



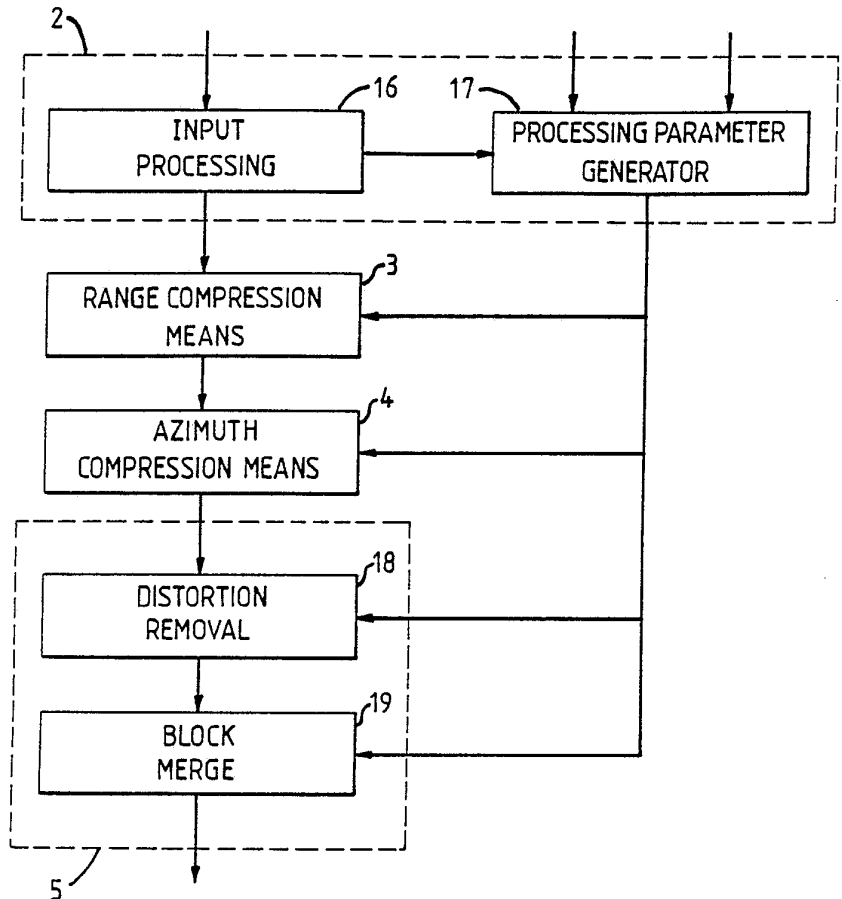
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(54) Title: PROCESSING PARAMETER GENERATOR FOR SYNTHETIC APERTURE RADAR

(57) Abstract

A signal processor for synthetic aperture radar comprises a processing parameter generator (17) for generating processor filter parameters for use in squint compensation multiplication means (3) and azimuth replica evaluation (4). The parameter generator produces and stores tables of data to be used in the subsequent processing.



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Processing parameter generator for synthetic aperture radar.

The present invention relates to a synthetic aperture processing system for processing data required from Spaceborne or Airborne sensors.

5 It has been known for many years that images of the earth's surface may be produced using microwave radiation by the technique known as Sideways-Looking Airborne Radar (SLAR). More recently radars carried in space satellites rather than in aircraft have used. However, the basic technique is the same.

10 SLAR in its simplest form is described by Jensen et al, Side-looking airborne radar, "Scientific American", (1977) and by Lillesand and Keifer, "Remote Sensing and Image Interpretation", Wiley, New York, 1979. A vehicle carrying a radar transmitter, e.g. an aircraft, is flown over the surface to be studied. Microwave radiation is emitted from the vehicle and the radiation  
15 reflected from the underlying surface is received by the vehicle. Two directions may be defined in relation to the vehicle. The azimuth direction is the direction in which the vehicle is moving. The range direction is the direction at right angles to the direction of movement of the vehicle.

20 The above mentioned publications describe the operation of SLAR in terms of the emission of pulses of microwave radiation and indicate that the resolution (ie the ability to separate two adjacent features on the ground) in the range direction is dependent on the length of the pulse. Commonly a relatively long duration  
25 frequency swept pulse is transmitted, in conjunction with a

pulse correlation system to achieve an approximately equivalent effect to a short pulse. In the azimuth direction the resolution is dependent on the width of the beam emitted from the vehicle.

5 It is well known to increase the resolution to the azimuth direction by the technique of synthetic aperture radar. Originally this was done using optical techniques. However it is now possible to replace optical techniques by digital signal processing.

10 In synthetic aperture radar a vehicle, e.g. an aeroplane or a satellite, carrying a radar aerial or antenna is moved over a surface to be mapped. The radar beam illuminates the surface to be investigated and the movement of the vehicle results in an illuminated or irradiated swath being traced out. As the vehicle moves along its track it emits a succession of radar pulses, typically frequency swept, and receives back radar echoes from  
15 each pulse. If the echoes over a given period along track are recorded (sampled) at given time intervals they can be processed to give increased resolution in the azimuth direction. Instead of using a large physical antenna a synthetic aperture is produced. The amplitude of the radar echo at each sampling period is  
20 recorded. The echoes which are received after each pulse is emitted result from reflections from objects at successively greater distances from the vehicle. The individual sampled amplitudes can be considered as forming a matrix in which the rows in each column represent information about the illuminated surface in the azimuth  
25 direction and the columns represent information about the surface in the range direction. However as initially recorded information about any given object is distributed over the cells of the matrix and it is necessary to compress the data in range and in azimuth to concentrate the data about a given object in a picture cell (pixel)  
30 which will be used to represent it in the final image produced.

Synthetic aperture radar using digital signal processing techniques is disclosed in various references. Thus GB 1 540 950 discloses a synthetic aperture using an FFT signal processor. The specification explains that synthetic aperture radar may be used in  
35 either squinted or in side-looking mode and discusses the problems

of maintaining the data from the radar in range and azimuth focus. GB 1 540 950 proposes to overcome the problem by using a motion compensation computer responsive to the velocity of the vehicle and pulse repetition frequency to maintain the data in range focus, and  
5 to vary the pulse rate frequency of the radar to maintain the data in azimuth focus.

EP 83710 discloses a synthetic aperture radar using digital signal processing and discusses the necessity to focus the data in both the range and azimuth directions. The necessity of carrying  
10 out range curvature processing is mentioned. This is done to compensate for changes in the distances between the vehicle and a given point from which a signal is reflected.

A considerable number of other approaches to synthetic aperture processing have been described in the literature, of varying  
15 applicability, quality and speed of operation. High quality processing has however been restricted to two classes of processor; explicit time domain correlation and range-Doppler frequency domain processing. The primary disadvantage of the time domain correlation approach is that it is computationally demanding although in  
20 principle it is as flexible, and provides images of as high a quality, as desired. Frequency domain approaches are of interest because of their computational efficiency, with the best quality achieved prior to this invention by the range-Doppler approach. The basic range-Doppler approach to processing involves the following  
25 steps.

