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US 5402234 A
US 5194918 A
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(58) Field of Search
UK CL (Edition T) G1A ACEW ACEX
INT CL[7] G01B 9/02 11/24 11/30
Other: Online: WPI, EPODOC, JAPIO

(54) Abstract Title
Determining surface profile by measurement of interference fringes

(57) In a scanning interferometer, light from a broadband source (4) is split (at 5), reflected by a sample surface (7) and by a reference surface (6), and recombined (at 5) so that it interferes before reaching a detector, such as a CCD camera (10). A motion controller (11) connected to the reference surface varies the difference between the sample and reference path lengths, and the detector senses light intensities produced by interference fringes at intervals eg when triggered by a sensor responsive to the position of the reference surface (6). A data processor (3) has a concurrent processing section (34) for processing intensity values from the detector to identify the position of a coherence peak by correlating intensity values with a correlation function eg using a Gaussian distribution, and a post-processing section (35) for determining the height of a respective surface region from the position of the coherence peak.

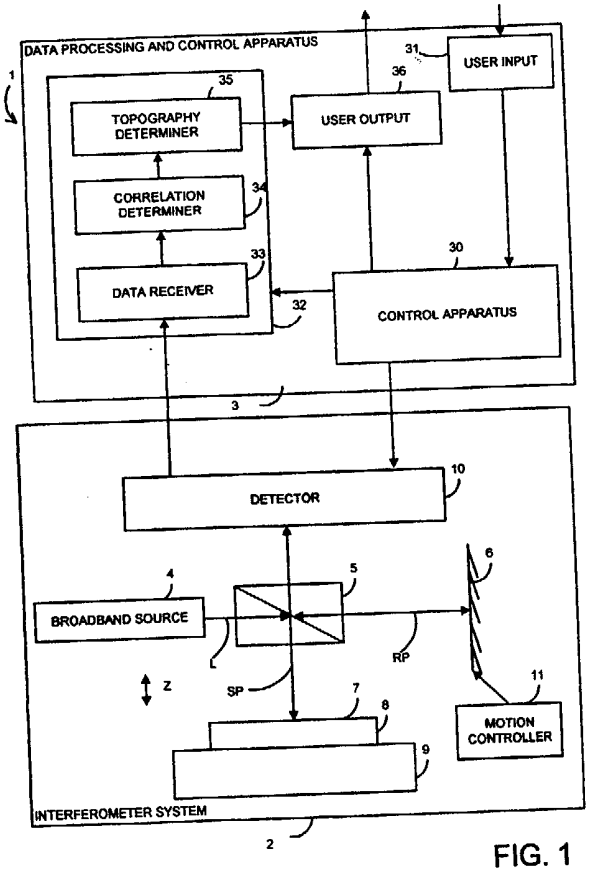


FIG. 1

GB 2 385 417 A

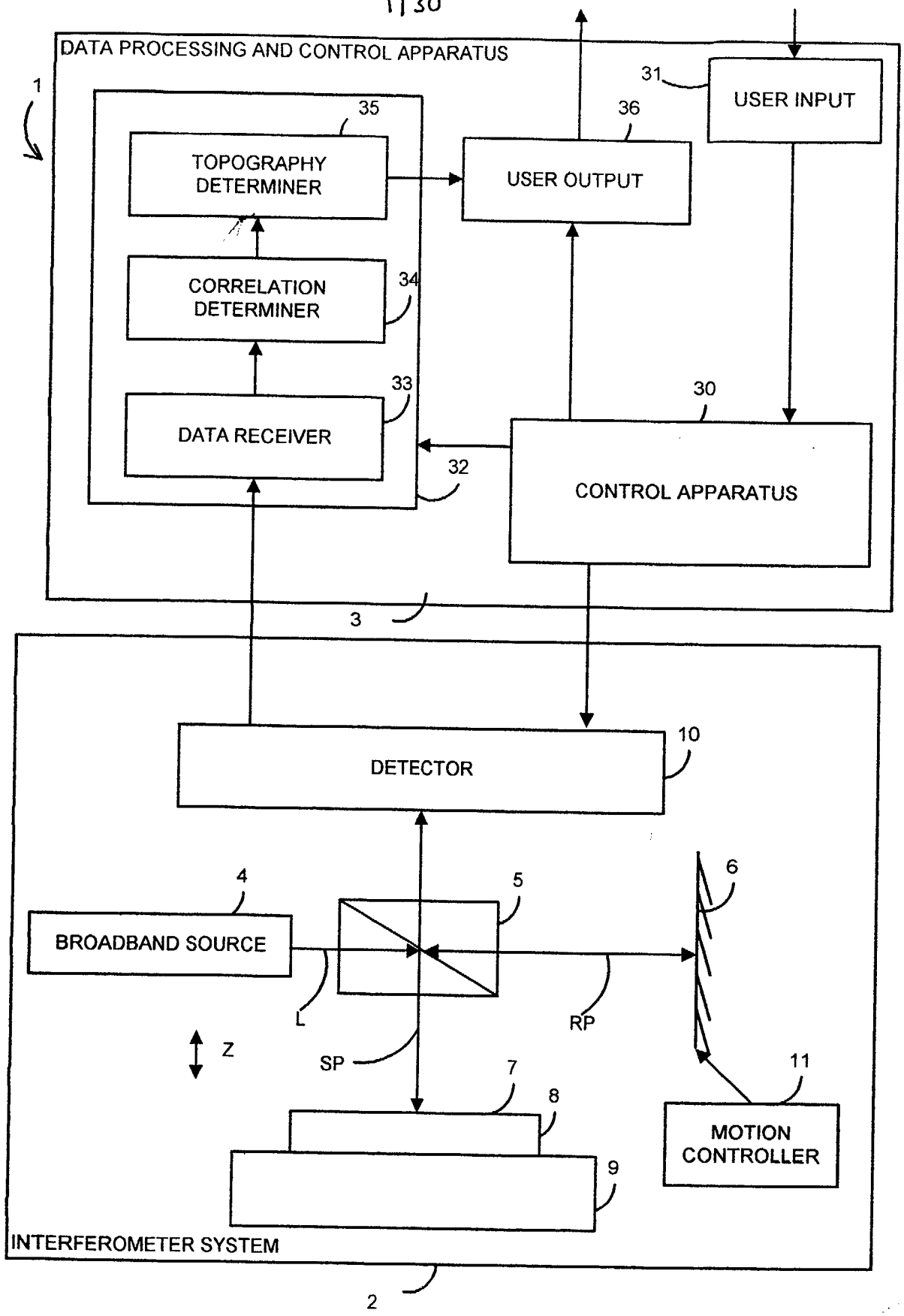
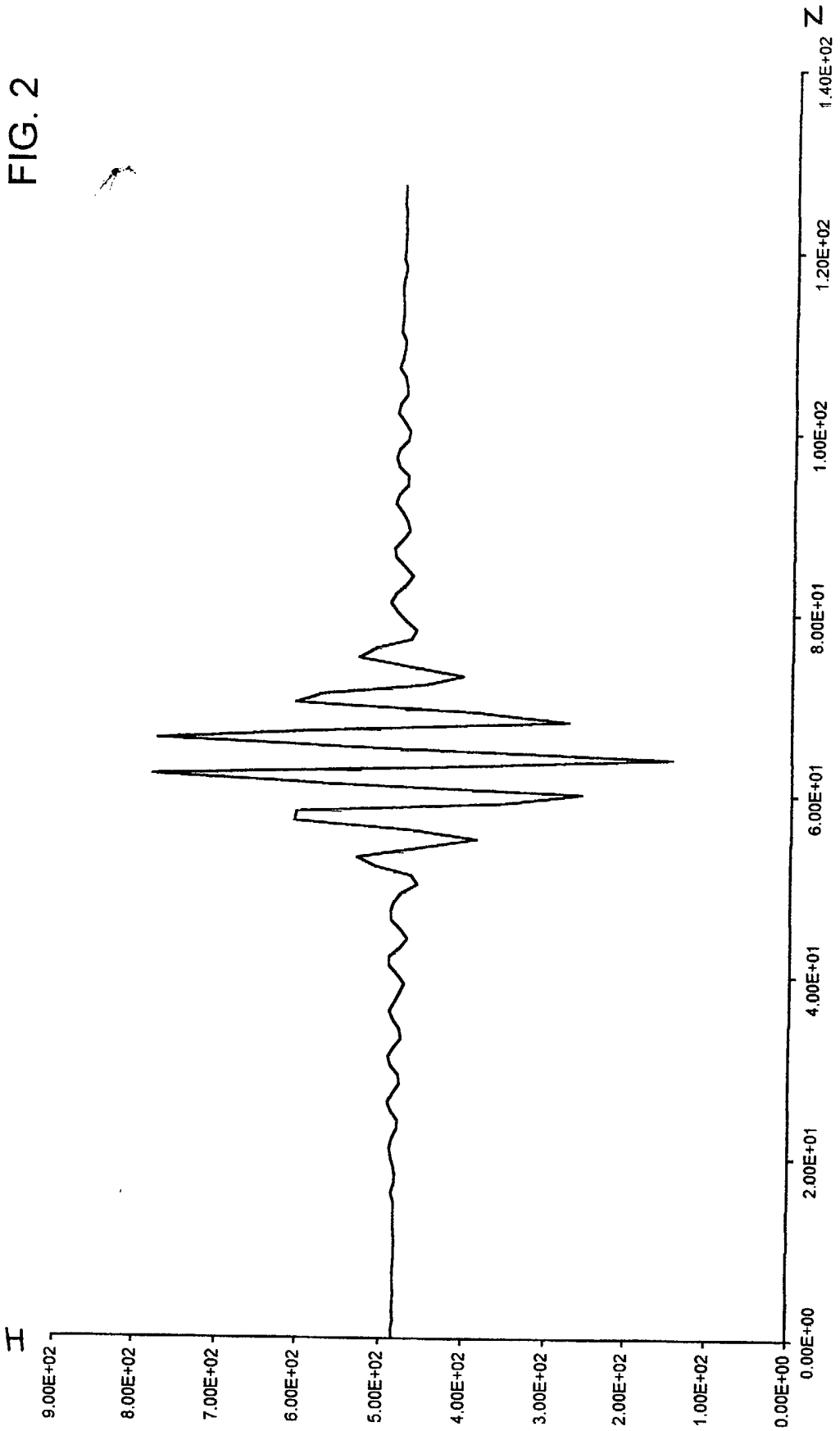

DATA PROCESSING AND CONTROL APPARATUS
1
31
USER INPUT
35
TOPOGRAPHY DETERMINER
36
USER OUTPUT
CORRELATION DETERMINER
34
33
DATA RECEIVER
30
32
CONTROL APPARATUS
3
DETECTOR
10
4
BROADBAND SOURCE
5
6
L
RP
Z
SP
7
8
11
MOTION CONTROLLER
9
INTERFEROMETER SYSTEM
2

FIG. 1

FIG. 2


I
9.00E+02
8.00E+02
7.00E+02
6.00E+02
5.00E+02
4.00E+02
3.00E+02
2.00E+02
1.00E+02
0.00E+00
0.00E+00
2.00E+01
4.00E+01
6.00E+01
8.00E+01
1.00E+02
1.20E+02
1.40E+02
Z

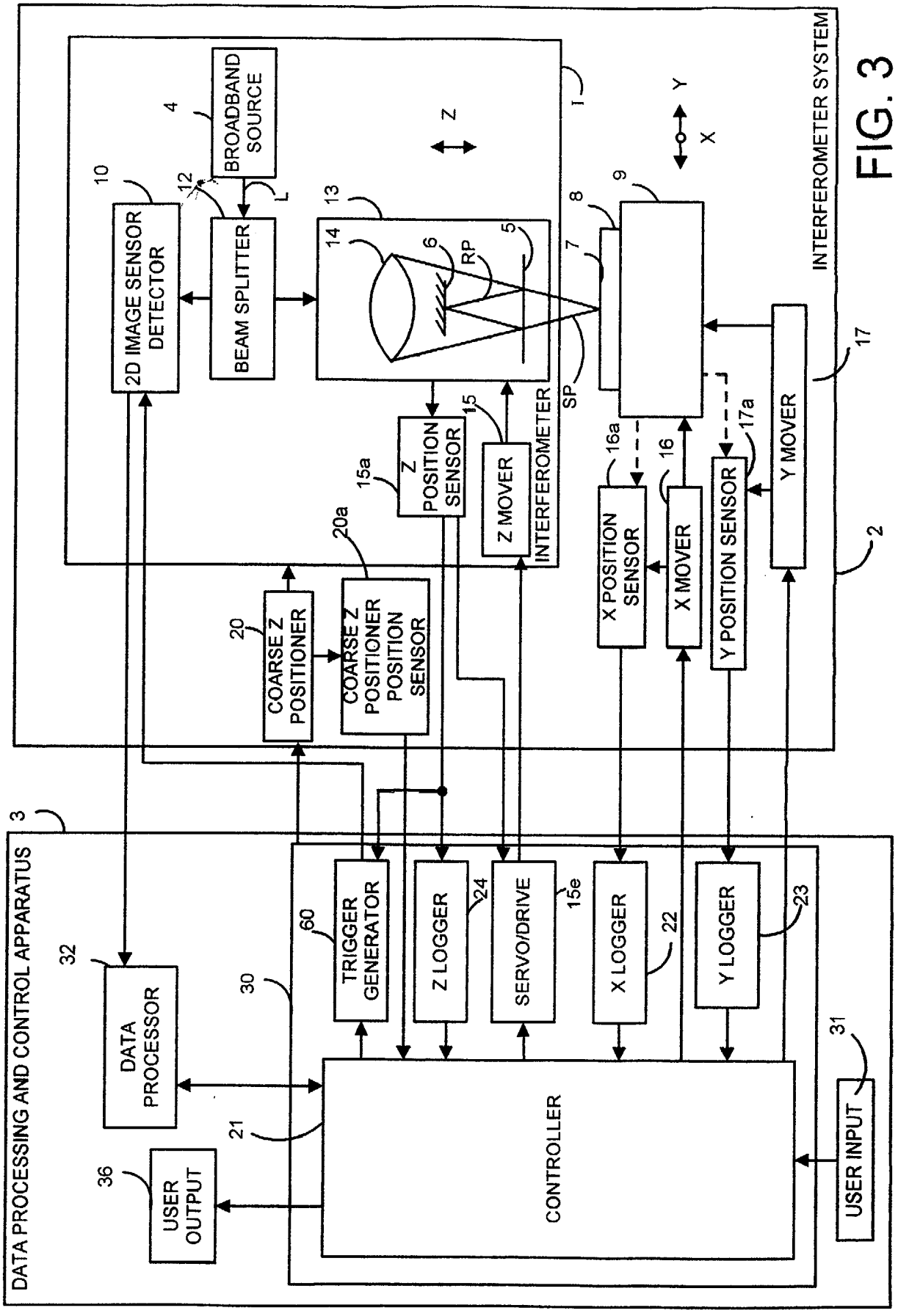

DATA PROCESSING AND CONTROL APPARATUS
3
DATA PROCESSOR
32
USER OUTPUT
36
CONTROLLER
21
30
TRIGGER GENERATOR
60
Z LOGGER
24
SERVO/DRIVE
15e
X LOGGER
22
Y LOGGER
23
USER INPUT
31
INTERFEROMETER SYSTEM
1
2D IMAGE SENSOR DETECTOR
10
BEAM SPLITTER
12
BROADBAND SOURCE
4
L
13
14
6
RP
5
7
SP
8
9
Z
Y
X
INTERFEROMETER
Z POSITION SENSOR
15
15a
Z MOVER
COARSE Z POSITIONER
20
COARSE Z POSITIONER POSITION SENSOR
20a
X POSITION SENSOR
16a
X MOVER
16
Y POSITION SENSOR
17a
Y MOVER
17

FIG. 3

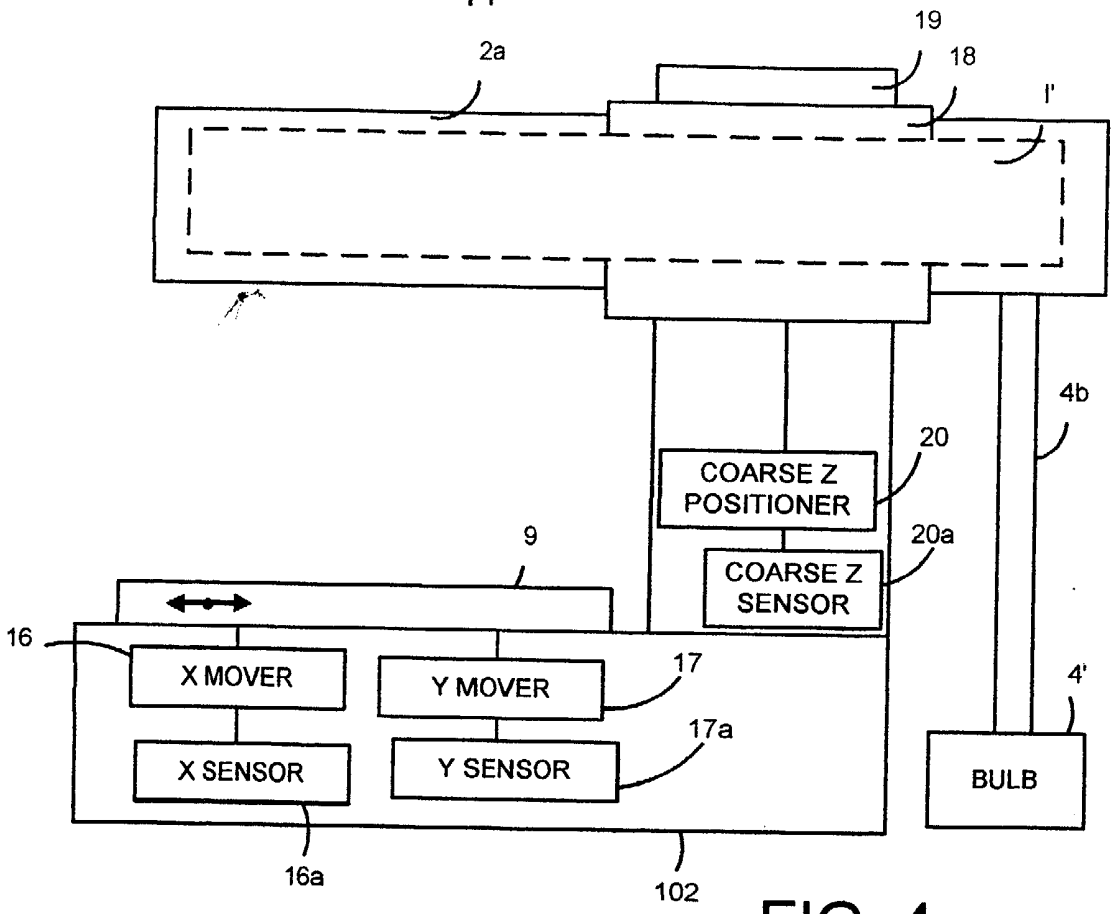

19
2a
18
I'
4b
20
COARSE Z POSITIONER
9
20a
COARSE Z SENSOR
16
X MOVER
Y MOVER
17
4'
17a
X SENSOR
Y SENSOR
BULB
16a
102

FIG. 4

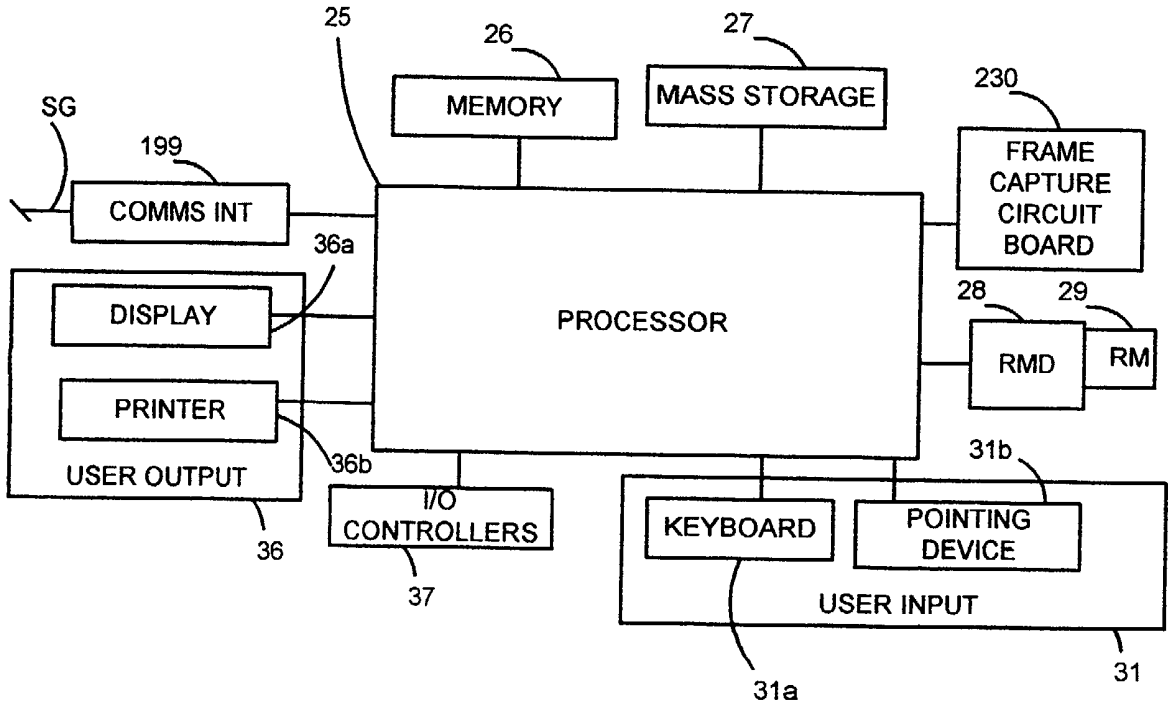

25
26
27
MEMORY
MASS STORAGE
230
SG
199
FRAME CAPTURE CIRCUIT BOARD
COMMS INT
36a
DISPLAY
PROCESSOR
28
29
RMD
RM
PRINTER
36b
31b
USER OUTPUT
I/O CONTROLLERS
KEYBOARD
POINTING DEVICE
36
37
USER INPUT
31
31a

