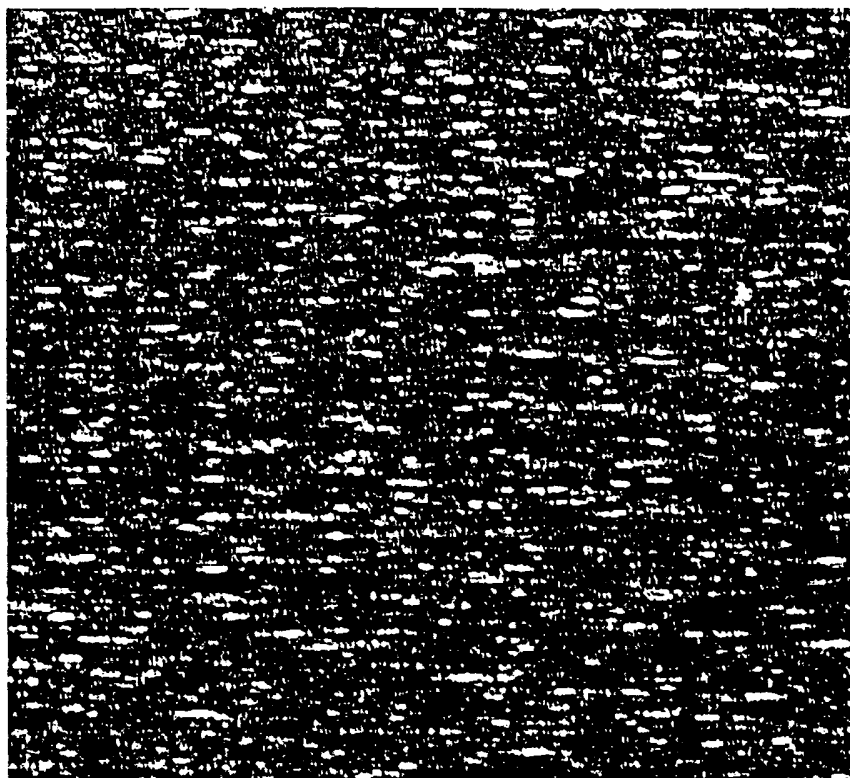
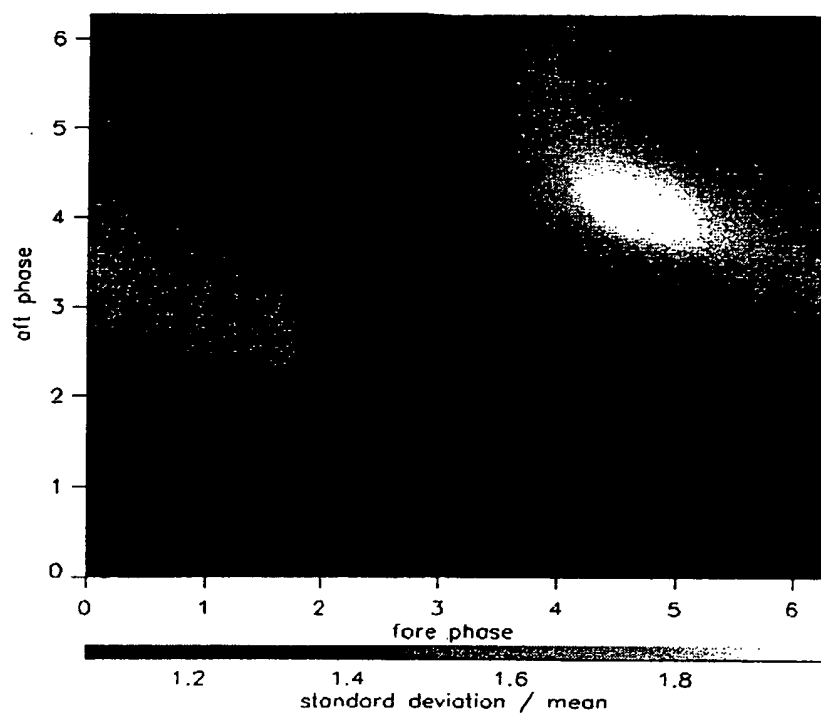
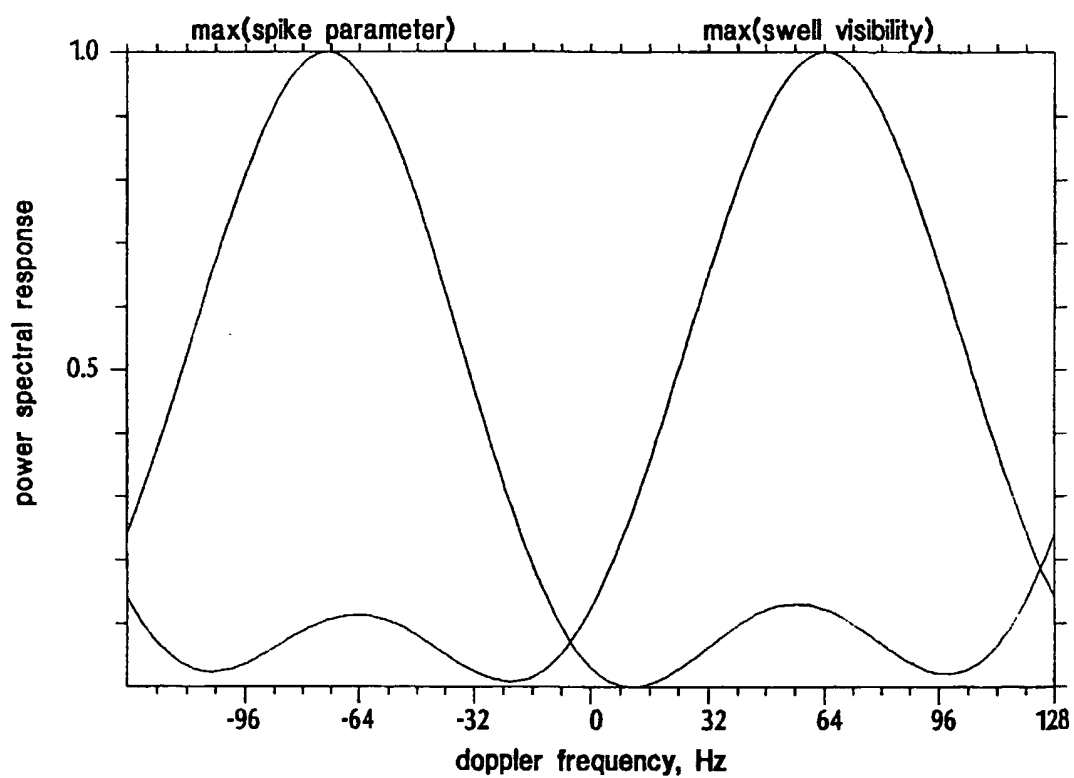