- 1) Pulse compression, which is performed by correlating pulse echoes intra pulse with a replica of the transmitted signal and achieved either by explicit correlation or frequency domain techniques as appropriate.
- 30 2) Formation of a sequence of overlapping processing blocks of compressed pulse data, with the size of the block and overlap determined by the maximum effective illumination time of a point on the ground by the antenna together with processing considerations.
- 3) Interpulse Fast Fourier Transform (FFT) of each processing  
35 block at constant range sample, to generate a PRF (Pulse Repetition

Frequency) ambiguous, range-Doppler representation of the data.

- 4) Formation of a modified range-Doppler processing block by the selection of a new set of rows of data from along curves in the range-Doppler processing block ("Range migration correction"); the  
5 locus for data collation corresponding to the range-frequency history of points illuminated by the radar.
- 5) The multiplication of rows of data in the modified range-Doppler block by an amplitude weighted phase function derived primarily from the reciprocal of the rate of change of Doppler  
10 frequency with time, and an inverse FFT of each row.
- 6) The collation of an image from successive blocks of output data.

Operations 2) through 5) are conventionally referred to as the "azimuth compression" operations.

- 15 In the general case of a squinted satellite sensor difficulties with this approach arise as a result of the non-stationarity of the processing functions with both range, and position in time, within a processing block, together with the more general problems of correctly specifying the range-Doppler migration locus and conjugate  
20 phase function.

- Processing of data by this technique from specific sensors within well defined constraints, has been reasonably successful, although implementations are noted for requiring a degree of ad hoc tuning in any given implementation and suffering quality degradation  
25 (in comparison with a time domain processor) to various degrees. Further than this, some combinations of radar system parameters may not allow, prior to this invention, full resolution processing to any reasonable quality by this approach.

- It would be advantageous to have a systematic and unified  
30 approach to range-Doppler processing which was extendable in principle to provide high quality processing for any balance of radar system parameters. It would also be advantageous to be able to engineer the processor to provide image quality as near to ideal as required.

- 35 According to the present invention there is provided a signal

processor for synthetic aperture radar comprising

(a) processing parameter generator for computation of processor filter parameters from the known vehicle motion and antenna geometry,

5 (b) range compression means comprising

(i) pulse FFT means for performing an FFT on pulse echoes

(ii) pulse replica multiplication means to effect pulse correlation

10 (iii) squint compensation multiplication means to effect second order migration corrections

(iv) inverse FFT means for performing an inverse FFT on the multiplied and compensated spectral data;

(c) azimuth compression means comprising

15 (i) row FFT means for performing an FFT on rows of data selected at constant range from overlapping blocks of range compressed data

(ii) azimuth replica evaluator means, comprising range and phase polynomial evaluators and a complex exponentiator

20 (iii) azimuth spectral buffer means, comprising a bank of storage to contain an adequately large number of row transforms.

(iv) data selection means comprising an interpolator to effect selection of data along curves in the spectral buffer according to values computed by the range polynomial evaluator.

25 (v) azimuth replica multiplication means to effect multiplication of the selected data with the complex data generated by the phase polynomial evaluators

(vi) inverse FFT means to effect the inverse transform of rows of the processed data;

30 (d) Image formation means comprising image resampling and buffering means to effect image block geometric and phase discontinuity removal and image collation.

The signal processor design of the present invention is capable of processing synthetic aperture data to a high quality. Quality  
35 may be enhanced by incorporating further features in the processor

depending upon the characteristics of the vehicle and antenna system providing the data. Thus in the azimuth compression means it may be desirable to provide additional precision curvature and migration compensation means comprising a short complex correlator with a non-stationary correcting filter selected according to values computed by the parameter generator, operated in the range dimension.

Such additional precision curvature migration compensation means would probably be unnecessary for data from a 5 GHz satellite with a 0.5 second integration time and modest antenna squint but may be desirable for a satellite operating in a frequency of 1.25 GHz with a 2 second integration time and small antenna squint.

The processor design is based on a novel appreciation of the processing problem, which is

- (i) to consider the two dimensional transform of the system transfer function;
- (ii) to factorise this two dimensional transform in such a way that non stationarities of the system transfer function may be accommodated, and
- (iii) to compute the elements of the factorisation of the system transfer function in terms of the co-efficients of the range polynomial, which is determined at all points in the image by the known relative motion.

The two dimensional transform of the system transfer function for a point with range and range time derivatives  $R_c$ ,  $\dot{R}_c$ ,  $\ddot{R}_c$  etc at some time  $T_c$  relative to time of closest point of approach with a corresponding instantaneous Doppler frequency  $F_c(f) = -\frac{2f}{c} \dot{R}_c$  is approximated as the following two dimensional phase screen as a function of video frequency  $f$  and Doppler frequency  $F$ :



$$\begin{aligned}
 & \exp 2\pi i \left[ \frac{(-2fR_c - F_c(f)T_c) - T_c(F - F_c(f))}{c} \right. \\
 & + \frac{c}{2f} \frac{1}{R_c} \frac{(F - F_c(f))^2}{2!} + \frac{c}{2f} \frac{2}{R_c^3} \frac{(F - F_c(f))^3}{3!} \\
 & \left. + \frac{c}{2f} \frac{3}{R_c^5} \frac{(3R_c^2 - R_c R_c)}{4!} \frac{(F - F_c(f))^4}{4!} + \dots \right] \\
 & = \exp 2\pi i \theta(f, F)
 \end{aligned}$$

Factorisation is achieved by expanding  $\theta(f, F)$  as a Taylor series about  $f_0$ , the centre video frequency; thus

$$\theta(f, F) = \theta(f_0, F) + \frac{\partial \theta}{\partial f}(f_0, F)(f - f_0) + g(f, F)$$

The function  $g(f, F)$ , representing the residual terms may be considered by its expansion about a central Doppler frequency  $\hat{F}_c$  and  $f_0$ ;

$$g(f, F) = \frac{\partial^2 \theta}{\partial f^2}(f_0, \hat{F}_c) \frac{(f - f_0)^2}{2!} + \dots$$

$$\frac{\partial^2}{\partial f^2} \theta(f_0, \hat{F}_c) = \frac{2}{cf_0} \frac{R_c^2}{R_c}$$

primary migration correction for the squint multiplication means b(iii).

$$-\frac{c}{2} \frac{\partial \theta}{\partial f}(f_0, F)$$

provides range -Doppler selection curves which can be used by the data selection means in the azimuth compression means, and  $\theta(f_0, F)$  provides the azimuth phase replica used by the azimuth replica multiplication means.