FIG. 5

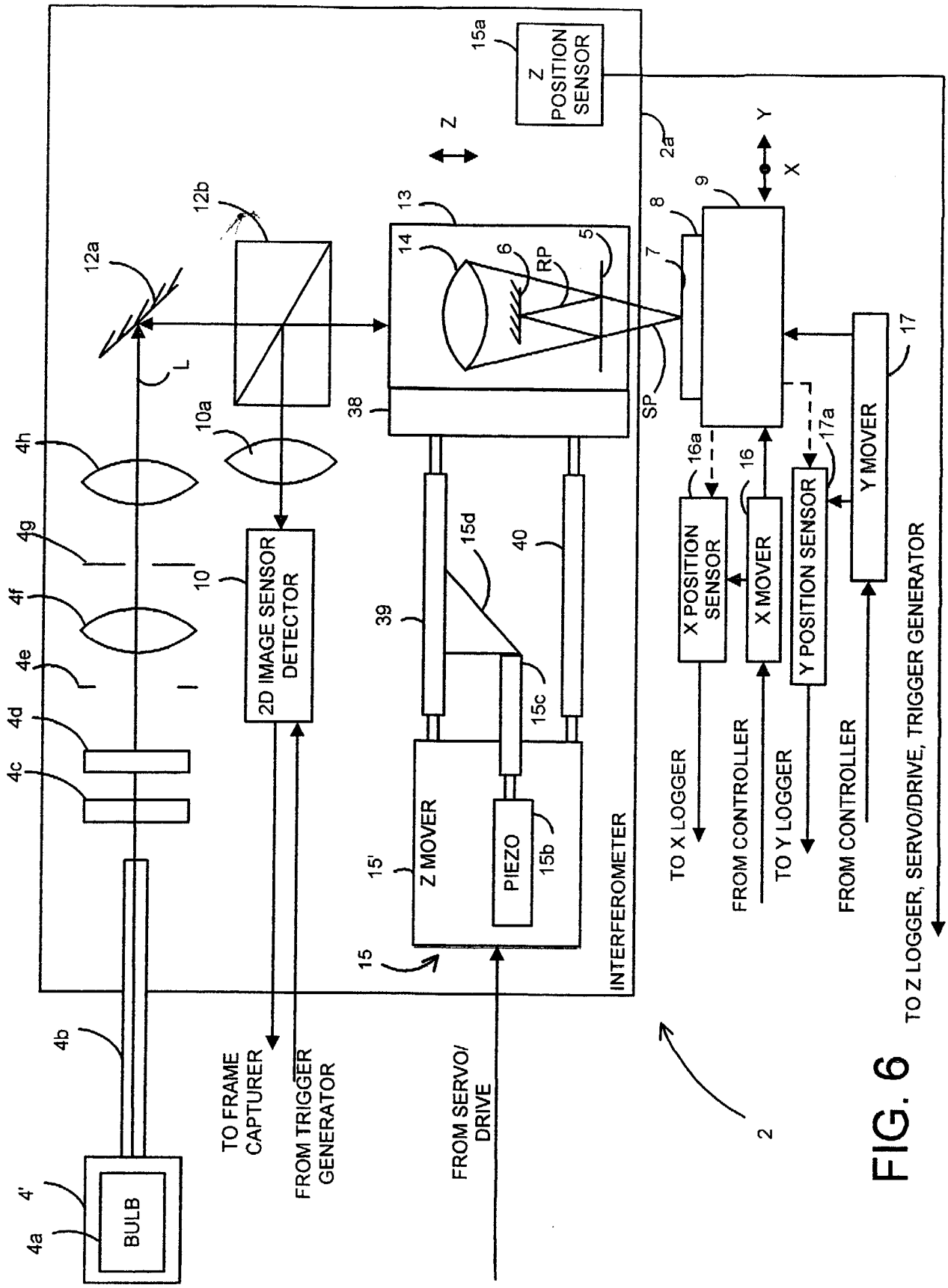

BULB
4a
4'
4b
4c
4d
4e
4f
4g
4h
L
12a
12b
10a
10
2D IMAGE SENSOR DETECTOR
TO FRAME CAPTURER
FROM TRIGGER GENERATOR
38
13
14
6
RP
5
Z
15a
Z POSITION SENSOR
2a
39
15d
40
15c
15'
Z MOVER
PIEZO
15b
15
FROM SERVO/ DRIVE
INTERFEROMETER
SP
7
8
9
Y
X
16a
16
17a
17
X POSITION SENSOR
X MOVER
Y POSITION SENSOR
Y MOVER
TO X LOGGER
FROM CONTROLLER
TO Y LOGGER
FROM CONTROLLER
TO Z LOGGER, SERVO/DRIVE, TRIGGER GENERATOR
2

FIG. 6

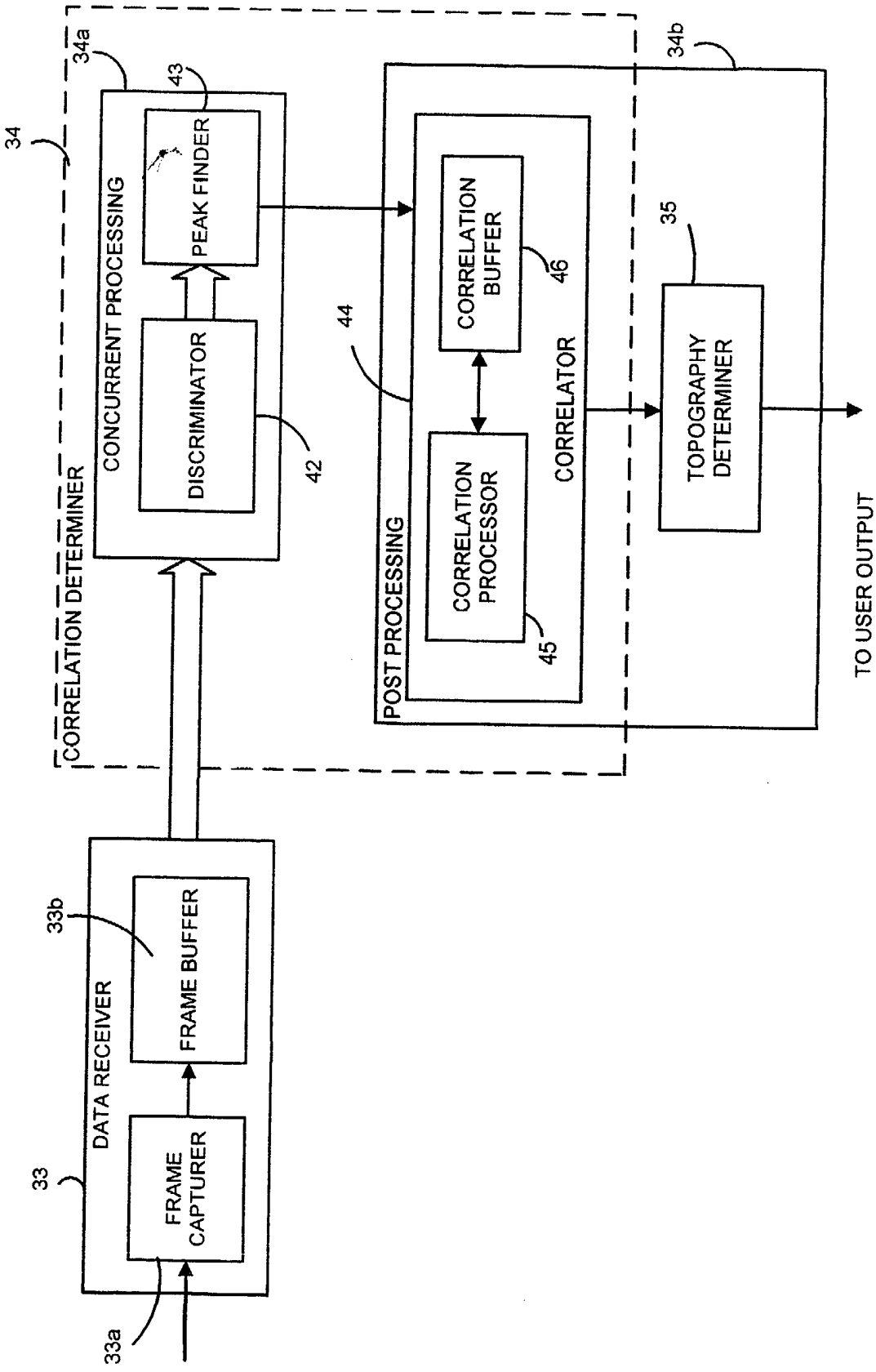

33a
33
DATA RECEIVER
FRAME CAPTURER
33b
FRAME BUFFER
34
CORRELATION DETERMINER
34a
CONCURRENT PROCESSING
DISCRIMINATOR
42
43
PEAK FINDER
34b
POST PROCESSING
44
CORRELATOR
CORRELATION PROCESSOR
45
CORRELATION BUFFER
46
35
TOPOGRAPHY DETERMINER
TO USER OUTPUT

FIG. 7

F1

I_1P_1	I_1P_2	I_1P_3
I_1P_4	I_1P_5	I_1P_6
I_1P_7	I_1P_8	I_1P_9

F2

I_2P_1	I_2P_2	I_2P_3
I_2P_4	I_2P_5	I_2P_6
I_2P_7	I_2P_8	I_2P_9

Fn

I_nP_1	I_nP_2	I_nP_3
I_nP_4	I_nP_5	I_nP_6
I_nP_7	I_nP_8	I_nP_9

FIG. 8

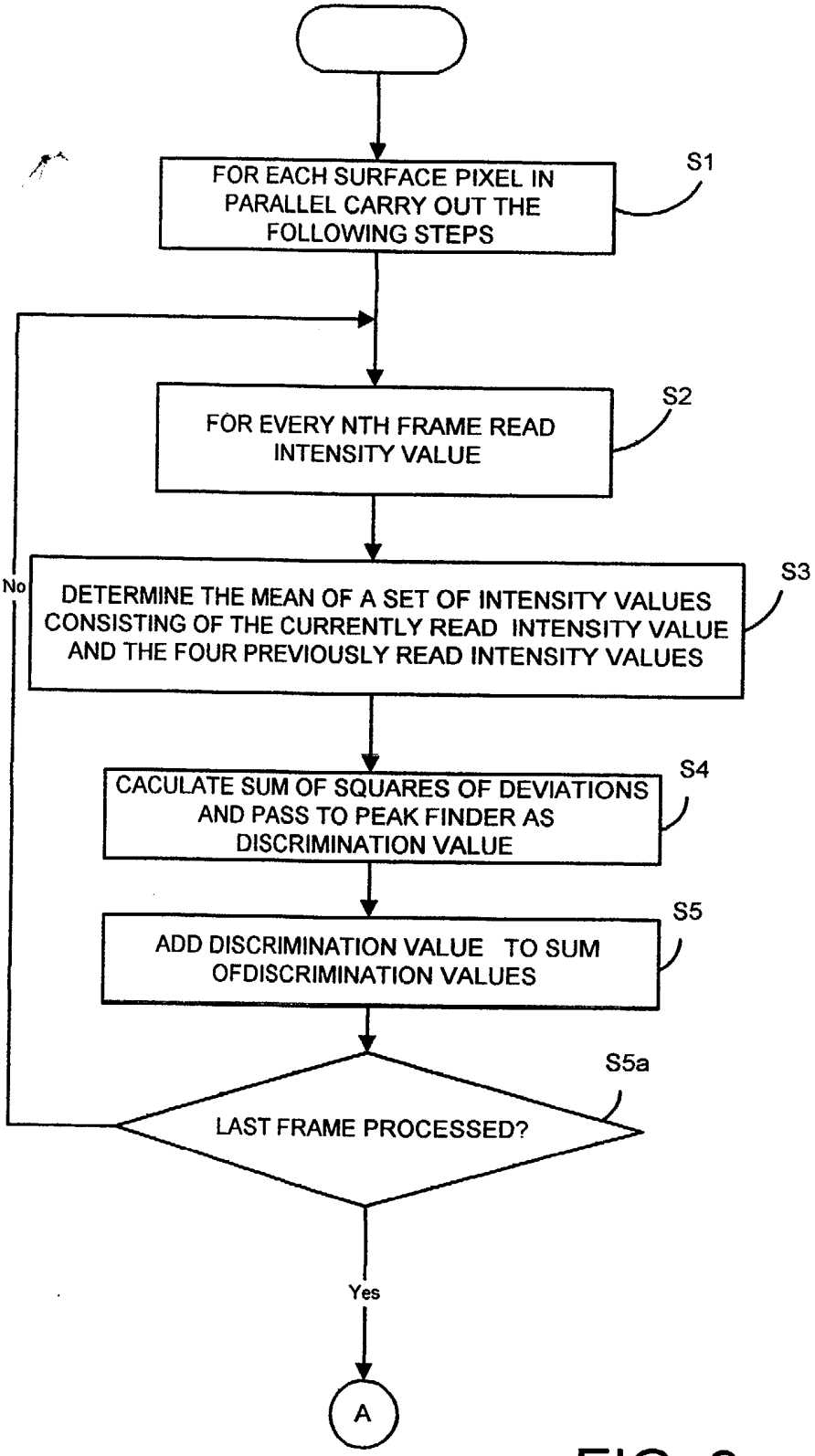

FOR EACH SURFACE PIXEL IN PARALLEL CARRY OUT THE FOLLOWING STEPS
S1
FOR EVERY NTH FRAME READ INTENSITY VALUE
S2
No
DETERMINE THE MEAN OF A SET OF INTENSITY VALUES CONSISTING OF THE CURRENTLY READ INTENSITY VALUE AND THE FOUR PREVIOUSLY READ INTENSITY VALUES
S3
CACULATE SUM OF SQUARES OF DEVIATIONS AND PASS TO PEAK FINDER AS DISCRIMINATION VALUE
S4
ADD DISCRIMINATION VALUE TO SUM OFDISCRIMINATION VALUES
S5
LAST FRAME PROCESSED?
S5a
Yes
A

FIG. 9

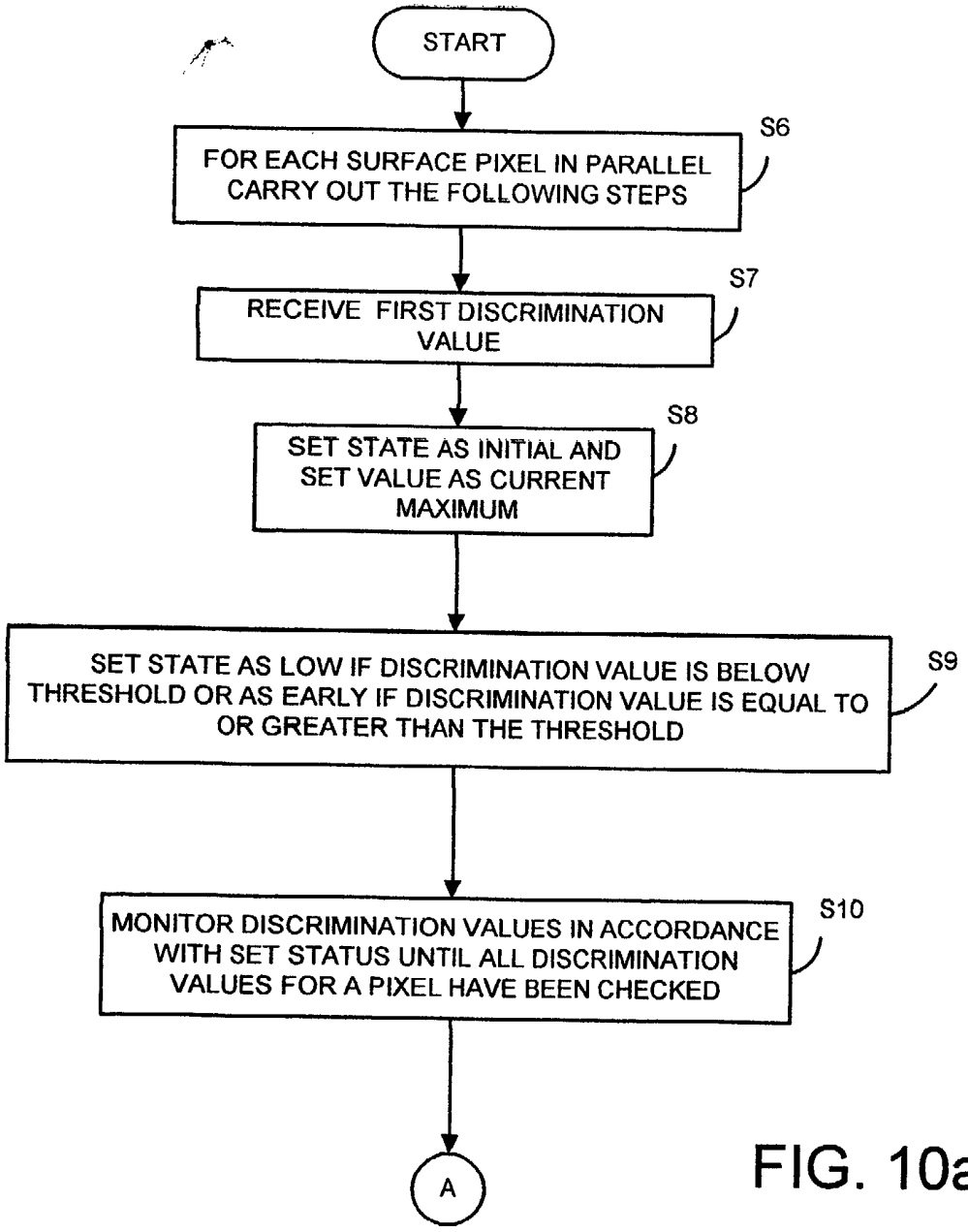

START
FOR EACH SURFACE PIXEL IN PARALLEL CARRY OUT THE FOLLOWING STEPS
S6
RECEIVE FIRST DISCRIMINATION VALUE
S7
SET STATE AS INITIAL AND SET VALUE AS CURRENT MAXIMUM
S8
SET STATE AS LOW IF DISCRIMINATION VALUE IS BELOW THRESHOLD OR AS EARLY IF DISCRIMINATION VALUE IS EQUAL TO OR GREATER THAN THE THRESHOLD
S9
MONITOR DISCRIMINATION VALUES IN ACCORDANCE WITH SET STATUS UNTIL ALL DISCRIMINATION VALUES FOR A PIXEL HAVE BEEN CHECKED
S10
A