FIG. 12

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FIG. 13FIG. 14

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FIG. 15FIG. 16

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 03/03698

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01S13/90

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	FRIEDLANDER B ET ALL: "VSAR: A high resolution radar system for ocean imaging" IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONICS, vol. 34, no. 3, July 1998 (1998-07), pages 755-776, XP002260954 cited in the application abstract paragraph '000I! - paragraph '00II! --- -/--	1-4, 14-17, 22-27, 38-41, 45,46

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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Date of the actual completion of the international search

11 November 2003

Date of mailing of the international search report

09/01/2004

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

van Norel, J

INTERNATIONAL SEARCH REPORT

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PCT/GB 03/03698

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 6 181 270 B1 (DWYER J CRAIG) 30 January 2001 (2001-01-30)	1-4, 14-17, 22-27, 38-41, 45, 46
A	claim 1	5-13, 28-37
A	figures 1A, 1B column 1, line 1 -column 5, line 8 abstract	18-21, 42-44
A	----- CURLANDER J C: "Interferometric synthetic aperture radar for terrain mapping" ACOUSTICS, SPEECH, AND SIGNAL PROCESSING, 1995. ICASSP-95., 1995 INTERNATIONAL CONFERENCE ON DETROIT, MI, USA 9-12 MAY 1995, NEW YORK, NY, USA, IEEE, US, 9 May 1995 (1995-05-09), pages 2801-2804, XP010151926 ISBN: 0-7803-2431-5 the whole document	1-3, 14-16, 24-26, 38-40
A	----- GRIFFITHS H: "INTERFEROMETRIC SYNTHETIC APERTURE RADAR" ELECTRONICS AND COMMUNICATION ENGINEERING JOURNAL, INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, GB, vol. 7, no. 6, 1 December 1995 (1995-12-01), pages 247-256, XP000545120 ISSN: 0954-0695 the whole document	1, 4-6, 14-16, 24, 27-30, 38-40
A	----- US 5 923 279 A (DAVIDSON GORDON ET AL) 13 July 1999 (1999-07-13) figures 3A, 3B column 1, line 1 -column 5, line 44	1, 14-24, 38-46
A	----- BARBER B.C.: "The phase statistics of a multichannel radar inteferometer" WAVES IN RANDOM MEDIA, vol. 3, no. 4, October 1993 (1993-10), pages 257-266, XP002260955 UK cited in the application paragraph '0001!	1, 14-24, 38-46
	----- -/--	

INTERNATIONAL SEARCH REPORT

International Publication No
PCT/GB 03/03698

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ENDER J H G: "SPACE-TIME PROCESSING FOR MULTICHANNEL SYNTHETIC APERTURE RADAR" ELECTRONICS AND COMMUNICATION ENGINEERING JOURNAL, INSTITUTION OF ELECTRICAL ENGINEERS, LONDON, GB, vol. 11, no. 1, February 1999 (1999-02), pages 29-38, XP000893874 ISSN: 0954-0695 cited in the application paragraphs '0001!, '0004!, '0006! -----	1,14-24, 38-46
A	BAOSEN ZHOU ET AL: "Effect of azimuth bandwidth spreading on SAR imaging and SAR interferometry over the ocean" GEOSCIENCE AND REMOTE SENSING, 1997. IGARSS '97. REMOTE SENSING - A SCIENTIFIC VISION FOR SUSTAINABLE DEVELOPMENT., 1997 IEEE INTERNATIONAL SINGAPORE 3-8 AUG. 1997, NEW YORK, NY, USA, IEEE, US, 3 August 1997 (1997-08-03), pages 1524-1526, XP010234496 ISBN: 0-7803-3836-7 page 1524 -----	1,14, 17-24, 38,41-46

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 03/03698

Patent document cited in search report		Publication date		Patent family member(s)	Publication date
US 6181270	B1	30-01-2001	WO AU	0052492 A2 5865100 A	08-09-2000 21-09-2000
US 5923279	A	13-07-1999	DE CA	19706158 C1 2229767 A1	20-05-1998 17-08-1998