Comparison of these parameters computed at the edges of the processing block with those applied during azimuth compression provides the resampling and phase adjustment parameters used by the image formation means.

The residual non stationary correlations used by the additional precision curvature and migration compensation means (if present) and by the image formation means are determined by the function  $\epsilon$  and are applied in range, in range -Doppler space and in along track, in image space respectively. The residual compensation required is very substantially reduced by the use of the preliminary compensation during range compression, such that further corrections may be applied by correlation with short pretabulated filter functions, determined by the difference between the two dimensional frequency domain transfer function applied and that which should have been applied on the basis of the local range polynomial coefficients.

The invention is illustrated by reference to Figure 1 which shows a version of the processor appropriate to a satellite mounted radar at 800 km altitude, 5 GHz operating frequency and squint less than 30 KHz. The version illustrated omits the additional precision curvature and migration compensation means. The range replica multiplication means and squint compensation multiplication means are combined by pre-multiplication of the range frequency domain replica with the primary migration correction. The invention may be implemented either as a software product on some appropriate general purpose architecture, or may be constructed in hardware as a special purpose fast processor.

A particularly preferred form of parameter generator comprises a signal processor according to claim 1 wherein the parameter generator comprises

- (1) means for computing the latitude and longitude of points approximately in the beam centre at the near far and centre swath positions on the earth's surface at times corresponding approximately to the start, centre and end pulses of the processing block;
- (2) means for computing the time offset of each of these points from the closest point of approach and the minimum range at the closest point of approach;

- (3) means for evaluating the range, Doppler frequency and successive derivatives of the range with respect to time at the given time;
- (4) means for quadratically fitting the calculated parameters as a function of minimum range;
- (5) means for generating parameters for each output range pixel comprising means for:-  
determining the range polynomial coefficients by quadratic expansion using the required minimum range values.
- (6) means for computing block geometric and phase correction factors;
- (7) means for computing block collation parameters.

The invention will now be further described with reference to the drawings where

- Figure 1 is a diagrammatic representation of the main elements of the processor,
- Figure 2 is a more detailed diagrammatic representation of a range compression means of the processor, and
- Figure 3 is a more detailed diagrammatic representation of the azimuth compression means, and
- Figure 4 is a detailed diagrammatic representation of a specific processor according to the invention.

The processor may be described as operating fundamentally according to a range-Doppler processing principles, but incorporating many novel features and principles.

Figure 1 shows the basic structure of the processor namely a preprocessor which receives data produced by for example a satellite, and includes a processing parameter generator which generates and stores a table of parameters for use by the successive parts of the processor. Data from the preprocessor is fed in turn to a range compression means 3, an azimuth compression means and an image formation means 5 which generates the final radar image. Figure 2 shows the range compression means 3 in more detail. It comprises a pulse FFT means 6, a pulse multiplication means 7, a squint compensation multiplication means 8 and an inverse FFT

means 9. Figure 3 shows the azimuth compression means in more detail. This comprises a row FFT means 10, an azimuth replica evaluator means 11, an azimuth spectral buffer means 12, a data selection means 13, an azimuth replica multiplication means 14 and an inverse FFT means 15.

Figure 4 shows the preprocessor and image formation means in more detail. The preprocessor 2 comprises an input processing means 16 which carries out conventional preprocessing of the radar pulses e.g. recorded from a satellite before feeding them to the range compression means. Processing parameter generator receives information about the orbit of the satellite producing the radar pulses together with additional information fed in by the operator of the processor, and information from the input processing of the radar pulses. The processing parameter generator generates and stores the parameters required by the range compression, azimuth compression and image formation means. The image formation means comprises distortion removal means 18 and block merge means 19.

A key element of the design is the processing parameter generator which generates data tables to allow signal processing to operate as a sequence of one dimensional vector operations. Accordingly the operation of the parameter generator and the contents of the data tables that it generates are described first, with the operation of the processor as a whole described with reference to these tables.

#### Parameter Generator

The primary inputs to the parameter generator are information concerning the relative motion of the platform to the surface to be imaged and the pointing angle and orientation of the antenna. Such data may be typically provided as sampled values of platform vector position and vector time derivatives, sampled values of platform pitch roll and yaw and system parameters describing the orientation of the boresight and boresight plane to the platform co-ordinate system.

Further inputs to the generator comprise information concerning the data start time and data sampling offsets, the radar parameters,

the size of image to be generated, the dimensions of processing block sizes to be used and the maximum duration of illumination of any point on the ground to be imaged.

The generator performs the following functions:

- 5 (i) It fits a spline to the sampled relative motion and pointing angles of the platform and its antenna, such that the vector position, vector velocity, vector acceleration and orientation of the platform may be evaluated at any required point in time; spline fitting procedures are well known to those skilled in the art;
- 10 (ii) It evaluates a centre time for each processing block according to  $T_n = T_{n-1} + (N_{AZFFT} - N_{AZREP})/PRF$ , where  $N_{AZFFT}$  is the defined processing block size in pulses,  $PRF$  is the system pulse repetition frequency, and  $N_{AZREP}$  is the maximum illumination time multiplied by the  $PRF$ ;  $T_1$  is provided by the time of the first pulse plus
- 15  $N_{AZFFT} * PRF / 2$ ; and evaluates a start and end pulse index for each processing block according to  $PRF * T_n \pm N_{AZFFT} / 2$ .
- (iii) It computes, for each processing block, at times  $T_n$  and  $T_n \pm (N_{AZFFT} - N_{AZREP}) / 2PRF$ , coordinates of points on the surface to
- 20 be imaged in the beam centre at the near side, far side and centre of the illuminated swath. The computation of the coordinates of such points is a routine problem in trigonometry and vector analysis and familiar to those skilled in the art.
- (iv) It computes, for each such point at such times, the range from the platform to the point,  $\Delta R$ , and its successive time derivatives
- 25 according to:

$$\Delta R = |\underline{\Delta R}|$$

$$\dot{\Delta R} = \frac{(\underline{\Delta R} \cdot \dot{\underline{R}})}{\Delta R}$$

30  $\Delta R$

$$\ddot{\Delta R} = (\dot{\underline{R}} \cdot \dot{\underline{R}} + \underline{\Delta R} \cdot \ddot{\underline{R}} - \dot{\Delta R}^2) / \Delta R$$

$$\ddot{\Delta R} = (\underline{\Delta R} \cdot \ddot{\underline{R}} + 3(\dot{\underline{R}} \cdot \dot{\underline{R}} - \dot{\Delta R} \dot{\Delta R})) / \Delta R,$$

35 where  $\underline{R}$ ,  $\dot{\underline{R}}$  etc are the platform relative vector time derivatives;

computes, for each such point at such times, the time offset of the point to its time of closest approach to the satellite,  $\Delta T$ , and the corresponding slant range at closest approach,  $\Delta R_{cpa}$ , by numerical minimisation of  $(\Delta R(T) \cdot \dot{R}(T))$  according to procedures familiar to those skilled in such art; computes an approximate fourth time derivative of the scalar range according to:

$$\Delta \ddot{\ddot{R}} = -6.0(\Delta \dot{R} + \Delta \ddot{R} \Delta T + \Delta \ddot{\ddot{R}} \Delta T^2 / 2.0) / \Delta T^3$$

so that the extrapolated truncated slant range polynomial satisfies  $\Delta \dot{R}(T) = 0$  at time of closest approach; computes a centre Doppler frequency for each such point at such times according to

$$F_c = \frac{-2f_0 \Delta \dot{R}}{c}$$

(v) It evaluates for each processing block, at each such times, the coefficients of a quadratic fit of each of  $\Delta R, \Delta \dot{R}, \Delta \ddot{R}, \Delta \ddot{\ddot{R}}, F_c$  and  $\Delta T$  as functions of minimum slant range,  $\Delta R_{cpa}$ .