FIG. 10a

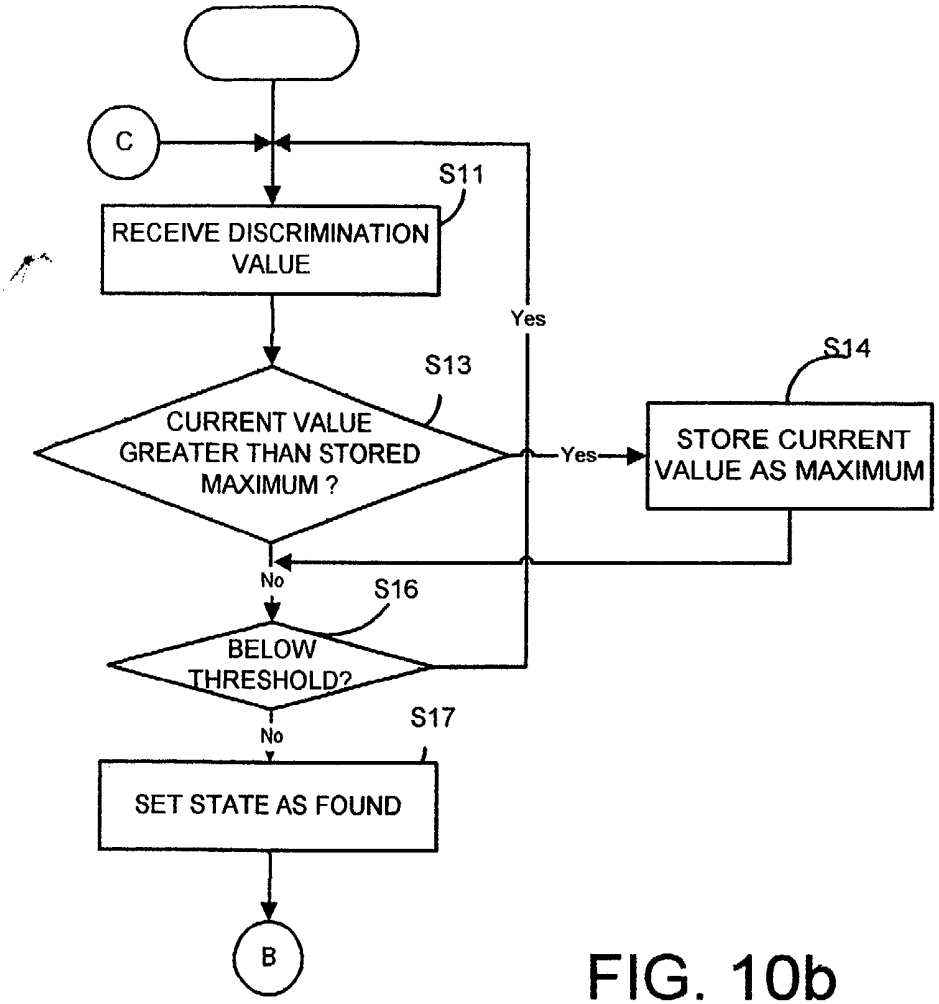


FIG. 10b

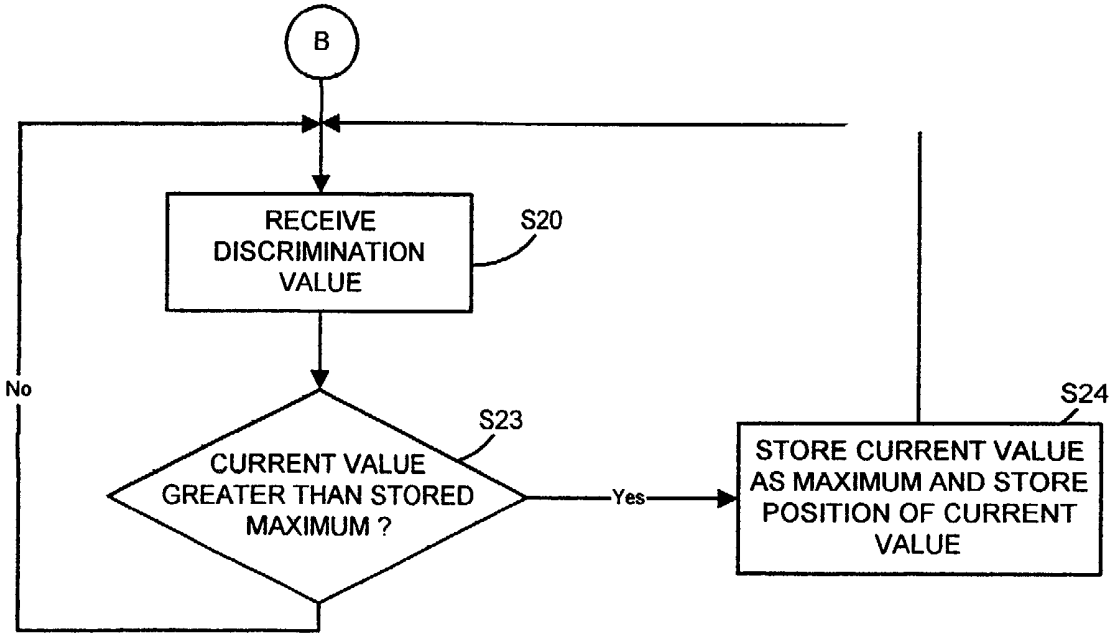


FIG. 10c

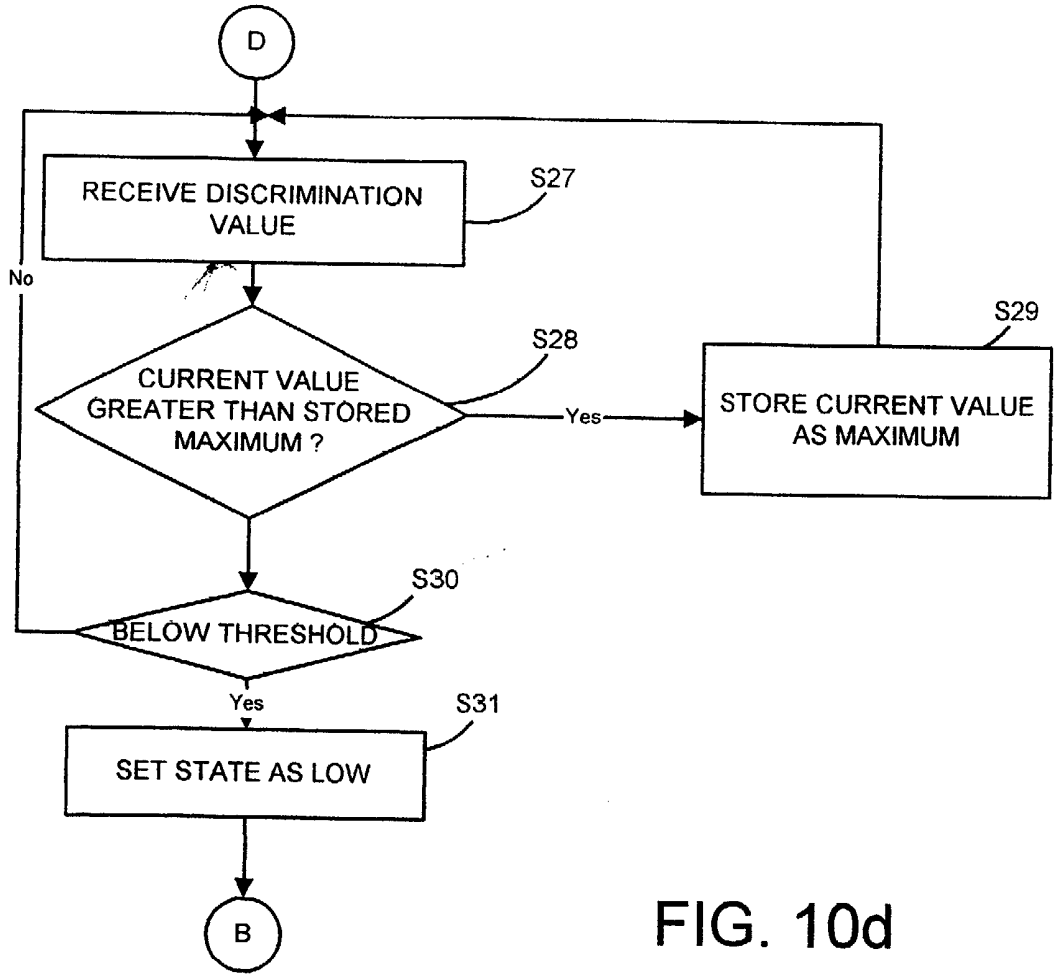


FIG. 10d

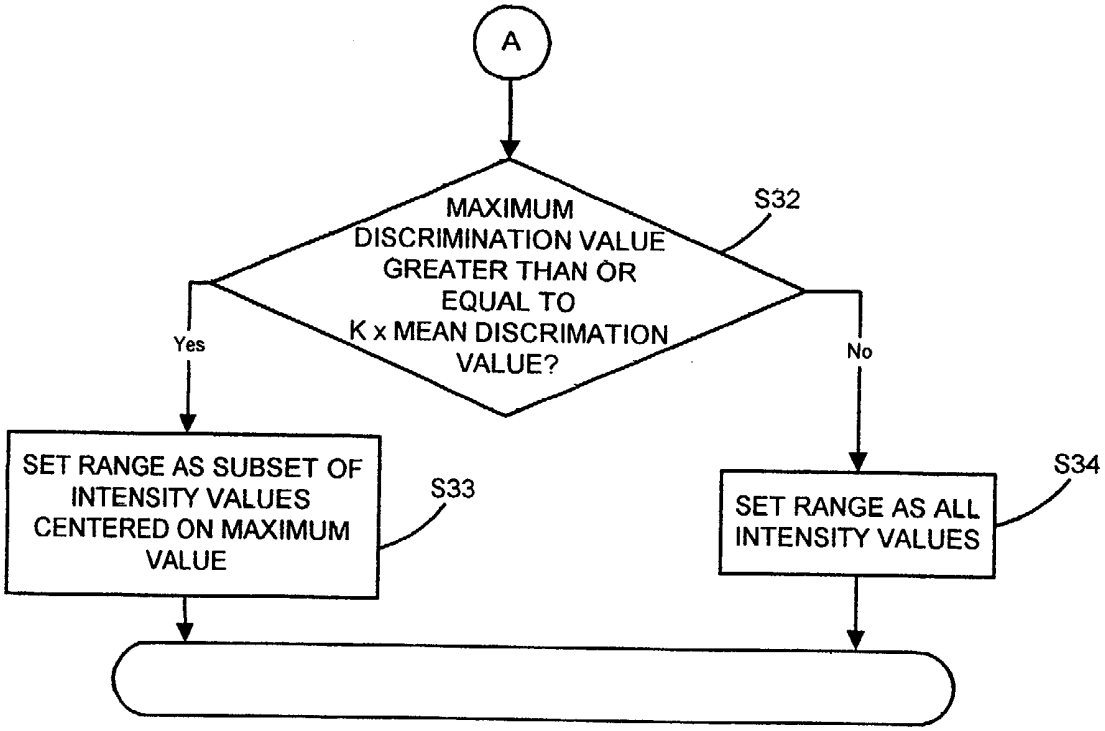
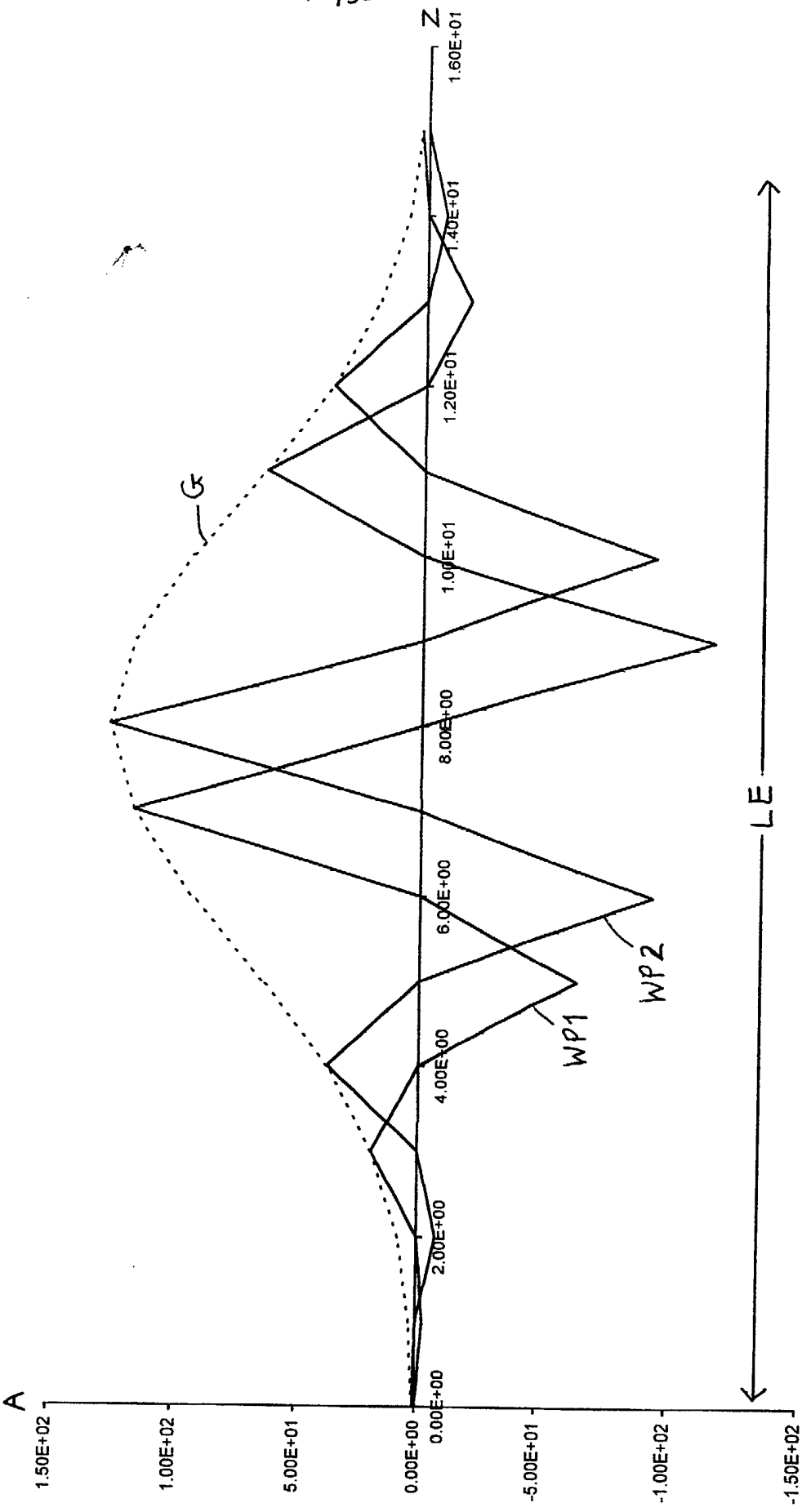


FIG. 11

FIG. 12


A
Z
1.50E+02
1.00E+02
5.00E+01
0.00E+00
-5.00E+01
-1.00E+02
-1.50E+02
0.00E+00
2.00E+00
4.00E+00
6.00E+00
8.00E+00
1.00E+01
1.20E+01
1.40E+01
1.60E+01
G
WP1
WP2
LE

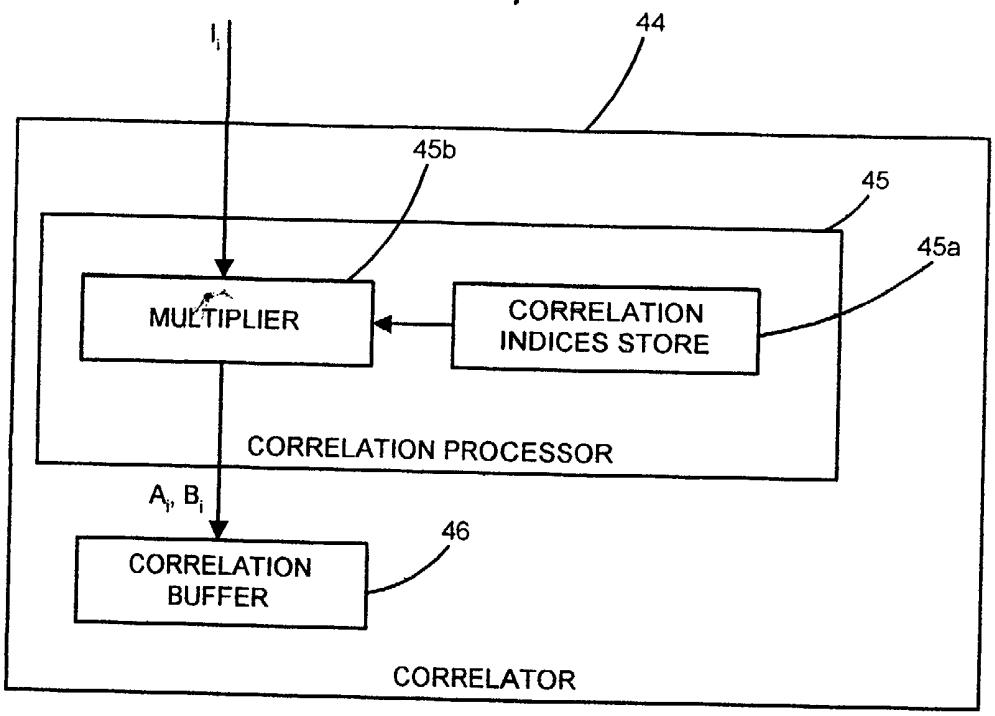

I_i
44
45b
45
45a
MULTIPLIER
CORRELATION INDICES STORE
CORRELATION PROCESSOR
A_i, B_i
46
CORRELATION BUFFER
CORRELATOR

FIG. 13

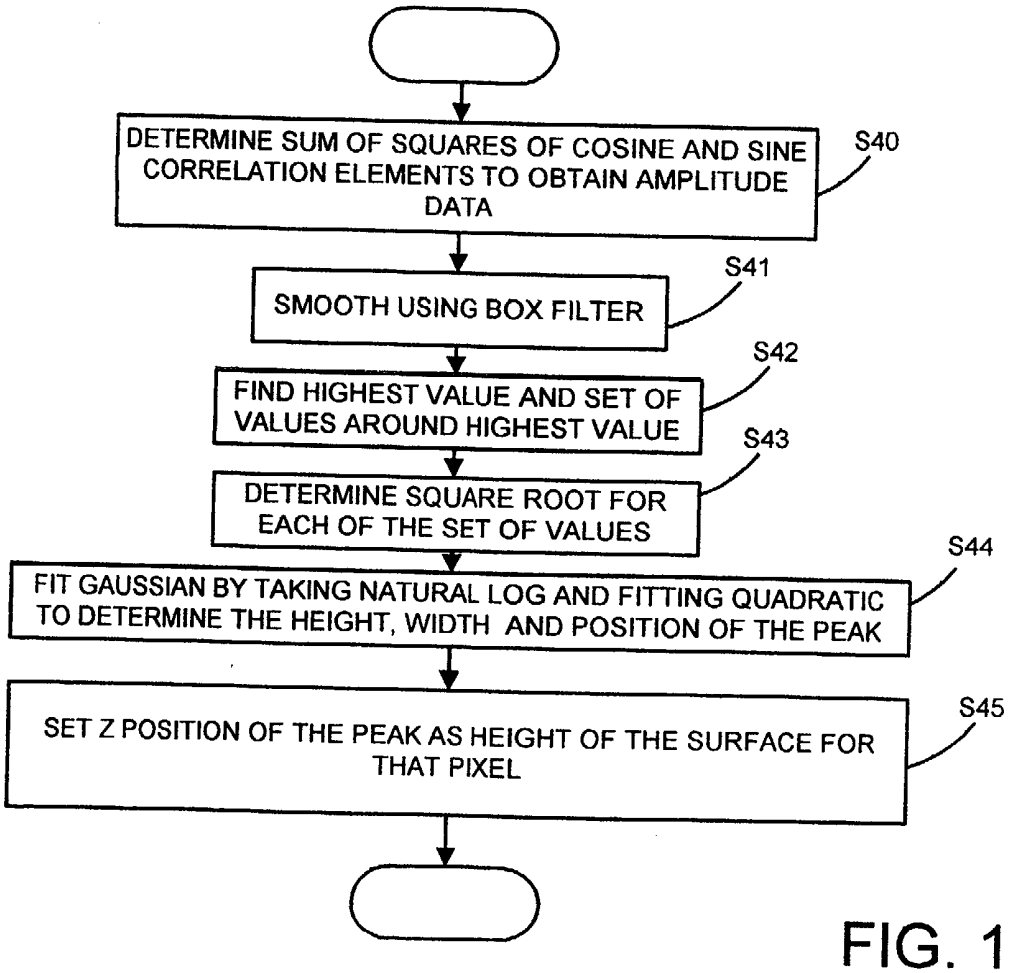

DETERMINE SUM OF SQUARES OF COSINE AND SINE CORRELATION ELEMENTS TO OBTAIN AMPLITUDE DATA
S40
SMOOTH USING BOX FILTER
S41
FIND HIGHEST VALUE AND SET OF VALUES AROUND HIGHEST VALUE
S42
DETERMINE SQUARE ROOT FOR EACH OF THE SET OF VALUES
S43
FIT GAUSSIAN BY TAKING NATURAL LOG AND FITTING QUADRATIC TO DETERMINE THE HEIGHT, WIDTH AND POSITION OF THE PEAK
S44
SET Z POSITION OF THE PEAK AS HEIGHT OF THE SURFACE FOR THAT PIXEL
S45