(vi) It evaluates, for each processing block, at each such times, for each output minimum range pixel position required,  $\Delta R, \Delta \dot{R}, \Delta \ddot{R}, \Delta \ddot{\ddot{R}}, F_c$  and  $\Delta T$  by expansion of the quadratic fitting coefficients.

(vii) It evaluates, for each such output minimum range pixel position required, the coefficients of slant range and phase Doppler frequency polynomials, expanded with reference to the centre frequency at the centre of the processing block  $F_{BS}$ , according to:

$$R(F) = R(1) + R(2)(F - F_{BS}) + R(3)(F - F_{BS})^2 + R(4)(F - F_{BS})^3$$

$$\theta(F) = \theta(1) + \theta(2)(F - F_{BS}) + \theta(3)(F - F_{BS})^2 + \theta(4)(F - F_{BS})^3$$

where the coefficients  $R(1)-R(4), \theta(1)-\theta(4)$  are initially evaluated according to the local centre frequency  $F_c$  and re-expanded with respect to  $F_{BS}$  according to:

$$R(1) = R'(1) + R'(2)(F_{BS} - F_c) + R'(3)(F_{BS} - F_c)^2 + R'(4)(F_{BS} - F_c)^3$$

$$R(2) = R'(2) + 2R'(3)(F_{BS} - F_c) + 3R'(4)(F_{BS} - F_c)^2$$

$$R(3) = R'(3) + 3R'(4)(F_{BS} - F_c)$$

$$R(4) = R'(4); \theta(1)-\theta(4) \text{ similarly, where}$$

$R'(1) - R'(4)$  are given in sample units by:

$$R'(1) = (\Delta R - \text{slant range to first sample}) / \Delta r;$$

$$R'(2) = - \left[ \frac{c}{2fo} \right] \frac{\Delta \dot{R}}{\Delta R \Delta r}$$

5

$$R'(3) = \left[ \frac{c}{2fo} \right]^2 \frac{(\Delta \ddot{R}^2 - \Delta \dot{R} \Delta \ddot{R})}{2 \Delta R^3 \Delta r}$$

10

$$R'(4) = - \left[ \frac{c}{2fo} \right]^3 \frac{(3 \Delta R \Delta \ddot{R}^2 - \Delta \dot{R} \Delta \ddot{R} \Delta \ddot{R} - 2 \Delta \dot{R} \Delta \ddot{R}^2)}{6 \Delta R^5 \Delta r} ; \text{ where}$$

$\Delta r$  is the range sample width in units of slant range;

$\theta'(2) - \theta'(4)$  are given by:

15

$$\theta'(2) = \Delta T$$

$$\theta'(3) = \left[ \frac{c}{2fo} \right]^2 \frac{1}{2 \Delta R}$$

20

$$\theta'(4) = \left[ \frac{c}{2fo} \right]^2 \frac{\Delta \ddot{R}}{6 \Delta R^3} ;$$

25 and the phase origin  $\theta'(1)$  is determined by the quadratic fitting coefficients of  $\Delta T$  and  $F_c$  as functions of  $R_{cpa}$ ; with a, b, c, d defined by:

$$\Delta T(R_o) = \Delta T_{mid} + a(\Delta R_o - \Delta R_{mid}) + b(\Delta R_o - \Delta R_{mid})^2$$

$$F_c(\Delta R_o) = F_{c \text{ mid}} + c(\Delta R_o - \Delta R_{mid}) + d(\Delta R_o - \Delta R_{mid})^2;$$

30  $\theta'(1)$  at  $\Delta R_o$  is evaluated according to

$$\theta'(1) = T_{mid} \cdot c \cdot \Delta R_o + \frac{1}{2}(ac + 2\Delta T_{mid} \cdot d)(\Delta R_o - \Delta R_{mid})^2 + \frac{1}{3}(bc + 2ad)(\Delta R_o - \Delta R_{mid})^3 + \frac{1}{2}bd(\Delta R_o - \Delta R_{mid})^4.$$

(viii) It computes, for each processing block, for each Doppler frequency column a table of parameters of the form of a set of values providing: the number of output samples to be generated at a

35

given frequency offset, and a frequency offset  $\Delta F$  which is  $(F-F_{BS})$  together with its second and third powers; the table is computed according to the following procedure:

5 First, for each output row to be generated during range migration correction; the column notionally dividing high and low Doppler frequencies (the "wrap around boundary") is computed from knowledge of the local centre Doppler frequency; then for the first row, the table is initialised for each column according to the relative position of the column to the wrap around boundary; then for each  
 10 subsequent row, the table entries are modified according to whether a column shift in the wrap around boundary has occurred;  
 (ix) It computes and tabulates for each processing block a phase adjustment for incorporation into the frequency domain range compression replica, the "linear range migration correction",  
 15 according to:

$$F(f) = \exp-2\pi i \left[ \frac{2 \Delta \dot{R}_c^2 (f-f_0)^2}{cf_0 \Delta \ddot{R}_c} \right],$$

20 where  $\Delta \dot{R}_c, \Delta \ddot{R}_c$  are taken from representative centre block values of  $\Delta \dot{R}$  and  $\Delta \ddot{R}$ .

(x) It computes and tabulates for each processing block n, for each output row  $R_0$  the absolute image start and end pixel indices  
 25 according to:

$$\begin{aligned} \text{start index}_n(R_0) &= \text{end index}_{n-1}(R_0) + 1 \\ \text{end index}_n(R_0) &= \text{INT}(\text{PRF} * T_n + (\text{N\_AZFFT} - \text{N\_AZREP}) / 2 + \text{PRF} * \Delta T_n(R_0)) \\ &\text{with end index}_0(R_0) = \text{INT}(\text{PRF} * T_1 - (\text{N\_AZFFT} - \text{N\_AZREP}) / 2 + \text{PRF} * T_1(R_0)) \end{aligned}$$

(xi) It computes for each processing block, for each output row a  
 30 geometric "stretch factor" to correct for residual block geometric distortion, according to:

$$\begin{aligned} \text{stretch factor}(R_0) &= 1 - \frac{\Delta \dot{\theta}}{\Delta \text{TCPA}}, \text{ where} \\ \Delta \dot{\theta} &= \theta_R(2) - \theta_L(2) + 2.0 * (\theta_R(3) * (F_c - F_{BSR}) - \theta_L(3) * (F_c - F_{BSL})) \\ &+ 3.0 * (\theta_R(4) * (F_c - F_{BSR})^2 - \theta_L(4) * (F_c - F_{BSL})^2), \\ \Delta \text{TCPA} &= (\text{N\_AZFFT} - \text{N\_AZREP} - 1) / \text{PRF} + \Delta T_R(R_0) - \Delta T_L(R_0), \end{aligned}$$

35



where the suffices R and L relate to function values evaluated at end and start of the processing block respectively;

computes for each processing block, for each output row, a real, that is fractionally valued, start sample modulo the processing block according to:

$$\text{start sample}_n(R_o) = (\text{start index}_n(R_o) + (1 - \text{stretch factor}_n(R_o)) * (\text{end index}_n(R_o) + 1 - \text{start index}_n(R_o)) / 2) \text{mod } N\_AZFFT$$

and tabulating: start sample<sub>n</sub>(R<sub>o</sub>), stretch factor<sub>n</sub>(R<sub>o</sub>) and (end index<sub>n</sub>(R<sub>o</sub>) - start index<sub>n</sub>(R<sub>o</sub>) + 1);

(xii) It computes, for each processing block, for each output row, an approximate centre frequency FCINT(R<sub>o</sub>) which is a multiple of PRF/N\_AZFFT, and the corresponding column offset ΔCOL(R<sub>o</sub>) according to:

$$FCINT(R_o) = \frac{PRF \times INT(F_c \times N\_AZFFT / PRF)}{N\_AZFFT}$$

$$\Delta COL(R_o) = (F_c \text{mod } PRF) \times N\_AZFFT / PRF$$

(xiii) It computes and tabulates for each processing block, for each output row, a heterodyning frequency, FHET(R<sub>o</sub>), and a phase offset, φ(R<sub>o</sub>), according to:

$$FHET(R_o) = \frac{\Delta \theta(R_o)}{\Delta T_{CPA}(R_o)} - FCINT(R_o)$$

$$\phi(R_o) = -\frac{\Delta \theta(R_o)}{\Delta T_{CPA}(R_o)} * T_{CENTRE}$$

where:

$$\Delta \theta(R_o) = (\theta_R(1) - \theta_L(1)) + (\theta_R(2)(F_c - F_{BSR}) - \theta_L(2)(F_c - F_{BSL})) + (\theta_R(3)(F_c - F_{BSR})^2 - \theta_L(3)(F_c - F_{BSL})^2) + (\theta_R(4)(F_c - F_{BSR})^3 - \theta_L(4)(F_c - F_{BSL})^3)$$

$$\Delta T_{CPA}(R_o) = (N\_AZFFT - N\_AZREP - 1) / PRF + \Delta T_R(R_o) - \Delta T_L(R_o)$$

$$T_{CENTRE} = T_n(R_o) + PRF * (N\_AZFFT / 2)$$

(xiv) It tabulates operator specified range and azimuth compression weighting functions.

Data Tables

The following tables are generated for each processing block:

Block Control

- (i) Start pulse
- (ii) End pulse
- (iii) For each output image row: start and end image pixel location.

5 Range Compression

- (i) Frequency domain pulse reference  $\times g(f)$   $\times$  user specified weighting function.

Azimuth Compression

- (i) For each output image row:
  - 10 -  $R(1), R(2), R(3), R(4)$  coefficients
  - $\theta(1), \theta(2), \theta(3), \theta(4)$  coefficients
- (ii) For each Doppler frequency column ( $N_{AZFFT}$ ):
  - For each wraparound:
    - Number of output rows to be generated
    - 15 -  $\Delta F, \Delta F^2, \Delta F^3$  where  $\Delta F$  is the difference between the column frequency and the centre block expansion frequency.
  - (iii) For each output image row:
    - $\Delta COL$
    - $F_{HET}$
    - 20 -  $\phi$
  - (iv) For each output image row:
    - start sample
    - stretch factor
    - number of samples to output.
  - 25 (v) User specified azimuth compression weighting function.

Range Compression

The system loads each pulse, performs an FFT, multiplies the spectral data by the tabulated range compression replica, performs an inverse FFT and outputs the range compressed data; the range compression replica is selected according to the relevant processing block but the update rate is non-critical; the fine detail of the process is well known to those skilled in this art.

Azimuth Compression

Data is processed in overlapping blocks, defined by the block start and end pulse indices. An FFT at constant range is performed

on each row of each block; for each frequency column a sampling comb and phase conjugate function is generated, according to:

For each wraparound:

For each output row:

$$5 \quad R_{\text{INDX}}(R_0) = R(1) + R(2)\Delta F + R(3)\Delta F^2 + R(4)\Delta F^3$$

$$\theta(R_0) = 2\pi * (\theta(1) + \theta(2)\Delta F + \theta(3)\Delta F^2 + \theta(4)\Delta F^3);$$

For each column, data is interpolated to generate a new column, defined by the sampling comb  $R_{\text{INDX}}(R_0)$ , by procedures known to

those skilled in this art, and multiplied by  $\exp-i\theta(R_0)$ . Each row

10 of this modified block is then logically shifted in a cyclic fashion by  $\Delta\text{COL}$ , multiplied by the user specified azimuth compression weighting function and an inverse FFT performed;

For each resulting row a sampling comb,  $A_{\text{INDX}}$ , and phase function,

$\theta$ , are generated according to:

$$15 \quad A_{\text{INDX}}(N) = (\text{start sample} + (N-1) \times \text{stretch factor}) \bmod N_{\text{AZFFT}},$$

for  $N = 1$  to number of samples to output;

$$\theta(N) = 2\pi * \left( \phi + \frac{F_{\text{HET}}}{\text{PRF}} \times (\text{start image location} + (N-1) - \text{start pulse}) \right);$$

and a modified row is interpolated according to the cyclic sampling

20 comb  $A_{\text{INDX}}$ , according to procedures known to those skilled in such art, and each resulting pixel is multiplied by  $\exp-i\theta(N)$ . The resulting block of output image is then output to storage.

#### Block Merge

The final coherent image is assembled row by row from the  
25 contiguous blocks of image data; each row is offset in the image frame by the start pixel location of the row in the first image block less the minimum start pixel location.