FIG. 14

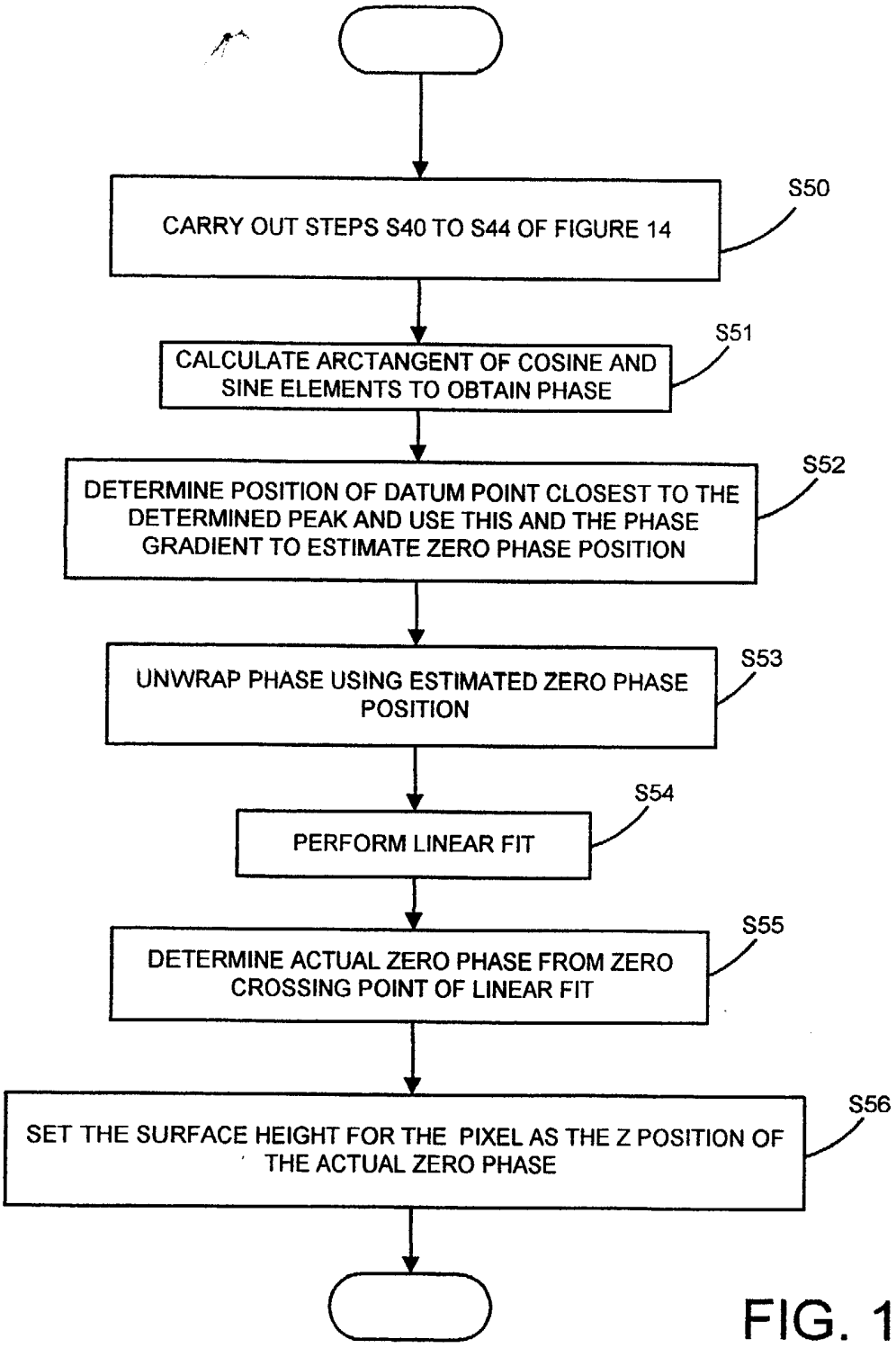

CARRY OUT STEPS S40 TO S44 OF FIGURE 14
S50
CALCULATE ARCTANGENT OF COSINE AND SINE ELEMENTS TO OBTAIN PHASE
S51
DETERMINE POSITION OF DATUM POINT CLOSEST TO THE DETERMINED PEAK AND USE THIS AND THE PHASE GRADIENT TO ESTIMATE ZERO PHASE POSITION
S52
UNWRAP PHASE USING ESTIMATED ZERO PHASE POSITION
S53
PERFORM LINEAR FIT
S54
DETERMINE ACTUAL ZERO PHASE FROM ZERO CROSSING POINT OF LINEAR FIT
S55
SET THE SURFACE HEIGHT FOR THE PIXEL AS THE Z POSITION OF THE ACTUAL ZERO PHASE
S56

FIG. 15

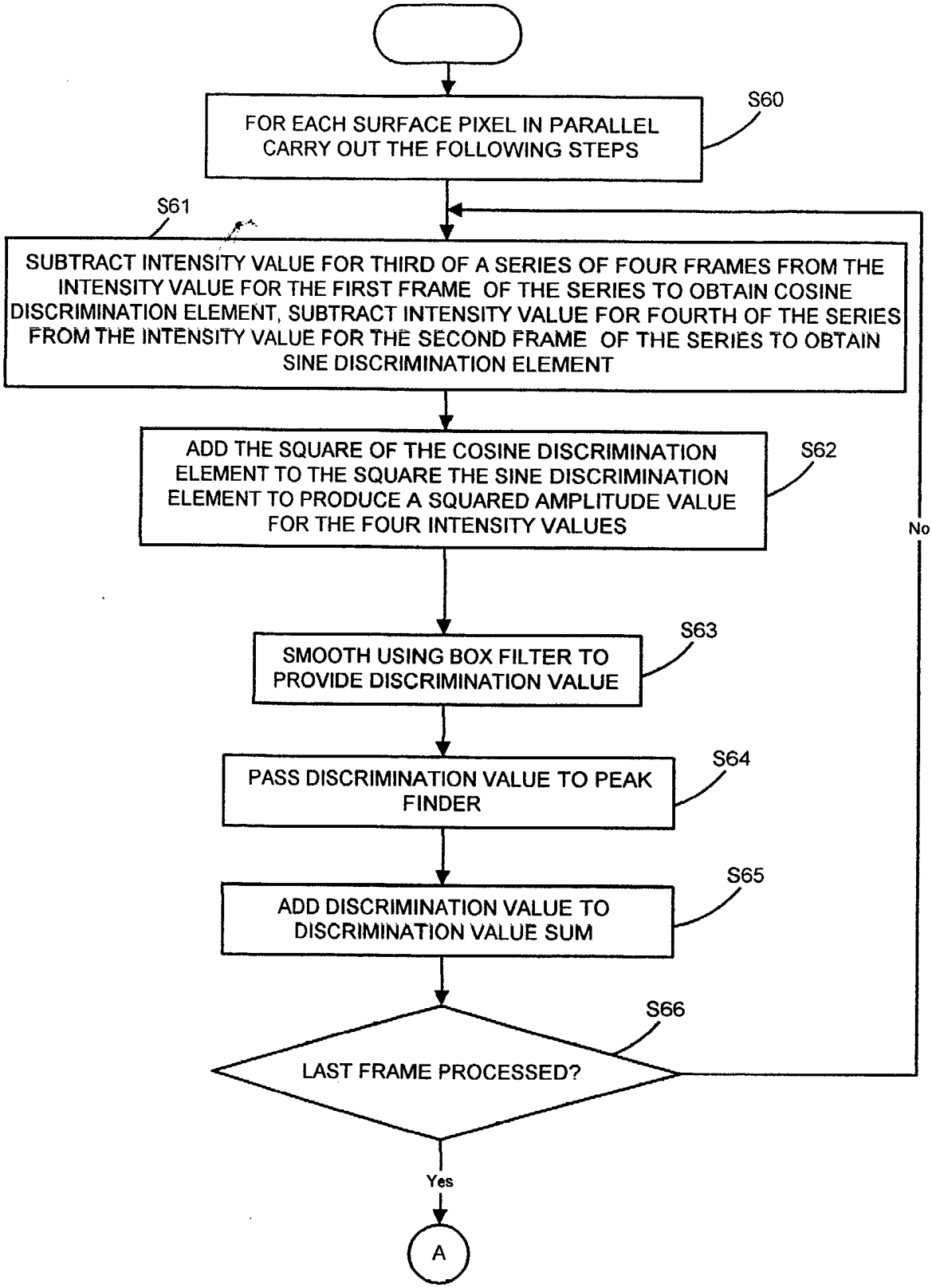
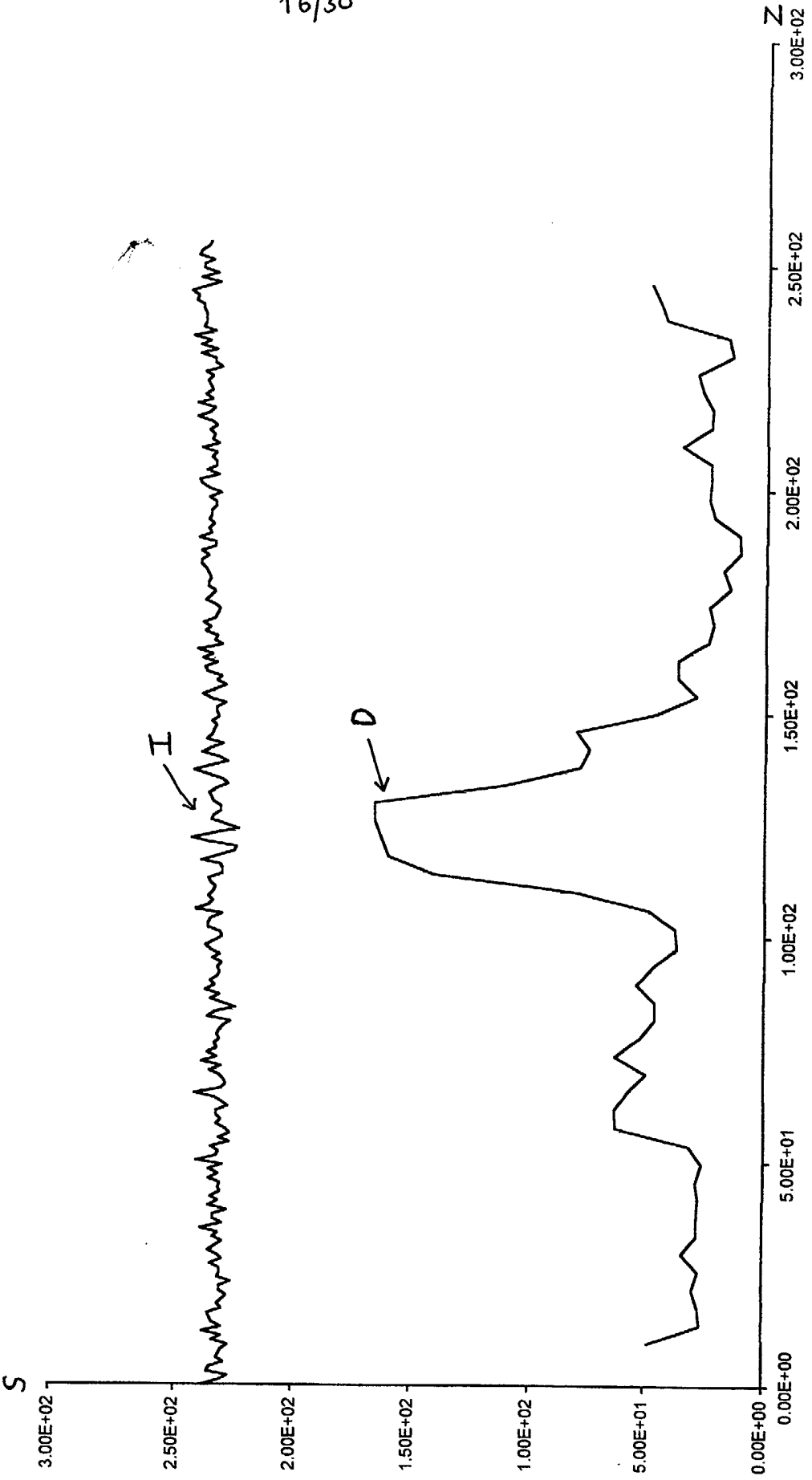

FOR EACH SURFACE PIXEL IN PARALLEL CARRY OUT THE FOLLOWING STEPS
S60
S61
SUBTRACT INTENSITY VALUE FOR THIRD OF A SERIES OF FOUR FRAMES FROM THE INTENSITY VALUE FOR THE FIRST FRAME OF THE SERIES TO OBTAIN COSINE DISCRIMINATION ELEMENT, SUBTRACT INTENSITY VALUE FOR FOURTH OF THE SERIES FROM THE INTENSITY VALUE FOR THE SECOND FRAME OF THE SERIES TO OBTAIN SINE DISCRIMINATION ELEMENT
ADD THE SQUARE OF THE COSINE DISCRIMINATION ELEMENT TO THE SQUARE THE SINE DISCRIMINATION ELEMENT TO PRODUCE A SQUARED AMPLITUDE VALUE FOR THE FOUR INTENSITY VALUES
S62
SMOOTH USING BOX FILTER TO PROVIDE DISCRIMINATION VALUE
S63
PASS DISCRIMINATION VALUE TO PEAK FINDER
S64
ADD DISCRIMINATION VALUE TO DISCRIMINATION VALUE SUM
S65
LAST FRAME PROCESSED?
S66
No
Yes
A

FIG. 16

FIG. 16a


S
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
I
D
0.00E+00
5.00E+01
1.00E+02
1.50E+02
2.00E+02
2.50E+02
3.00E+02
Z

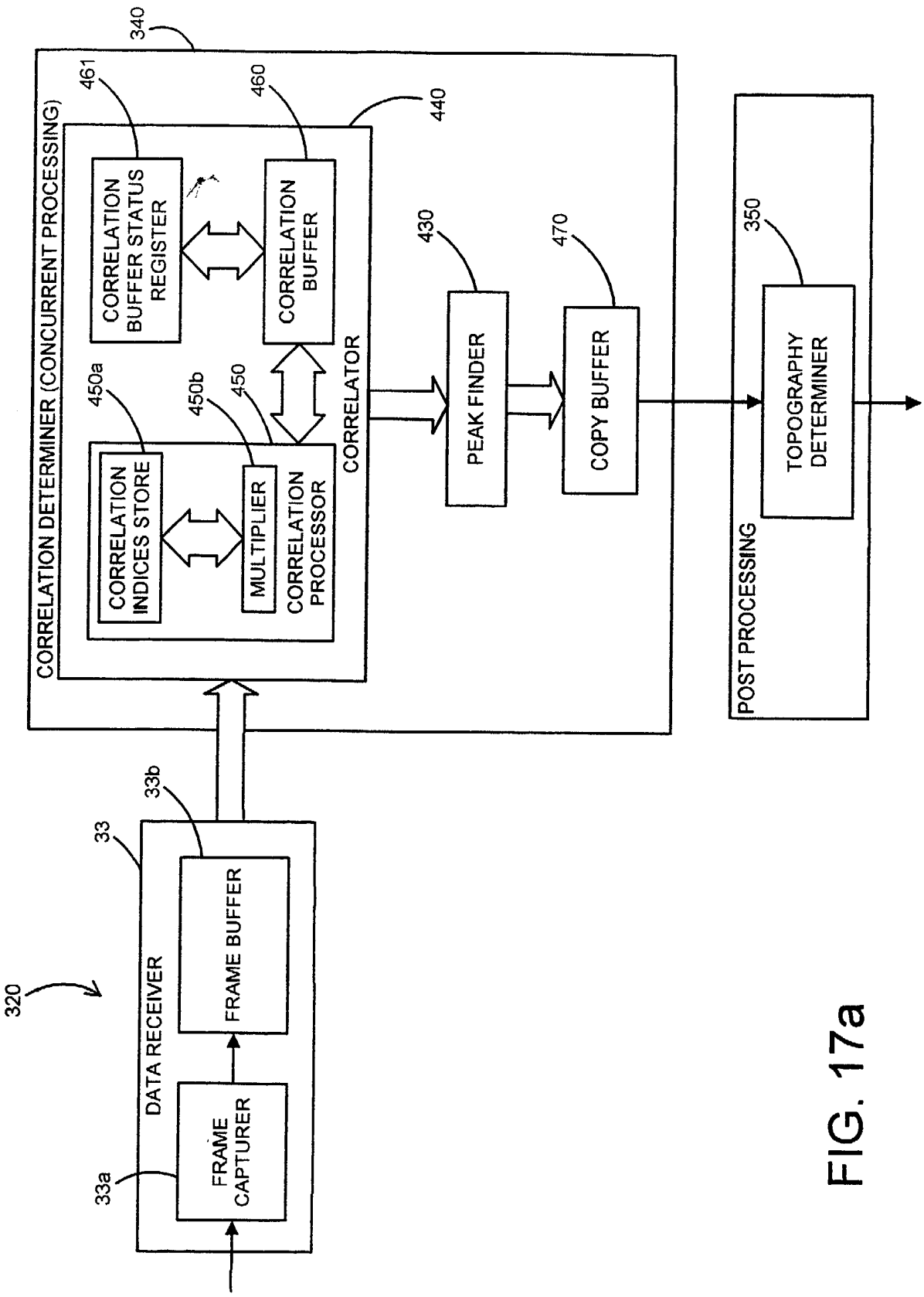

320
DATA RECEIVER
FRAME CAPTURER
FRAME BUFFER
33
33a
33b
CORRELATION DETERMINER (CONCURRENT PROCESSING)
340
CORRELATOR
440
CORRELATION BUFFER STATUS REGISTER
461
CORRELATION BUFFER
460
CORRELATION PROCESSOR
450
CORRELATION INDICES STORE
450a
MULTIPLIER
450b
PEAK FINDER
430
COPY BUFFER
470
POST PROCESSING
350
TOPOGRAPHY DETERMINER