The resulting coherent image is obtained in coordinates of  
minimum slant range and time of closest approach, is at baseband  
30 with respect to the range dimension and at offset Doppler frequencies provided by the  $F_{\text{HET}}$  tabulation.

## Claims:

1. A signal processor for synthetic aperture radar which comprises
  - (a) processing parameter generator for computation of processor filter parameters from the vehicle motion and antenna geometry,
  - (b) range compression means comprising
    - 5 (i) pulse FFT means for performing an FFT on pulse echoes
    - (ii) pulse replica multiplication means to effect pulse correlation
    - (iii) squint compensation multiplication means to effect second order migration correction
    - 10 (iv) inverse FFT means for performing an inverse FFT on the multiplied and compensated spectral data;
  - (c) azimuth compression means comprising
    - 15 (i) row FFT means for performing an FFT on rows of data selected at constant range from overlapping blocks of range compressed data
    - (ii) azimuth replica evaluator means, comprising range and phase polynomial evaluators and a complex exponentiator
    - (iii) azimuth spectral buffer means, comprising a bank of storage to contain an adequately large number of row
    - 20 transforms.
    - (iv) data selection means comprising an interpolator to effect selection of data along curves in the spectral buffer according to values computed by the range polynomial evaluator.
    - (v) azimuth replica multiplication means to effect
    - 25 multiplication of the selected data with the complex data

generated by the phase polynomial evaluators

(vi) inverse FFT means to effect the inverse transform of rows of the processed data;

(d) Image formation means comprising image resampling and buffering  
5 means to effect image block geometric and phase discontinuity removal and image collation.

2. A signal processor according to claim 1 wherein the parameter generator comprises

- (1) means for computing the latitude and longitude of points  
10 approximately in the beam centre at the near far and centre swath positions on the earth's surface at times corresponding approximately to the start, centre and end pulses of the processing block;
- (2) means for computing the time offset of each of these points  
15 from the closest point of approach and the minimum range at the closest point of approach;
- (3) means for evaluating the range, Doppler frequency and successive derivatives of the range with respect to time at the given time;
- 20 (4) means for quadratically fitting the calculated parameters as a function of minimum range;
- (5) means for generating parameters for each output range pixel comprising means for:-  
determining the range polynomial coefficients by quadratic  
25 expansion using the required minimum range values.
- (6) means for computing block geometric and phase correction factors;
- (7) means for computing block collation parameters.

3. The processor according to claims 1 or 2 wherein the parameter  
30 generator has means for generating and storing for each block of data to be processed to produce the image, the following data tables;

a block control data table comprising the start pulse, the end pulse and the start and end image pixel location for each output row;

35 a range compression data table comprising the product of a frequency

domain pulse reference, and  $g(f)$  where  $g(f)$  is

$$\exp(-2\pi i \left[ \frac{2}{cf_0} \frac{\Delta R c^2}{\Delta R c} \frac{(f-f_0)^2}{2} \right])$$

5

and a user specified weighting function,

an azimuth compression data table comprising for each output image row

- 10 (i) coefficients of slant range polynomials in Doppler frequency expanded with reference to the centre frequency at the centre of the processing block;
- (ii) and for each wraparound in each Doppler frequency column, the number of output rows to be generated, and  $\Delta F$ ,  $\Delta F^2$  and  $\Delta F^3$  where  $\Delta F$  is the difference in absolute Doppler frequency between the column frequency and the centre block expansion frequency.
- 15 (iii) for each output range row, a column offset, a heterodyning frequency and a phase offset;
- (iv) for each output image row, a start sample, a stretch factor, and a number of samples to output, and
- 20 (v) a user specified azimuth compression weighting function.

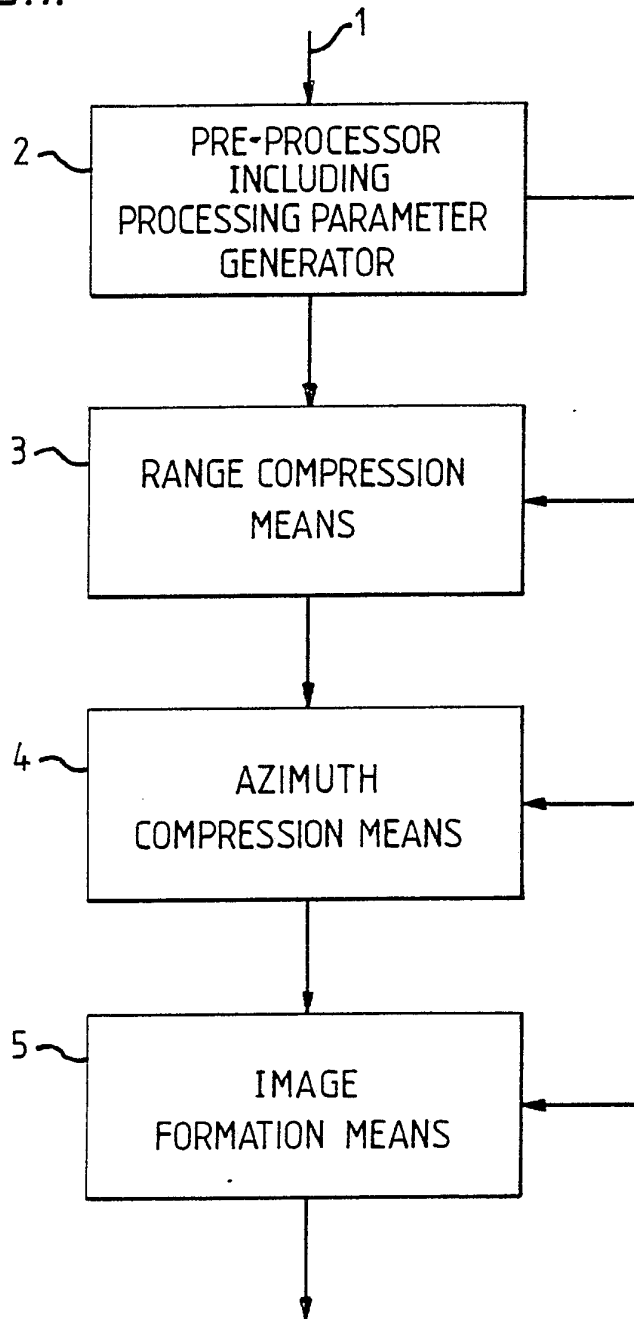
25

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FIG.1.



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FIG. 2.

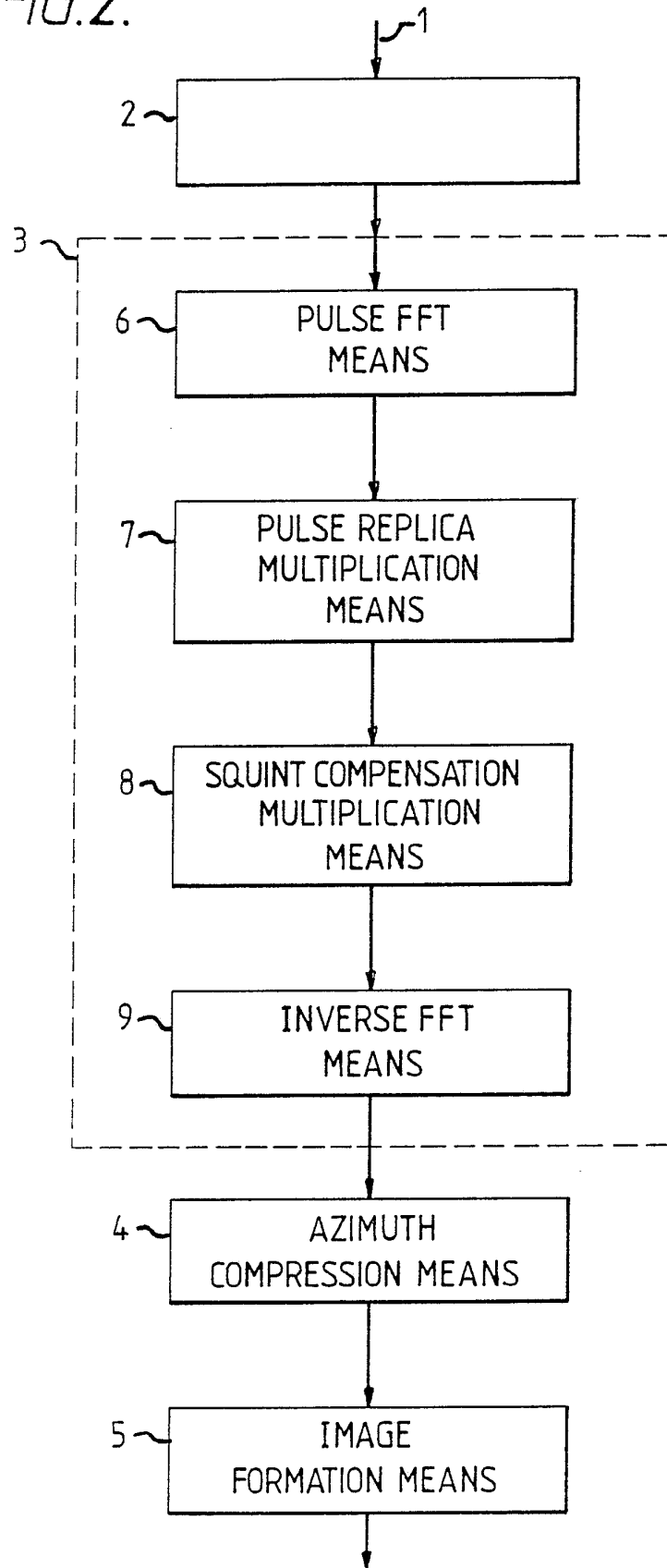
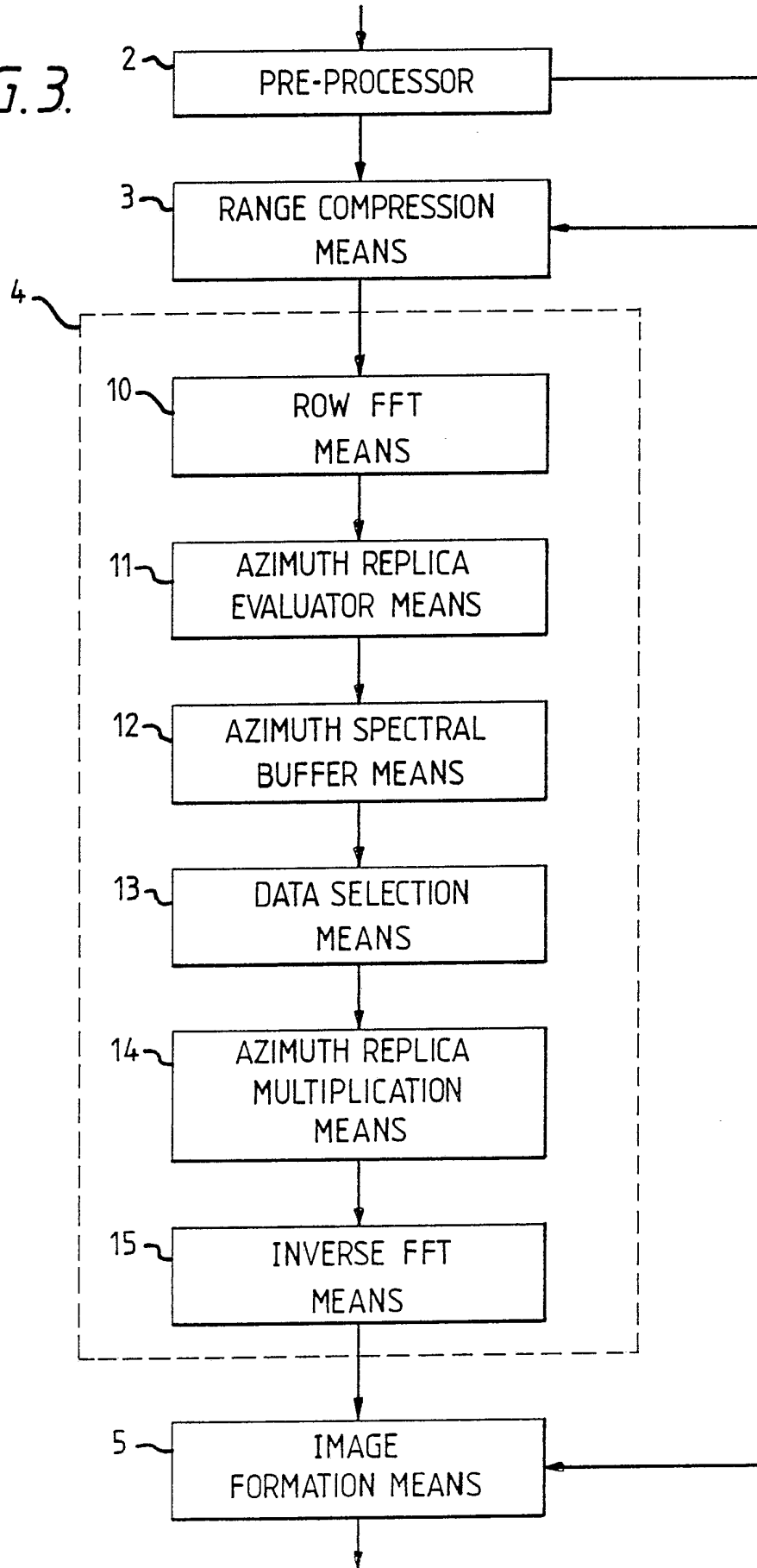