FIG. 17a

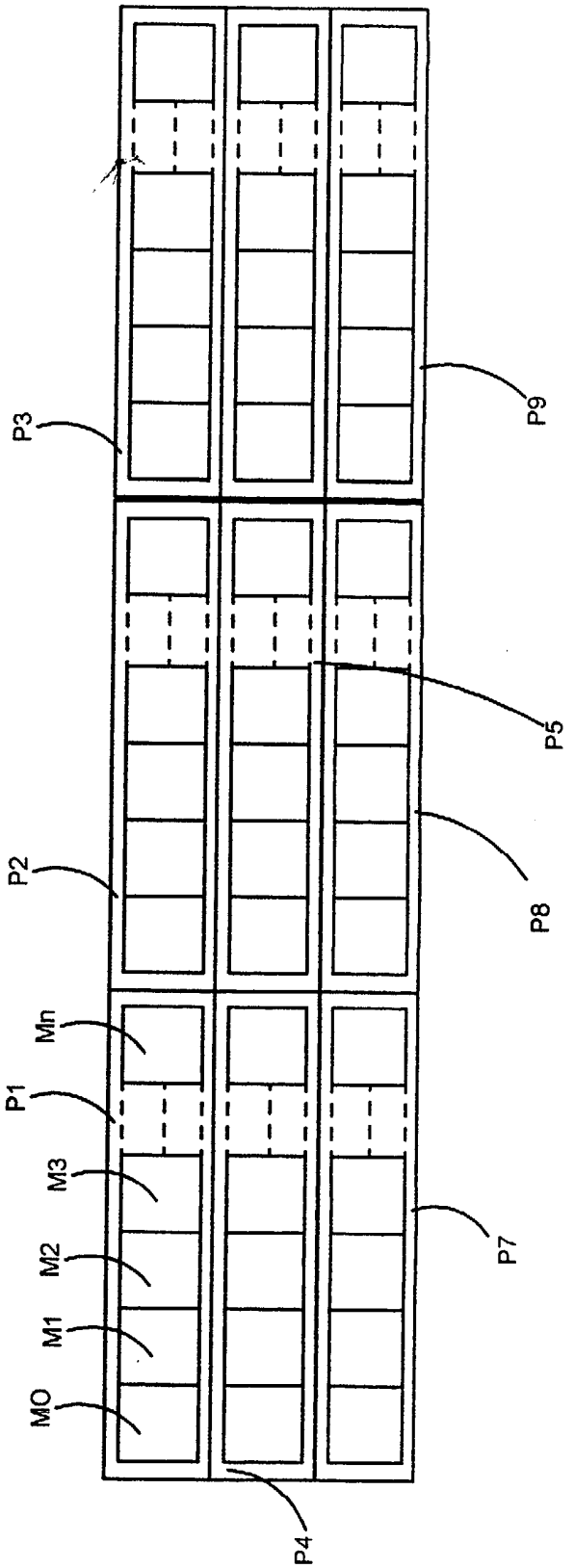


FIG. 17b

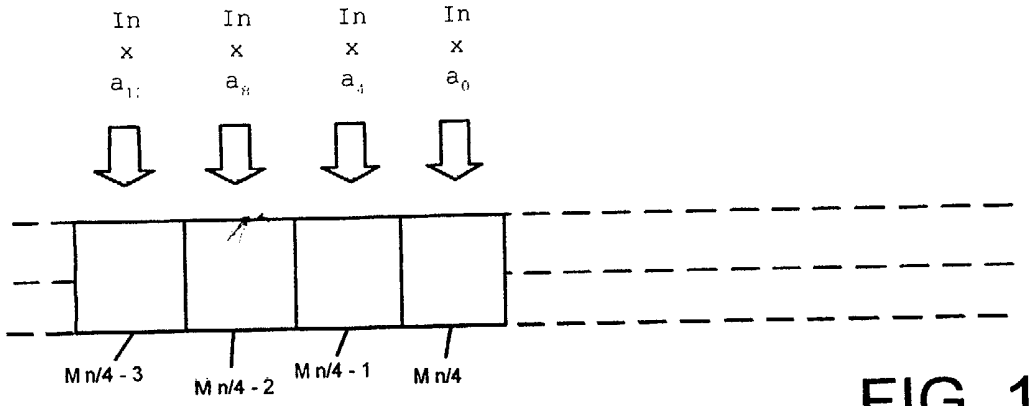


FIG. 18a

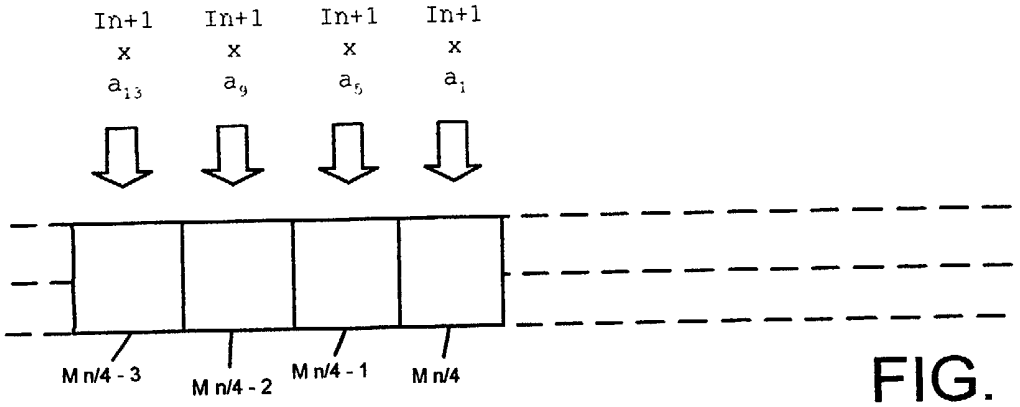


FIG. 18b

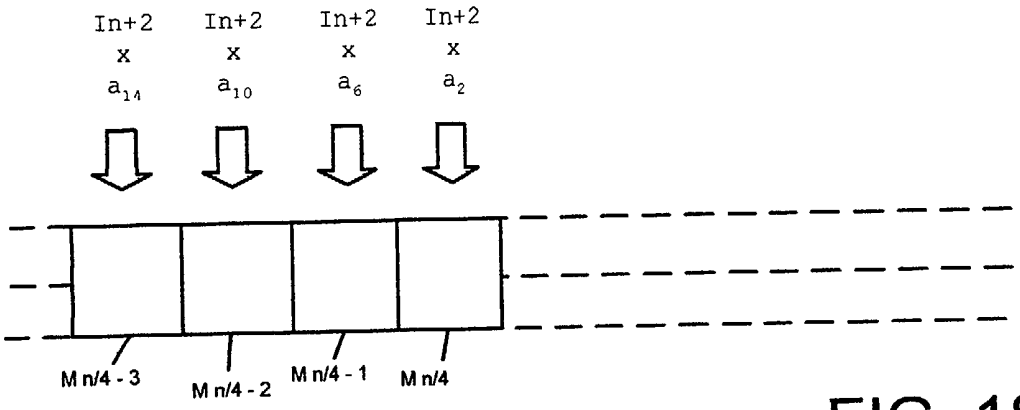


FIG. 18c

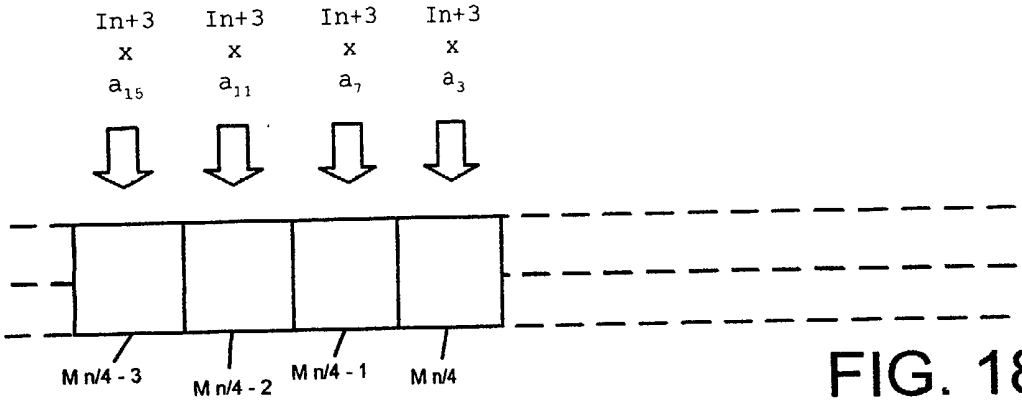


FIG. 18d

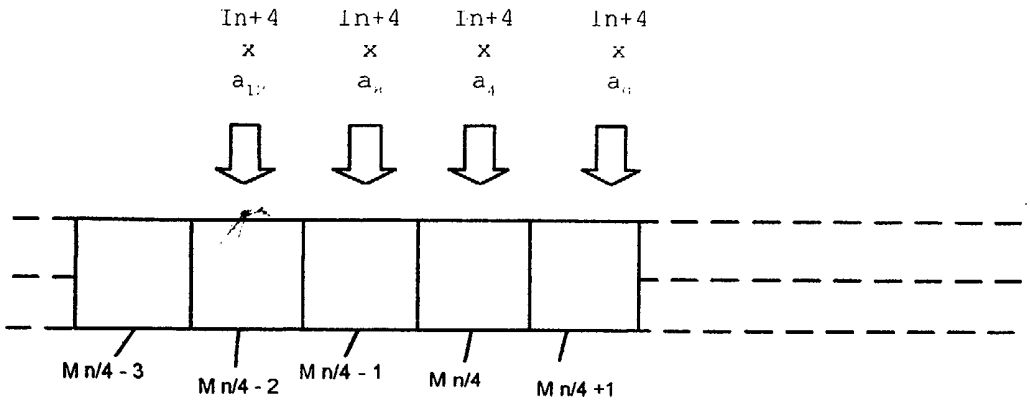


FIG. 18e

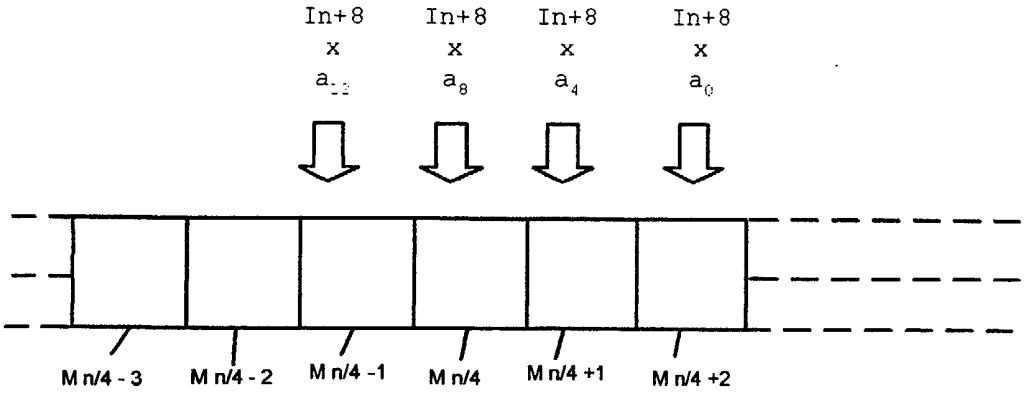


FIG. 18f

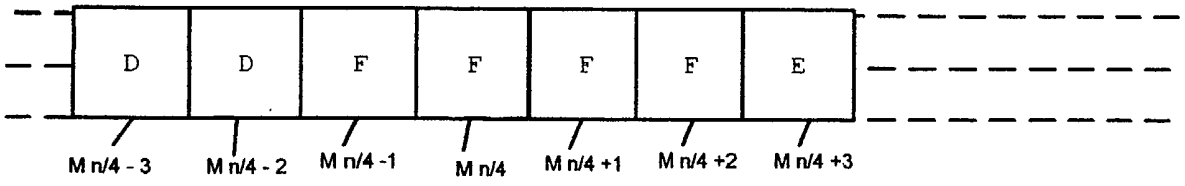


FIG. 18g

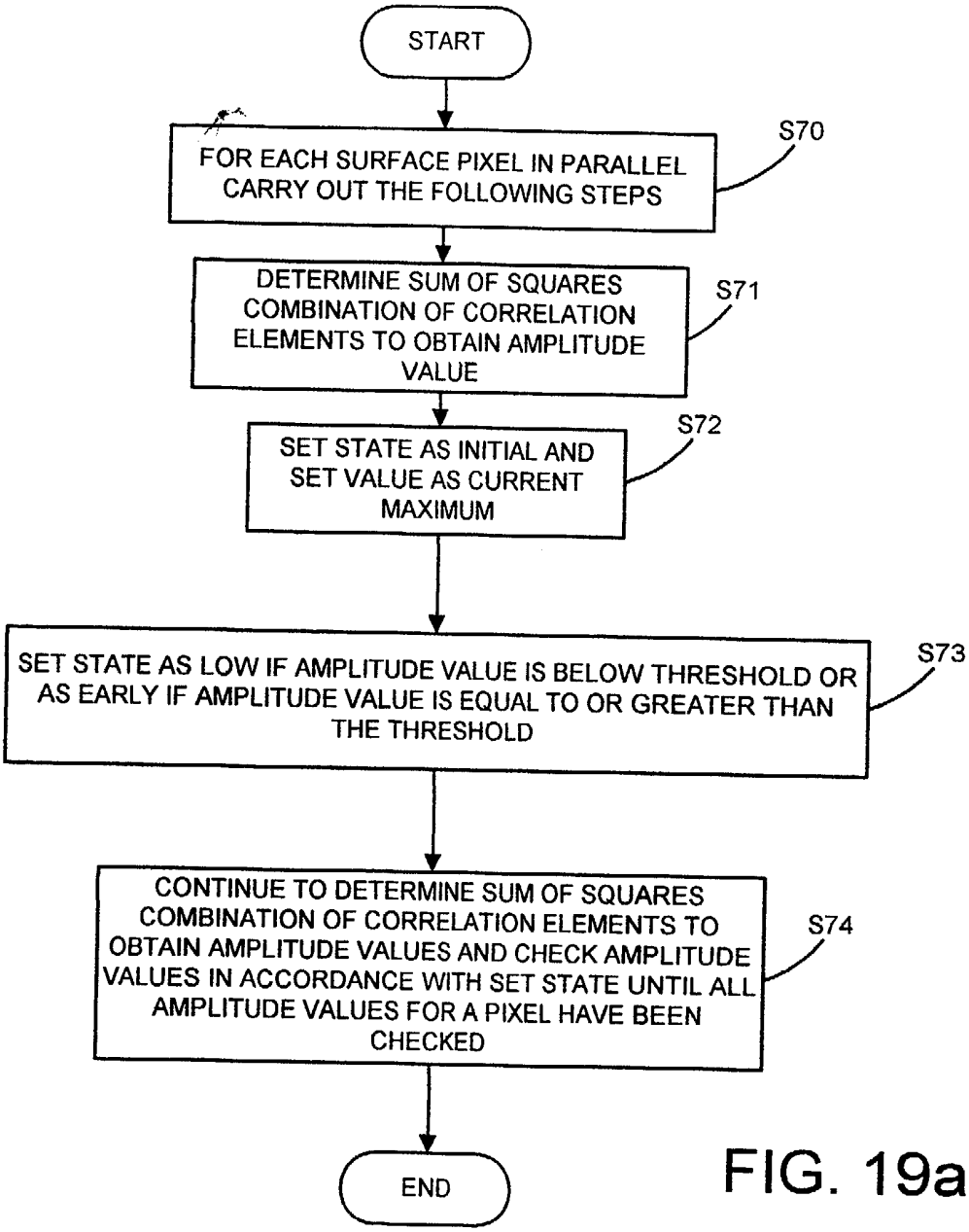

START
FOR EACH SURFACE PIXEL IN PARALLEL CARRY OUT THE FOLLOWING STEPS
S70
DETERMINE SUM OF SQUARES COMBINATION OF CORRELATION ELEMENTS TO OBTAIN AMPLITUDE VALUE
S71
SET STATE AS INITIAL AND SET VALUE AS CURRENT MAXIMUM
S72
SET STATE AS LOW IF AMPLITUDE VALUE IS BELOW THRESHOLD OR AS EARLY IF AMPLITUDE VALUE IS EQUAL TO OR GREATER THAN THE THRESHOLD
S73
CONTINUE TO DETERMINE SUM OF SQUARES COMBINATION OF CORRELATION ELEMENTS TO OBTAIN AMPLITUDE VALUES AND CHECK AMPLITUDE VALUES IN ACCORDANCE WITH SET STATE UNTIL ALL AMPLITUDE VALUES FOR A PIXEL HAVE BEEN CHECKED
S74
END

FIG. 19a

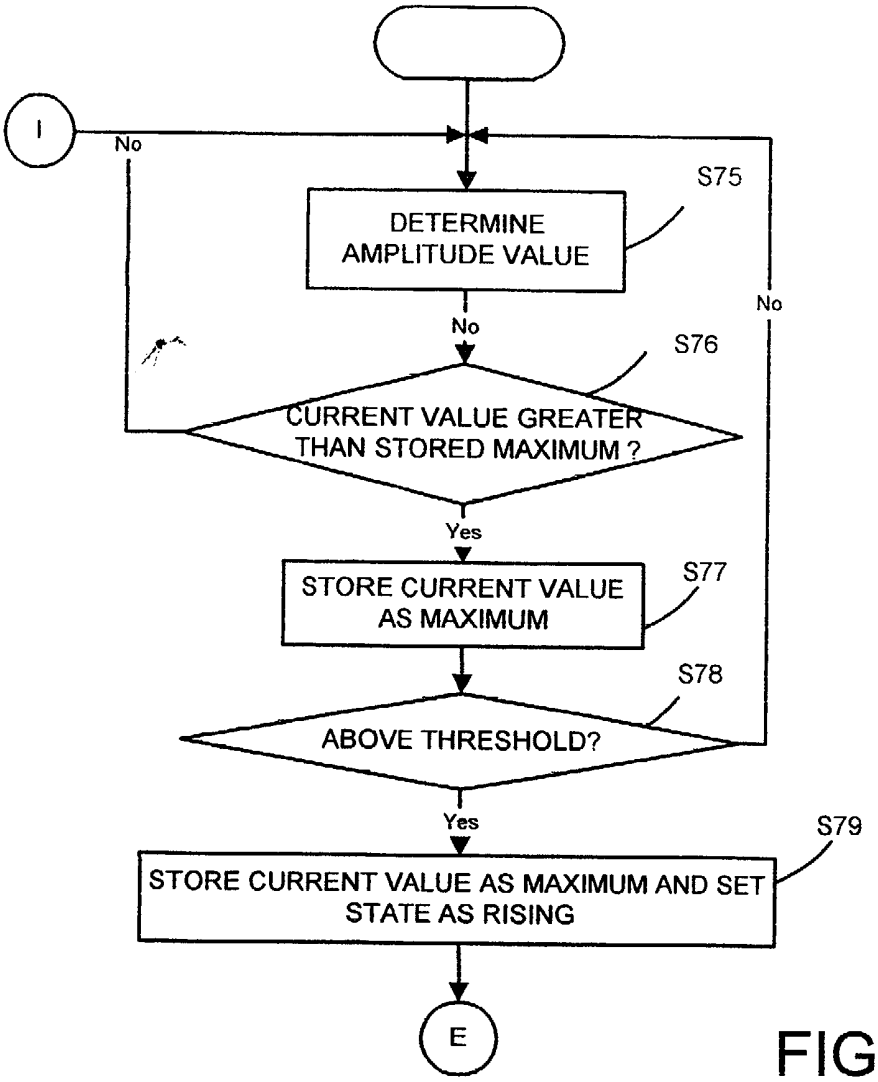


FIG. 19b

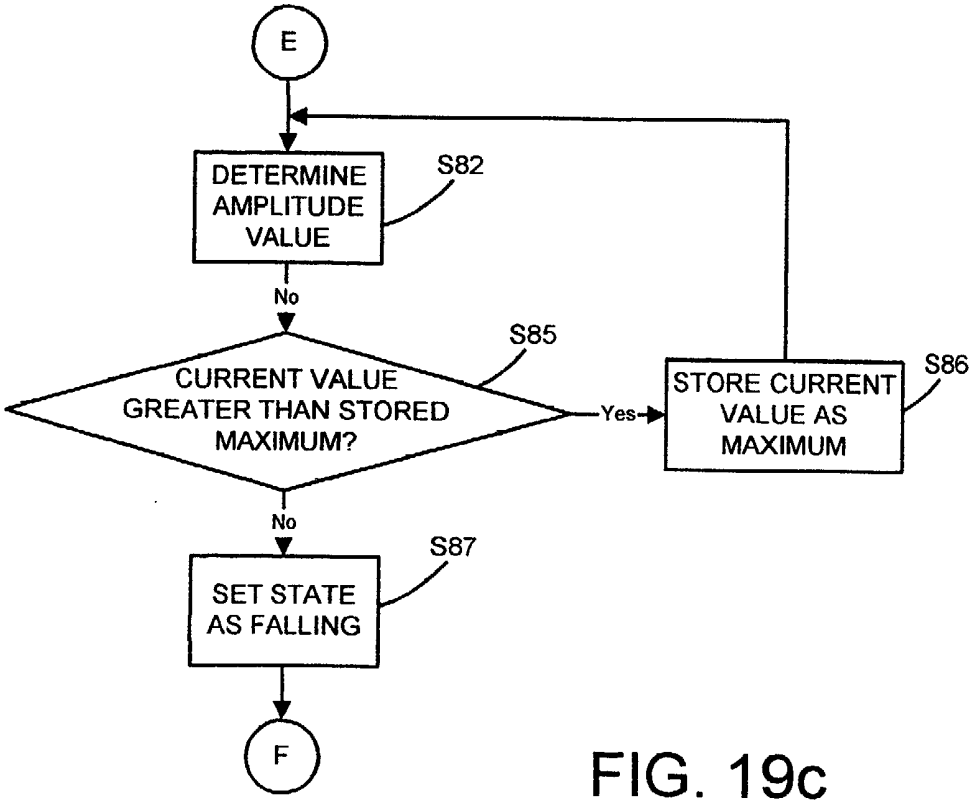


FIG. 19c

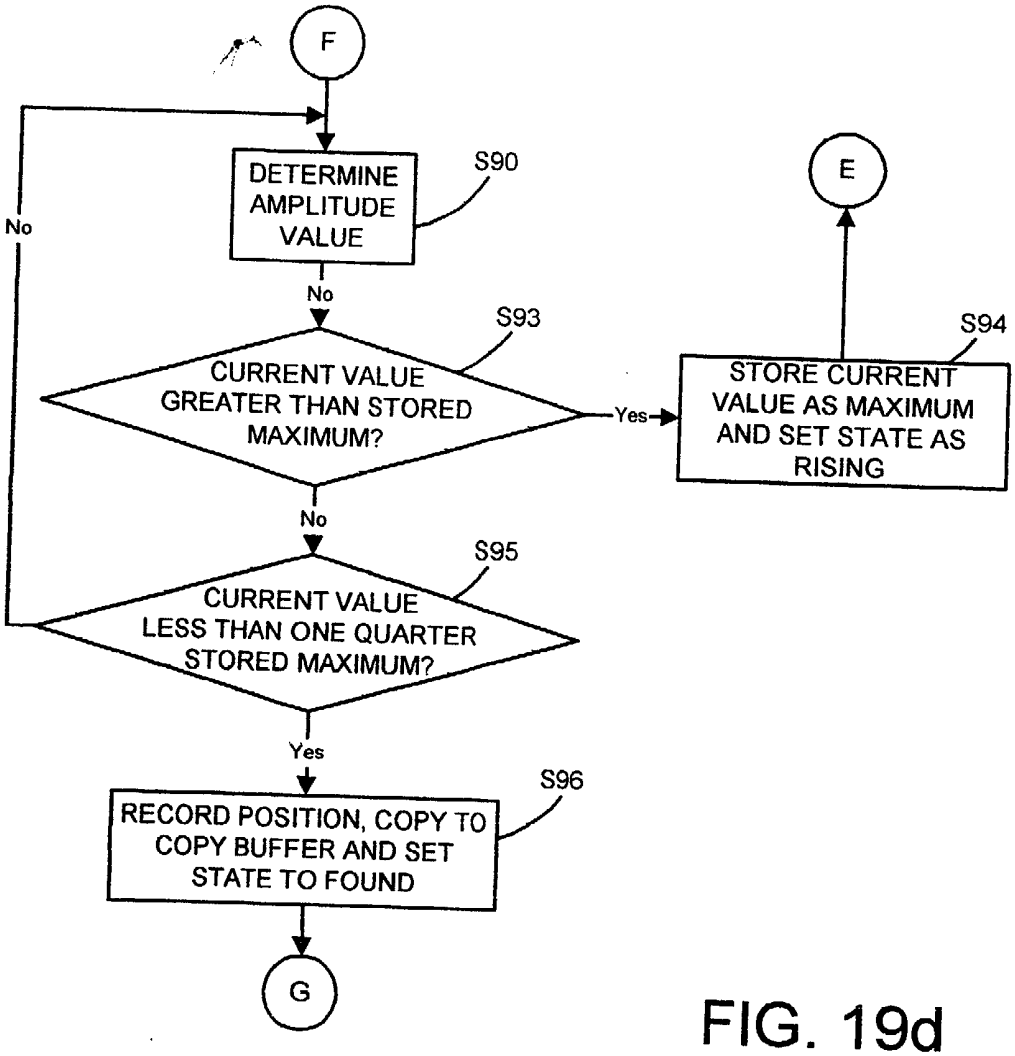

F
DETERMINE AMPLITUDE VALUE
S90
No
S93
CURRENT VALUE GREATER THAN STORED MAXIMUM?
Yes
E
S94
STORE CURRENT VALUE AS MAXIMUM AND SET STATE AS RISING
No
S95
CURRENT VALUE LESS THAN ONE QUARTER STORED MAXIMUM?
No
Yes
S96
RECORD POSITION, COPY TO COPY BUFFER AND SET STATE TO FOUND
G

FIG. 19d

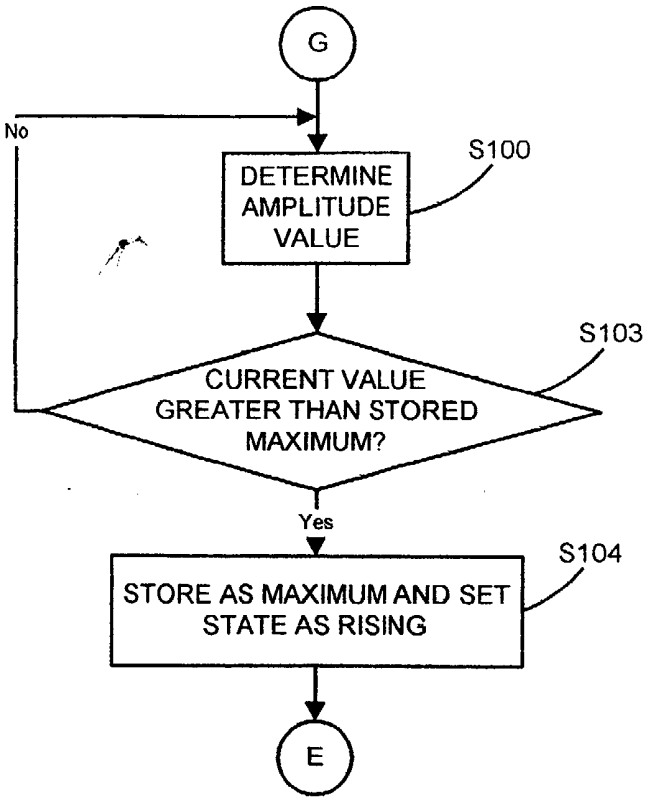


FIG. 19e

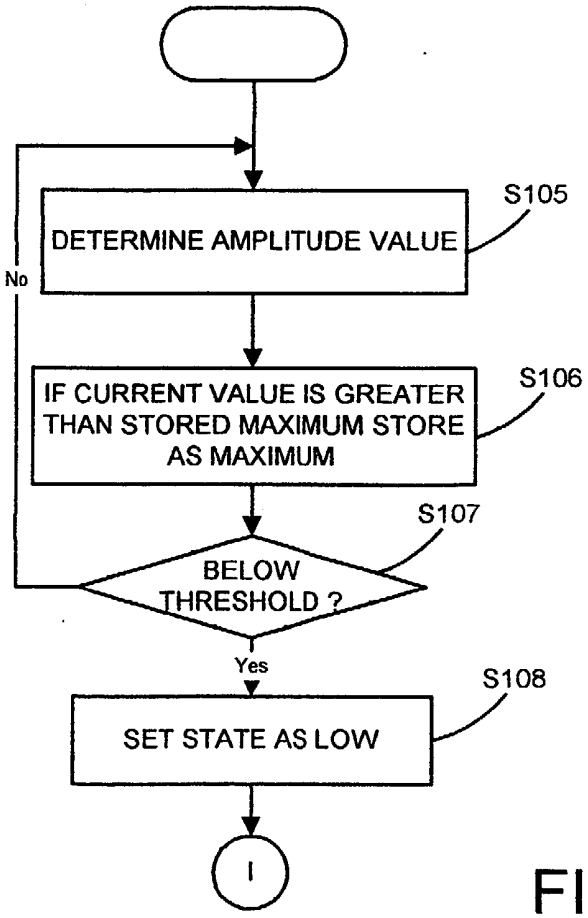


FIG. 19f

FIG. 20a

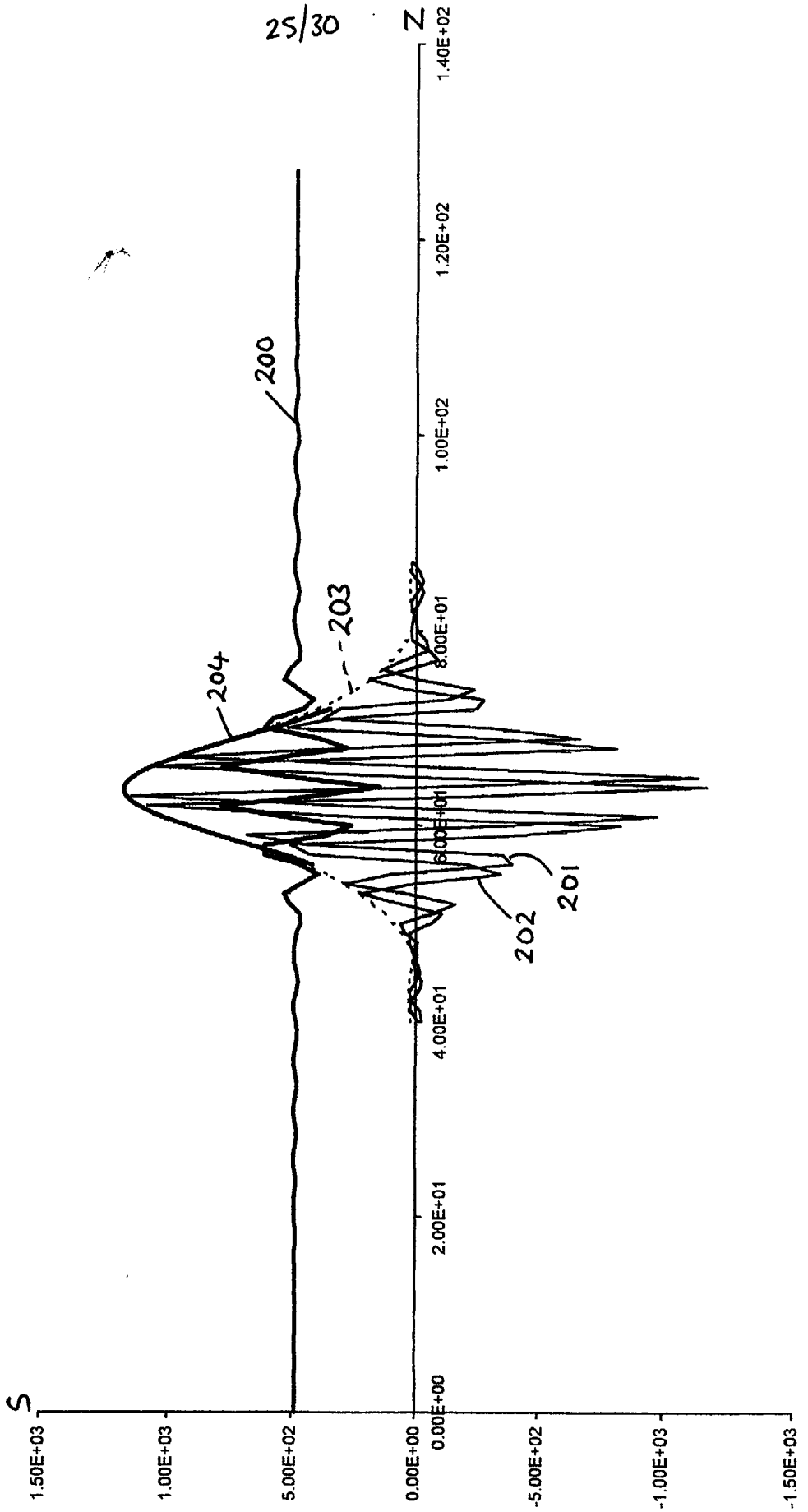

S
Z
1.50E+03
1.00E+03
5.00E+02
0.00E+00
-5.00E+02
-1.00E+03
-1.50E+03
0.00E+00
2.00E+01
4.00E+01
6.00E+01
8.00E+01
1.00E+02
1.20E+02
1.40E+02
200
203
204
202
201

FIG. 20b

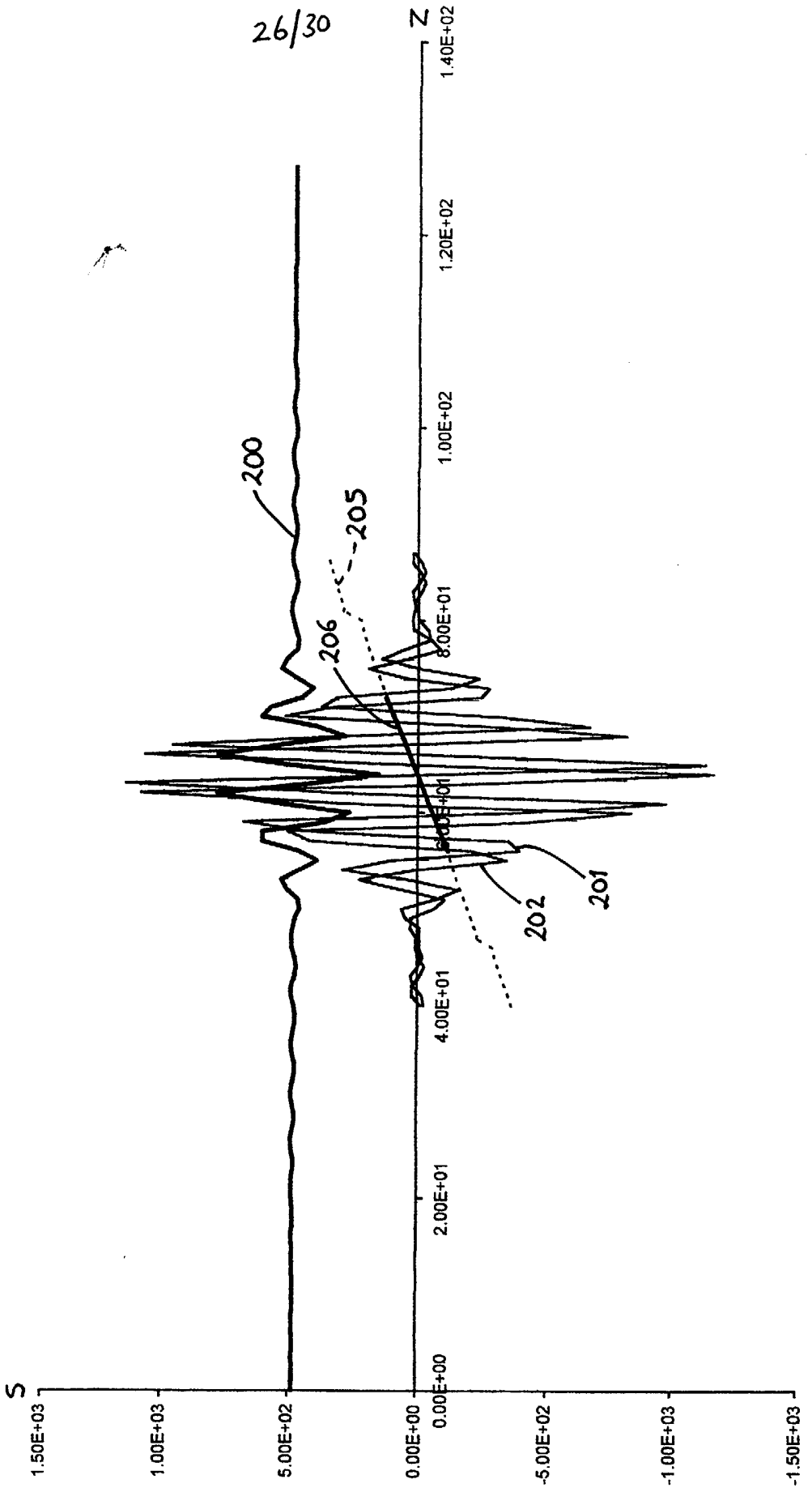

S
1.50E+03
1.00E+03
5.00E+02
0.00E+00
-5.00E+02
-1.00E+03
-1.50E+03
Z
1.40E+02
1.20E+02
1.00E+02
8.00E+01
4.00E+01
2.00E+01
0.00E+00
200
205
206
201
202

FIG. 20c

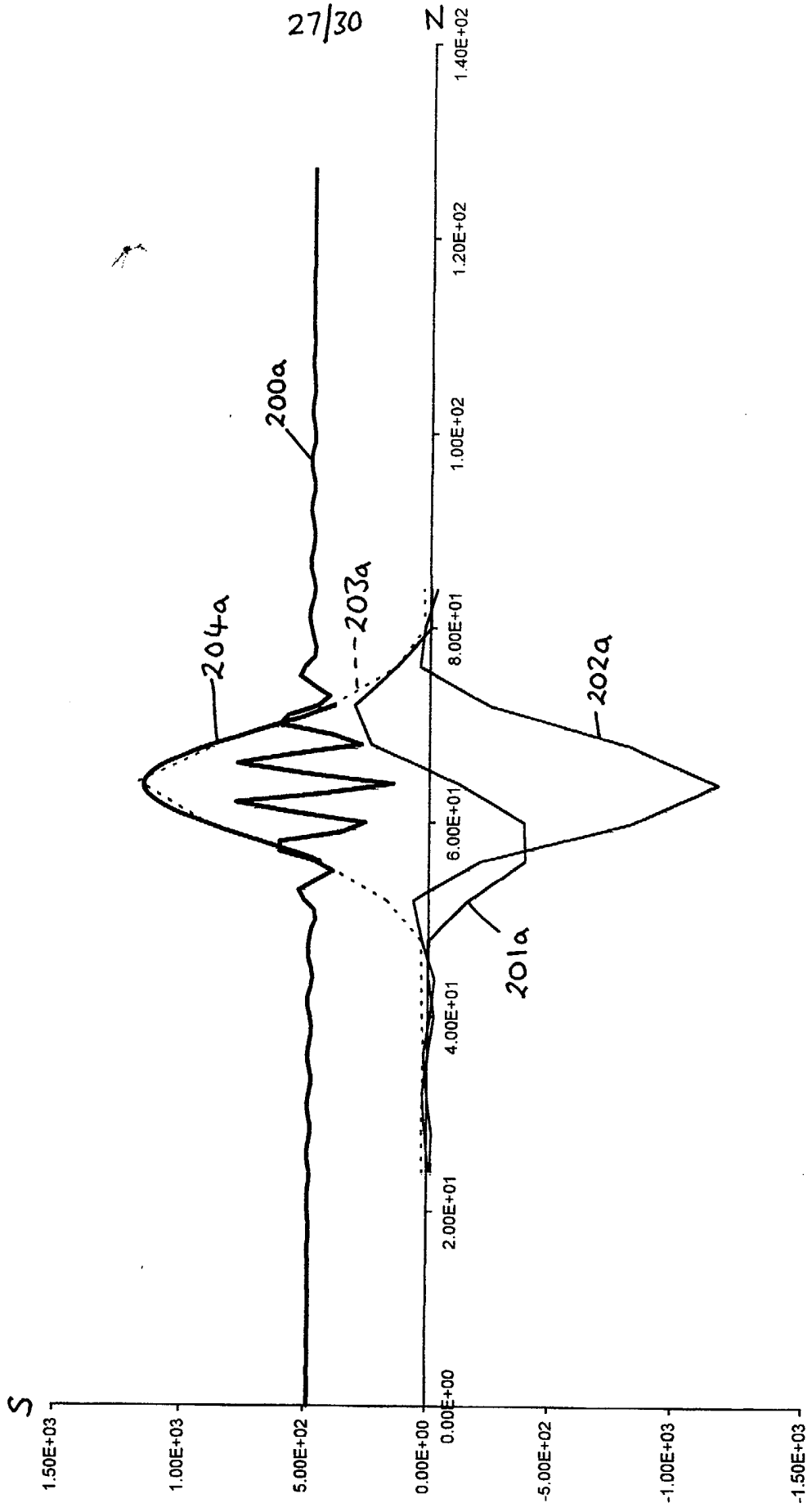

S
Z
1.50E+03
1.00E+03
5.00E+02
0.00E+00
-5.00E+02
-1.00E+03
-1.50E+03
0.00E+00
2.00E+01
4.00E+01
6.00E+01
8.00E+01
1.00E+02
1.20E+02
1.40E+02
200a
203a
204a
202a
201a