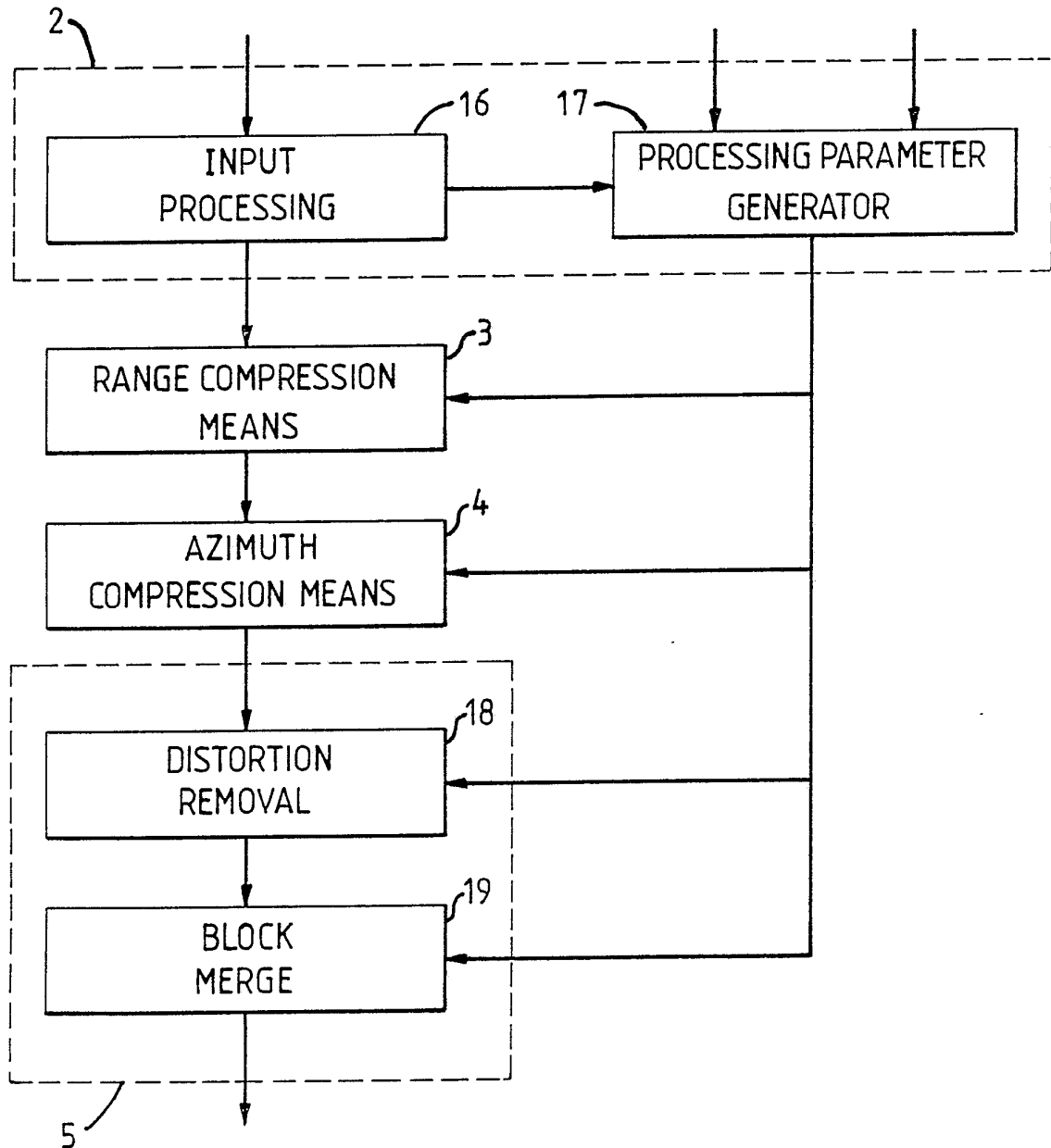


FIG. 3.



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FIG. 4.



# INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 88/00024

<b>I. CLASSIFICATION OF SUBJECT MATTER</b> (if several classification symbols apply, indicate all) <sup>6</sup>		
According to International Patent Classification (IPC) or to both National Classification and IPC		
IPC <sup>4</sup> : G 01 S 13/90		
<b>II. FIELDS SEARCHED</b>		
Minimum Documentation Searched <sup>7</sup>		
Classification System	Classification Symbols	
IPC <sup>4</sup>	G 01 S	
Documentation Searched other than Minimum Documentation to the extent that such Documents are included in the Fields Searched <sup>8</sup>		
<b>III. DOCUMENTS CONSIDERED TO BE RELEVANT <sup>9</sup></b>		
Category <sup>9</sup>	Citation of Document, <sup>11</sup> with indication, where appropriate, of the relevant passages <sup>12</sup>	Relevant to Claim No. <sup>13</sup>
Y	US, A, 4471357 (C. WU et al.) 11 September 1984 see abstract; column 3, line 53 - column 4, line 39; column 13, line 1 - column 15, line 34; figures 1,11	1
A	---	2,3
Y	1981 IEEE International Symposium on Circuits and Systems Proceedings, 27-29 April 1981, Chicago, Illinois, volume 1 of 3, IEEE, (New York, US), H.R. Anderson: "Digital processing of synthetic array radar data", pages 71-73 see the whole document	1
A	IEEE Transactions on Aerospace and Electronic Systems, volume AES-21, no. 3, May 1985, Canadian Crown, (New York, US), K.H. Wu et al.: "Extensions to the step transform SAR processing technique", pages 338-344 see paragraphs I and IV	1
<p><sup>9</sup> Special categories of cited documents: <sup>10</sup>      --</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> <p>"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</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"G" document member of the same patent family</p>		
<b>IV. CERTIFICATION</b>		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
29th April 1988	16 JUN 1988	
International Searching Authority	Signature of Authorized Officer	
EUROPEAN PATENT OFFICE	 <b>P.C.G. VAN DER PUTTEN</b>	

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A	IEEE Transactions on Geoscience and Remote Sensing, volume GE-24, no. 4, July 1986, IEEE, (New York, US), J.C. Curlander: "Performance of the SIR-B digital image processing sub-system", pages 649-652 see paragraph II --	1,2
A	US, A, 4034370 (J.H. MIMS) 5 July 1977 see column 6, line 2 - column 7, line 62; figure 4 --	1
A	US, A, 4183024 (S.R. BROOKS) 8 January 1980 see column 6, line 58 - column 11, line 6; figures 4-6 -----	1-3

ANNEX TO THE INTERNATIONAL SEARCH REPORT  
ON INTERNATIONAL PATENT APPLICATION NO.

GB 8800024

SA 20569

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 02/06/88. The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 4471357	11-09-84	None	
US-A- 4034370	05-07-77	None	
US-A- 4183024	08-01-80	GB-A- 1568291	29-05-80