FIG. 20d

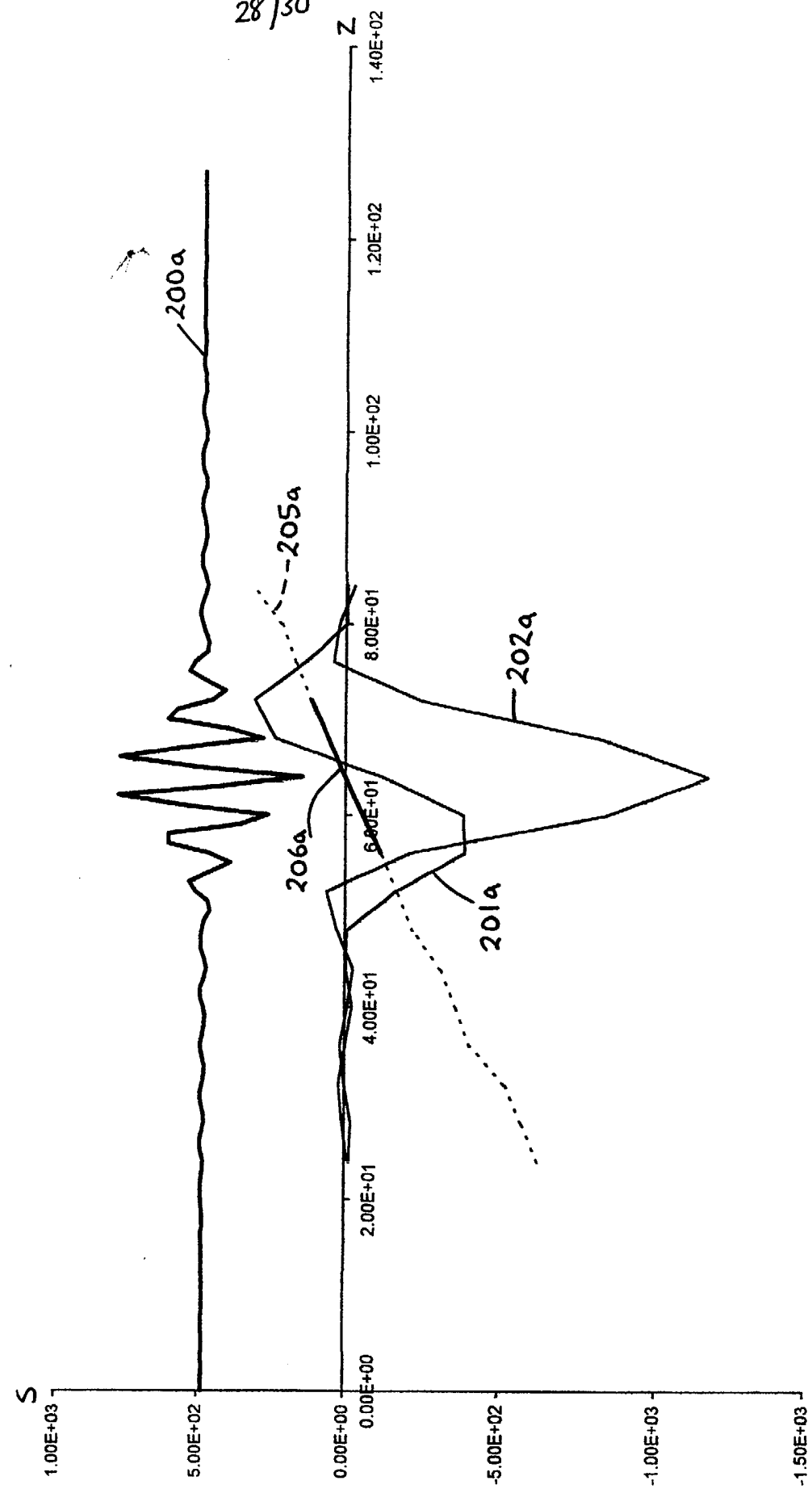

S
1.00E+03
5.00E+02
0.00E+00
-5.00E+02
-1.00E+03
-1.50E+03
Z
0.00E+00
2.00E+01
4.00E+01
6.00E+01
8.00E+01
1.00E+02
1.20E+02
1.40E+02
200a
205a
206a
202a
201a

FIG. 20e

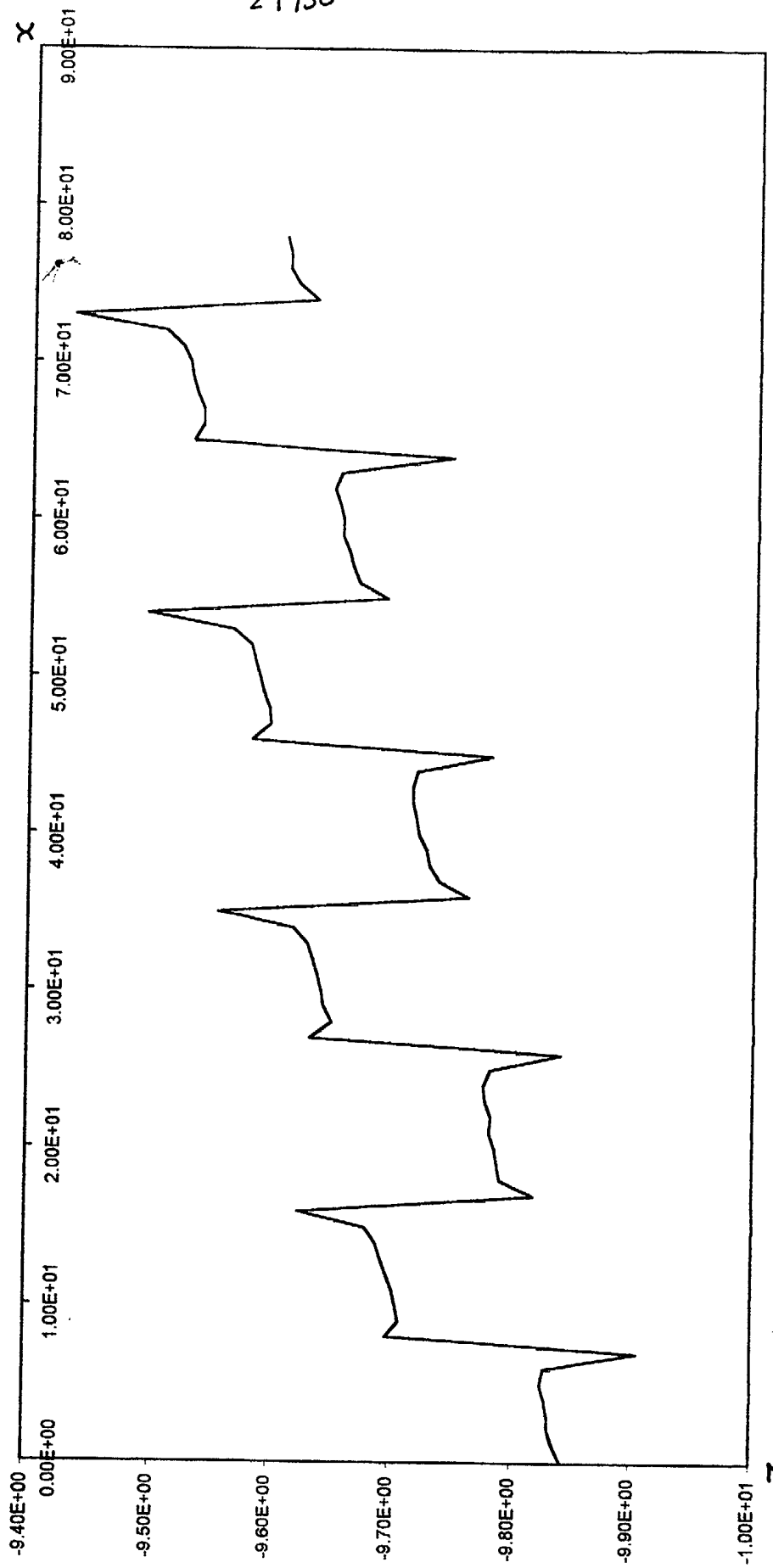
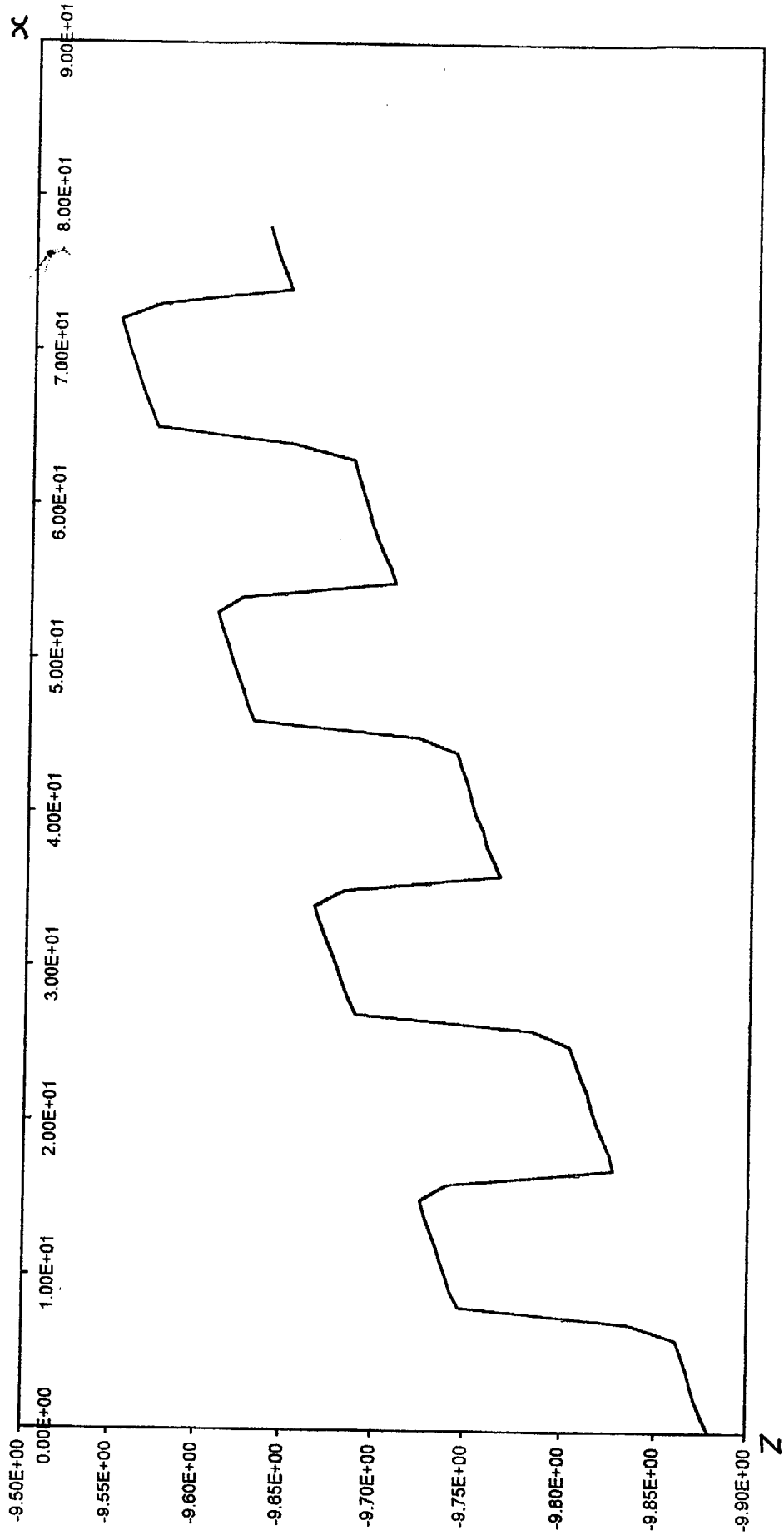

X
Z
0.00E+00
1.00E+01
2.00E+01
3.00E+01
4.00E+01
5.00E+01
6.00E+01
7.00E+01
8.00E+01
9.00E+01
-9.40E+00
-9.50E+00
-9.60E+00
-9.70E+00
-9.80E+00
-9.90E+00
-1.00E+01

FIG. 20f


X
Z
0.00E+00
1.00E+01
2.00E+01
3.00E+01
4.00E+01
5.00E+01
6.00E+01
7.00E+01
8.00E+01
9.00E+01
-9.50E+00
-9.55E+00
-9.60E+00
-9.65E+00
-9.70E+00
-9.75E+00
-9.80E+00
-9.85E+00
-9.90E+00

SURFACE PROFILING APPARATUS

This invention relates to surface profiling apparatus, in particular surface profiling apparatus for determining surface profile data using interferometric techniques.

As discussed in a paper entitled "Profilometry with a Coherence Scanning Microscope" by Byron S. Lee and Timothy C Strand published in Applied Optics Volume 29, No. 26 10 September 1990 at pages 3784 to 3788, as manufacturing tolerances have reduced, demands have increased on optical metrology techniques for improved lateral and vertical resolution. Conventional monochromatic interferometric surface profiling apparatus offers good vertical resolution in the nanometre to Angstrom range but phase ambiguity limits the measurement range to phase shifts of less than 2π. Various techniques have been proposed to extend this measurement range including, for example, phase unwrapping, heterodyne interferometry and multi-wavelength interferometry. However, phase unwrapping generally requires a smooth continuous measurement surface if phase ambiguity errors are not to arise. Heterodyne interferometry involves mixing beams at two separate frequencies and uses the resultant beat frequency for interferometry measurements. Heterodyne interferometry has an unambiguous range based on the wavelength of the beat frequency and this range is therefore limited by the limit on how close the two frequencies used can be. Multi-wavelength interferometry produces at least two different interferometric profiles

using different wavelengths and again the unambiguous range is determined by the wavelength of the difference in frequency between the at least two wavelengths used.

As discussed in the paper by Lee and Strand, these problems can be addressed by the use of coherence scanning or broadband scanning interferometry which can provide practical measurement ranges easily exceeding hundreds of micrometres.

Coherence scanning or broadband scanning interferometry uses a standard interferometer such as a Michelson interferometer with a broadband spatially incoherent light source such as a quartz halogen lamp. Generally, but not necessarily, the broadband source will be a white light source. One of the sample surface whose profile is to be determined and the reference mirror of the interferometer is moved relative to the other along a scan path to change the relative path length and a two dimensional image sensor such as a CCD camera is used to sense the resulting interference pattern which changes as the sample surface and reference mirror are moved relative to one another.

Each sensing element or pixel of the image sensor senses the portion of the interference pattern for a corresponding region or surface pixel of the sample surface and, as the sample surface and the reference mirror are moved relative to one another, the amount or intensity of light received by the sensing element will

vary in accordance with the change in the interference fringes. The intensity of light received from a region of the sample surface will increase or decrease in amplitude in dependence upon the path length difference between the light paths from the reference mirror and the sensing surface and will have a coherence peak or extremum (maximum or minimum amplitude) at the position of zero path difference. Where different regions of the surface have different relative heights, then those different regions will have coherence peaks at different positions along the scan path. Accordingly, the relative positions of the coherence peaks can be used to provide surface profile data, that is data representing the relative height of the different regions of the sample surface.

In one aspect, the present invention provides surface profiling apparatus having a broadband scanning interferometer and a data processor for locating the coherence peak in the interference fringes produced for a region of a sample surface on-the-fly by multiplying at least some of the set of signals representing the interference fringes for that region as they are received by a correlation function to produce a set of correlation signals for that region and then identifying the coherence peak in the interference fringes for that region with the highest peak in the set of correlations signals for that region.

In one aspect, the present invention provides surface profiling apparatus having a broadband scanning interferometer and a data processor for locating the coherence peak in the interference fringes produced for a region of a sample surface by determining a sub-set of the signals likely to contain a coherence peak on-the-fly as the signals representing the interference fringes are received, and subsequently applying a correlation function to the signals of the sub-set to produce a set of correlation signals and using the correlation signals to identify the coherence peak.

In an embodiment, the correlation function comprises two reference wave packets that together have an amplitude and phase variation. In an embodiment, the reference wave packets are represented as a Gaussian envelope modulated by cosine and sine waves.

In an embodiment, the two reference wave packets are stored as an array of pairs.

In an embodiment, the position of the peak in the set of correlations signals is set as the height of the surface for that surface region. The peak may be found by fitting a Gaussian to the set of correlation signals.

As described above, the position of the peak in a set of correlation signals is set as the surface height for that region. In another embodiment or additionally, phase data in the correlation signals is used to determine the

position of a predetermined phase, for example zero phase, which is then used to determine the height data.

In another aspect, the present invention provides surface profiling apparatus that comprises a broadband scanning interferometer having control means for controlling triggering of sensing means of the interferometer in accordance with position data obtained from moving means for effecting relative movement between the sample surface and the reference of the interferometer so that the interference patterns are sensed at intervals determined in accordance with the position data. In this case, the moving means effects continuous movement. Alternatively, stepped movement may be effected.

In another aspect, the present invention provides a surface profiling apparatus having a broadband scanning interferometer having sensing means comprising a 2D array of sensing pixels arranged to receive light from an area larger than the area of the sample surface that is of interest and control means for processing the signals by doing at least one of combining the signals sensed by two or more adjacent pixels and selecting only a subset of the sensing pixels for use. This enables the range from maximum field of view to maximum lateral resolution to be covered without the need for a zoom lens or the provision of extra lenses to magnify or demagnify the image.

In another embodiment, the present invention provides surface profiling apparatus having a broadband scanning interferometer and a datum providing means for relating height and gradient data obtained for one area of a sample surface to that obtained for another area of a sample surface to enable surface profile data to be obtained over a sample surface area larger than the area that can be imaged by the sensing means of the interferometer by combining surface profile data obtained from surface profile measurements on different areas of the sample surface.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a schematic block diagram of a surface profiling apparatus using a broadband scanning interferometer;

Figure 2 shows a graph of intensity against position Z to illustrate the interference fringes for a sample surface region around a coherence peak;

Figure 3 shows a functional block diagram of surface profiling apparatus;

Figure 4 shows a simplified side-elevational, part sectional view of the surface profiling apparatus shown in Figure 3 but excluding the control apparatus;

Figure 5 shows a functional block diagram of computing apparatus that may be configured to provide the control apparatus shown in Figure 3;

Figure 6 shows a diagram illustrating one example of an interferometer that may be used in the surface profiling apparatus;

Figure 7 shows a functional block diagram of one example of a data processor shown in Figure 3;

Figure 8 shows schematic representations of frames of data provided by an image sensor of the interferometer;

Figure 9 shows a flow chart for illustrating steps carried out by one example of a discriminator shown in Figure 7;

Figures 10a to 10d show flow charts for illustrating steps carried out by a peak finder shown in Figure 7;

Figure 11 shows a flow chart for illustrating further steps carried out by the discriminator shown in Figure 7;

Figure 12 shows a graphical representation of a correlation function used by a correlator shown in Figure 7;

Figure 13 shows a functional block diagram of the correlator shown in Figure 7;

Figure 14 shows a flow chart for illustrating steps carried out by a surface topography determiner shown in Figure 7;

Figure 15 shows a flow chart for illustrating further steps that may be carried out by the surface topography determiner shown in Figure 7;

Figure 16 shows a flow chart for illustrating operation of another example of a discriminator for use in the data processor shown in Figure 7;

Figure 16a shows a graph illustrating results obtained using the discriminator described with reference to Figure 16;

Figure 17a shows a functional block diagram of another example of the data processor shown in Figure 3;

Figure 17b shows a diagram for explaining the structure of a correlation buffer shown in Figure 17a;

Figures 18a to 18f show diagrams representing part of the correlation buffer for explaining the operation of a correlator shown in Figure 17a;

Figure 18g shows a diagrammatic representation of a part of a correlation buffer status store shown in Figure 17a;

Figure 19a to 19f shows flow charts for illustrating steps carried out by a peak finder shown in Figure 17a;

Figures 20a and 20b show graphs illustrating results obtained using the data processor shown in Figure 7 with Figure 20a showing determination of the Z position of the coherence peak and Figure 20b showing determination of the Z position of zero phase;

Figures 20c and 20d show graphs illustrating results obtained using the data processor shown in Figure 17a and 17b with Figure 20c showing determination of the Z position of the coherence peak and 20d showing determination of the Z position of zero phase; and

Figures 20e and 20f show graphs representing the determined surface for a 100 nanometre grating with Figure 20e showing the results obtained where the surface height is determined as the position of the coherence peak and Figure 20f showing the results obtained where

the surface height is determined as the position of zero phase.

Referring now the drawings, the basic principles of surface profile or topography determination using broadband scanning or coherent scanning interferometry techniques will first be described with reference to Figures 1 and 2.

Figure 1 shows a simplified schematic block diagram of a surface profiling apparatus 1 which consists of a broadband or coherence scanning interferometer system 2 and data processing and control apparatus 3.

The broadband scanning interferometer system 2 is based on a conventional interferometer but, as discussed in the introduction, instead of having a monochromatic spatially coherent light source, the broadband scanning interferometer system 2 has a broadband source 4 which may be, for example, a white light source such as a quartz halogen lamp coupled to a regulated DC power supply.

The broadband source 4 provides broadband light L which is split by a beam splitter (illustrated as a single beam splitting prism) 5 into a first light beam which is directed along a reference path RP towards a reference mirror 6 and a second light beam which is directed along a sample path SP towards a surface 7 of a sample 8 mounted on a sample support stage 9. Light reflected

from the reference mirror 6 returns along the reference path RP to the beam splitter 5 where it interferes with light reflected from the sample surface 7 back along the sample path SP. As the interferometer is an imaging interferometer it will also include at least one focussing element (not shown in Figure 1) for focussing the image onto the detector. Typically, the interferometer may have a configuration such as a Mirau, Michelson or Linnik configuration.

A detector 10 senses the resulting interference pattern. In this embodiment, the detector 10 has a 2D (two-dimensional) image sensing array. Each individual sensing element of the 2D sensing array of the detector 10 detects the portion of the interference pattern produced by a corresponding region or pixel of the area of the sample surface 7 falling within the field of view of the detector 10. In this example, the detector 10 is a CCD (Charge Coupled Device) camera, for example, a Vosskühler GmbH:CCD 1300 CCD camera.

A motion controller 11 is provided to effect relative movement between the sample surface 7 and the reference mirror 6 so as to change the difference in the lengths of the paths travelled by light reflected from the reference mirror 6 and light reflected from the sample surface 7. As shown in Figure 1, the motion controller 11 is arranged to move the reference mirror 6 along the reference path RP. This is equivalent to moving the

sample surface 7 along a scan path in the Z direction shown in Figure 1.

The detector 10 is arranged to capture or sense the light intensity (ie the interference pattern) at intervals as the reference mirror 6 is moved. In this example, the detector captures or senses the light intensity at intervals corresponding to movement of the reference mirror 6 by 75nm. 2D image or frame data representing the intensity pattern for the field of view of the detector 10 is acquired by the detector 10 at each interval.

The intensity of the illumination sensed by one sensing element of the 2D sensing array (that is the light reflected from the corresponding region or surface pixel of the sample surface 7 imaged on that sensing element) varies as the path length difference changes with movement of the reference mirror 6, resulting in a series of fringes which have a coherence peak at the position along the scan path corresponding to zero path length difference. Figure 2 shows a graph of light intensity against position Z to illustrate the change in intensity of the light sensed by a sensing element of the 2D sensing array of the detector 10 as the relative positions of the reference mirror 6 and sample surface 7 change. The envelope of the intensity distribution is the Fourier transform of the spectral distribution of wavelength in the broadband source.

As is well known in the art of surface metrology, although the surface 7 may be nominally flat, the surface may have some surface form and surface roughness so that different regions or surface pixels on the surface have different heights. The position or point along the scan path at which the coherence peak occurs will be different for surface pixels at different heights. Accordingly, the surface profile or topography of an area of a surface imaged by the detector can be determined by conducting a measurement operation during which the motion controller 11 causes effective movement along the scan path and images are captured at intervals by the detector and by analysing the results to determine the coherence peaks for each surface pixel imaged by the detector.

The data processing and control apparatus 3 has control apparatus 30 for controlling operation of the interferometer system 2. In this example, the control apparatus is associated with a user input 31 that enables a user to control operation of the control apparatus. The data processing and control apparatus 3 also has a data processor 32 for processing data provided by the detector 10 to determine the surface profile or surface topography of a surface area imaged by the detector 10 by determining, for each surface pixel imaged by the detector 10, the position along the scan path at which the coherence peak or a position having a predetermined relationship to the coherence peak (for example a

position half-way down the coherence peak curve from the actual peak) occurs.

The data processor 32 has a data receiver 33 for receiving frame data from the detector 10, a correlation determiner 34 for determining the coherence peaks by using a correlation function as will be described in greater detail below and a topography determiner 35 for determining a surface topography or profile for the surface 7 from the results supplied by the correlation determiner 34. The control apparatus 3 also has a user output 36 for providing a data output representing the results of processing by the data processor 32 of the data acquired during a measurement operation and/or messages such as error messages to a user.

One example of a surface profiling apparatus in which the interferometer has a Mirau configuration will now be described in greater detail with reference to Figures 3 to 6 in which Figure 3 shows an overall functional block diagram of the surface profiling apparatus, Figure 4 shows a simplified side elevational view of the apparatus, Figure 5 shows a block diagram of computing apparatus suitable for providing the data processing and control apparatus 3 and Figure 6 shows a more detailed diagram of the broadband scanning interferometer system 2.

Referring firstly to Figure 3, as described above, an interferometer I of the broadband scanning interferometer

system 2 has a broadband source 4, typically a quartz halogen lamp, which directs broadband light L via a beam splitter 12 to an objective lens assembly 13 which includes, in addition to an objective lens 14, the beam splitter 5 and the reference mirror 6. The beam splitter 5 splits the light beam provided by the beam splitter 12 into a first reference beam that is directed along the reference path RP (Figure 1) and a second sample beam that is directed along the sample path SP (Figure 1) from the interferometer I towards the surface 7 of the sample 8 mounted on the sample support stage 9.

In this embodiment, the beam splitter 5 is a thin film beam splitter, in particular a Herpin filter, or a neutral density partially reflective metal filter, designed to have (over the required bandwidth and the expected angles of incidence) a reflectance of less than 50% so that a smaller proportion of the light is reflected than is transmitted. This compensates for the fact that, due to surface roughness or Fresnel reflectance, the reflectance of the sample surface 7 will generally be less than that of the reference mirror 6. Such a partially reflecting filter having a reflectance of about 20% should provide a good compromise in terms of signal-to-noise for surfaces having a reflectance in the range from about 1% to 100%, enabling the surface topography of, for example, of both glass and metal surfaces to be examined.

The objective lens assembly 13, and thus the reference mirror 6, is movable in the Z direction by a Z direction mover 15, in this example a piezoelectric mover, under the control of servo/drive circuitry 15e. The sample support stage 9 is movable in X and Y directions by an X mover 16 and a Y mover 17, respectively, to enable different areas of the sample surface 7 to be brought within the field of view of the detector 10.

Figure 6 shows a diagram illustrating in greater detail one example of the broadband scanning interferometer system 2. In this example, the broadband source 4 comprises a quartz halogen projector bulb 4a optically coupled to an optical fibre cable 4b from which light is transmitted via a diffuser 4c, a changeable filter 4d, an aperture stop 4e, a lens 4f, a field stop 4g and a collimating lens 4h to provide an emergent light beam L. The filter 4d may be a neutral density filter or a band pass filter, designed to restrict the wavelength range of the light emitted by the broadband source 4, such as a Helium-Neon laser line filter designed to pass light having a Helium-Neon laser line wavelength.

Typically the optical fibre cable 4b will be several feet long, in this case about 4 feet (about 1200 mm) allowing the projector bulb 4a to be placed in a separate housing 4' to facilitate changing of the bulb when necessary and more importantly keeping a heat source away from the remainder of the interferometer.

The light beam L emerging from the broadband light source is supplied to the beam splitter 12 which, in this case, consists of a mirror 12a arranged at 45° to the incident light beam and a beam splitting prism 12b through which light is directed towards the objective lens assembly 13. The mirror 12a may be replaced by a right angle prism. Light returned to the beam splitter 12b is reflected towards the detector by the beam splitter and focussed onto the detector 10 by lens 10a.

The objective lens assembly 13 is mounted on an objective support 38 coupled by parallel ligaments 39 and 40 to a Z mover housing 15' mounted to the interferometer housing 2a. In this case, the Z mover comprises a piezoelectric element (PIEZO)15b coupled via a linkage 15c and a support 15d to one of the parallel ligaments 39 so that, when a voltage is applied to the piezoelectric element 15b by the servo/drive circuitry 15e under the control of the controller 21, the piezoelectric element changes shape causing the ligament 15c and support 15d to push the ligament 39 up or down causing the objective lens assembly 13 (and thus the reference mirror 6) to move along the scan path with the degree of movement being determined by the voltage applied to the piezoelectric element 15b. The controller 21 may be programmed in known manner to compensate for any error in the Z position due to the slight arcuate nature of the motion of the objective lens assembly 13.

As shown schematically in Figures 4 and 6, the components of the interferometer I of the broadband scanning interferometer system 2 (apart from the projector bulb 4a housing in housing 4') are mounted within a housing 2a mounted via a carriage 18 to a Z axis datum column 19. The carriage 18 is coupled via a drive mechanism (not shown) such as a ball screw or lead screw drive mechanism to a coarse Z positioner 20 in the form of a manually operable control or, in this example, a DC motor that enables the carriage 18 and thus the interferometer I to be moved up and down the column 19 in the Z direction to enable the interferometer to be moved to different scanning start positions.

As shown in Figure 4, a support 102 houses the X and Y movers 16 and 17 and supports the sample support stage 9. The X and Y movers 16 and 17 comprise in this example DC motors coupled to the sample support stage 9 by appropriate conventional drive mechanisms such as rack and pinion or ball screw drive mechanisms (not shown).

As shown in Figures 3 and 4, each of the Z, X and Y movers is associated with a corresponding position sensor 15a, 16a and 17a while the coarse Z positioner 20 may be associated with a coarse Z positioner position sensor 20a. The control apparatus 30 has X, Y and Z loggers 22, 23 and 24 each of which receives the output of the corresponding position sensor 15a, 16a and 17a and supplies a signal to a controller 21 of the control apparatus that controls overall operation of the

interferometer system 2. The control apparatus also receives an output from the coarse Z positioner position sensor 20a, if provided. The control apparatus has a trigger generator 60 for triggering operation of the detector 10 in response to the output of the Z position sensor 15a to capture images at the required intervals.

In the case of the X or Y mover, where the mover is a motor, then the corresponding position sensor may be a linear grating encoder. The dashed lines between the support stage 9 and the X and Y position sensors 16a and 17a indicate that the position sensors may sense movement of the support stage 9 directly. Where the Z mover 15 is a piezoelectric mover, then the position sensor 15a may be, for example, an interferometric system, such as a grating system, or an LVDT that provides signals representing movement of the objective lens assembly 13 relative to the housing 2a of the interferometer. For example, the housing of the objective lens assembly 13 may carry a diffraction grating and a fringe detection interferometric system may be mounted within the housing 2a, providing a count of the fringes to the Z logger 24 as the objective lens assembly 13 moves relative to the housing 2a. As another possibility, a capacitive sensor may be used. As a further possibility a Michelson interferometer (with a corner cube attached to the housing 13) may be used.

The control apparatus 30 may be implemented by programming computing apparatus, for example a personal

computer. Figure 5 shows a simplified block diagram of such computing apparatus. As shown, the computing apparatus has a processor 25 associated with memory 26 (ROM and/or RAM), a mass storage device 27 such as a hard disk drive, a removable medium drive (RMD) 28 for receiving a removable medium (RM) 29 such as a floppy disk, CDROM, DVD or the like, input and output (I/O) controllers 37 for interfacing with the components of the broadband scanning interferometer system to be controlled by the control apparatus (for example, the Z, X and Y movers 15 to 17 , the coarse Z positioner 20 and the detector 10) to enable the processor 25 to control operation of these components, the user input 31 consisting, in this example of a keyboard 31a and a pointing device 31b, and the user output 36 consisting, in this example, of a display such as a CRT or LCD display 36a and a printer 36b. The computing apparatus may also include a communications interface (COMMS INT) 199 such as a modem or network card that enables the computing apparatus to communicate with other computing apparatus over a network such as a local area network (LAN), wide area network (WAN), an Intranet or the Internet. In this example, the data receiver 33 is provided as a dedicated frame capture circuit board 230 installed within the computing apparatus.

The processor 25 may be programmed to provide the control apparatus 30 shown in Figure 3 by any one or more of the following ways:

1. by pre-installing program instructions and any associated data in a non-volatile portion of the memory 26 or on the mass storage device 27;

2. by downloading program instructions and any associated data from a removable medium 29 received within the removable medium drive 28; and

3. by downloading program instructions and any associated data as a signal SG supplied from another computing apparatus via the communications interface 199.

The computing apparatus, when programmed by program instructions to provide the control apparatus 30, enables a measurement operation to be controlled in accordance with instructions received by a user, and the resulting frame data supplied by the detector 10 to be analysed to determine the surface profile or topography of the area of the surface imaged onto the 2D array of the detector 10.

Figure 7 shows a functional block diagram of one embodiment of the data processor 32.

As shown in Figure 7, the data receiver 33 comprises a frame capturer 33a and a frame buffer 33b both provided by the dedicated frame capture circuit board 230 (Figure 5). The frame buffer 33b stores frames of data received from the detector 10 and in this example has

sufficient capacity to store frame data for all the frames to be processed by the correlation determiner 34.

In this example, the data processor has a concurrent processing section 34a that carries out processing operations in parallel on different pixels of a frame of image data and a post processing section 34b that carries out processing operations in series or sequentially on different pixels of a frame of image data. The broad arrows in Figure 7 indicate parallel processing while the single line width arrows indicate serial processing.

The concurrent processing section 34a includes part of the correlation determiner, in particular a discriminator 42 and a peak finder 43, for monitoring or checking the incoming frames of data as they are supplied by the detector 10 to identify, for each surface pixel in parallel, which portion of the intensity data for that surface pixel is likely to contain the coherence peak. The peak finder 43 stores data identifying, for each surface pixel, the likely coherence peak data region.

The post-processing section comprises the remaining parts of the correlation determiner, namely a correlator 44 having a correlation processor 45 and a correlation buffer 46, and the topography determiner 35.

The correlator 44 is configured, once all of the frames of data for a measurement operation have been received, to access the intensity data flagged by the peak finder

43 as including the likely coherence peak region for a surface pixel, to carry out a correlation procedure to be described below on that data to determine the position of the correlation peak for that surface pixel and then to repeat the process for each of the remaining surface pixels of the area of the surface imaged by the detector 10.

The results of the correlation procedure for each surface pixel are supplied to the surface topography or profile determiner 35 that determines the surface profile or topography using the results obtained by the correlator 44 and outputs surface topography or profile data to the user output 31.

The operation of surface profiling apparatus having the data processor 32 described above with reference to Figures 3 and 7 will now be explained, assuming that the surface profiling apparatus has been calibrated by making measurements on a surface of known form and/or roughness.

Generally, the operator will instruct the controller 21 to cause the broadband scanning interferometer system 2 to carry out a measurement operation with a user-selected scan path length and scan step or interval between acquisition of images by the detector 10. When a measurement operation is initiated, the controller 21 instructs the Z mover 15 to commence movement of the objective lens assembly 13 (and thus the reference mirror 6) along the scan path at a specified speed, as

determined by the pre-programmed routine, and the detector 10 senses the interference pattern at predetermined intervals when triggered by the trigger generator 60 and supplies the resultant image data to the data receiver 33 so that images or frames of the interference pattern are captured by the frame capturer 33a at the required intervals or scan steps along the scan path and are stored in the frame buffer 33b in association with data identifying the corresponding scan step or interval determined by the controller 21 from the signals logged by the Z logger 24 in accordance with the output of the Z position sensor 15a.

The operation of the data processor 32 shown in Figure 7 will now be described in greater detail with the assistance of Figures 8 to 16.

Figure 8 shows schematic representations of successive frames of data supplied by the data receiver 33. Each frame consists of a matrix of pixels with each pixel corresponding to a specific different surface pixel of the surface being measured. For ease of explanation and simplicity in the drawings, a 3 x 3 matrix of pixels P1 to P9 is shown. It will, however, be appreciated that in practice the number of pixels will be considerably greater. Typically, the detector 10 will have an array of sensing elements that enables the region of interest (ie the region of the sample surface processed by the data processor) to consist of a 256 x 256 sensing element

array, a 512 x 512 or a 1024 x 1024 sensing element array.

The intensity data for the kth pixel in the ith frame is indicated in Figure 8 as I_iP_k so that, as shown, the intensity value for pixel P1 in frame 1 is I_1P_1 while the intensity value for pixel P1 in the Nth frame is I_NP_1.

Figure 9 shows a flow chart for illustrating the operation of the discriminator 42.

As illustrated by step S1, the discriminator 42 carries out processing operations in parallel on the intensity value data for all of the surface pixels (P1 to P9 in Figure 8) imaged by the detector 10 as the frames of data F1, F2, F3 and so on are received. In order to increase the processing speed, the discriminator may examine only every Nth frame as it is received. The interval depends upon the frame interval (that is the interval between capture of images) and the mean wavelength and is in this example two so that the discriminator 42 examines every second frame, that is the first, third, fifth and so on frames, as they are received.

The procedure carried out by the discriminator will be described for a single surface pixel. The same procedure will be carried out in parallel for the other surface pixels.

The discriminator reads the intensity values for every Nth frame (step S2) and in order to determine the discrimination value D_n, the discriminator determines, at step S3, the mean of a set of intensity values I_{n-4}, I_{n-2}, I_n, I_{n+2}, I_{n+4} consisting of the most recently read intensity value and the four previous most recently read intensity values. Then at step S4, the discriminator calculates the sum of squares of deviations of the set of intensity values, that is:

$$D_n=(I_{n-4}-M_n)^2+(I_{n-2}-M_n)^2+(I_n-M_n)^2+(I_{n+2}-M_n)^2+(I_{n+4}-M_n)^2 \quad (1)$$

and passes this to the peak finder as the discrimination value D_n. Then, at step S5 the discriminator adds this discrimination value to a sum of discrimination values, thereby accumulating the discrimination values. Then at step S5a, the discriminator checks if the last frame has been processed and, if not, repeats steps S2 to S5 for every second further intensity value so that the next set of intensity values for which the mean is determined is intensity value I_{n-2}, I_n, I_{n+2}, I_{n+4}, I_{n+6} and the sum of squares of deviations for those intensity values provides the discrimination value D_{n+2} which is passed to the peak finder. This is repeated until all of the intensity values for the pixel have been processed.

The operation of the peak finder will now be described with reference to Figures 10a to 10d.

The peak finder has a number of different states with the current state and switching between different states being determined by changes in the discrimination values.

In this example, the peak finder 43 has an initial state which exists for the first discrimination value, a low state which exists when the discrimination value is below a threshold, a found state which exists when the discrimination value is above a threshold, a saturated state which exists if the light level is too high and so the discrimination value is out-of-range, that is above a highest possible maximum, and an optional early state which exists if the discrimination value falls after the initial value. The peak finder is configured to move from the initial to the low state if the received discrimination value is below the threshold, to move from the initial state to the early state if the discrimination value is above the threshold value, to move from the low state to the found state if the discrimination value rises above the threshold value, and to move from the early state to the low state if the discrimination value falls below the threshold value.

Figure 10a shows a top level flow chart illustrating the steps carried out by the peak finder 43. Again, as illustrated by step S6, the peak finder 43 carries out processing operations in parallel for all of the surface pixels.

When, at step S7, the peak finder receives a first discrimination value from the discriminator then, at step S8, the peak finder 43 sets the state as initial and the current discrimination value as the maximum value. At step S9, the peak finder 43 compares the current discrimination value with a threshold and sets the state as low if the discrimination value is below the threshold or as early if the discrimination value is equal to or greater than the threshold. At step S10, the peak finder continues to monitor the discrimination values as they are received in accordance with the set state until all discriminations values for a pixel have been checked.

Figures 10b to 10d show flow charts illustrating operations carried out by the peak finder in the low, found and early states, respectively.

If, at step S9 in Figure 10a the peak finder enters the low state then, at step S11 in Figure 10b, when the peak finder receives a discrimination value, the peak finder checks at step S13 whether the current discrimination value is greater than the stored maximum and, if so, stores the current value as the maximum at step S14. After step S13 (or step S14 if the answer at step S13 is yes) then, at step S16, the peak finder checks to see whether the discrimination value is still below the threshold and, if so, returns to step S11. If, however, the discrimination value is no longer below the threshold, then the peak finder sets the state as found at step S17.

Figure 10c shows operations carried out by the peak finder in the found state. Thus, when at step S20 the peak finder receives a discrimination value in the found state, the peak finder checks at step S23 whether the current discrimination value is greater than the stored maximum value and, if so, stores the current value as the new maximum and the Z position of the new maximum at step S24 and returns to step S20. If the answer at step S23 is no, then the peak finder returns to step S11 without storing the current value as the new maximum.

Figure 10d shows steps carried out by the peak finder in the early state. Thus, when at step S27, the peak finder receives a discrimination value in this state then it checks at step S28 whether the current value is greater than the maximum and, if so, stores current value as the maximum at step S29 and returns to step S27. If, however, the answer at step S28 is no, then the peak finder checks at step S30 if the discrimination value has fallen below the threshold and if so, sets the state as low at step S31. The early state prevents a peak being found, if the signal level is initially above the threshold, until after the intensity value has dropped below the threshold.

When, at step S10, in Figure 10a, the last discrimination value has been received, then the peak finder will set the peak as the currently stored maximum discrimination value and, in addition, will determine a mean discrimination value by dividing the accumulated

discrimination value total by the number of discrimination values.

The discriminator then carries out, for each pixel, a test to determine whether the results of the peak finding procedure can be relied upon or whether the signal-to-noise ratio is too small for the peak finding procedure to be reliable. The test for a pixel is illustrated by the flow chart shown in Figure 11.

Thus at step S32 the discriminator determines whether the maximum discrimination value is greater than or equal to the mean discrimination value multiplied by a threshold value k, which in this case is 10. If the answer is yes, then, at step S33, the discriminator 42 sets the range of intensity values to be processed by the correlator 44 as a sub-set of the intensity values centred on the frame corresponding to the maximum discrimination value and flags this data in the frame buffer. Typically, the range will be three times the length of the correlator, although it will depend upon the scanning speed. If, however, the answer is no, that is insufficient signal is found by the discriminator 42, then at step S34 the discriminator 42 sets the range of intensity values to be processed by the correlator 44 as the complete range of intensity values stored in the frame buffer 33b for that pixel. Thus, the discriminator ensures that the results of the peak finding procedure for a given pixel are only relied upon if the signal-to-noise ratio is sufficiently good that it can confidently be assumed that

the peak finding procedure has correctly located the peak. Otherwise the entirety of the intensity data for that pixel will be passed to the correlator.

When the measurement operation has been completed, then the post processing section 34b can process the results of the discrimination and peak finding procedures carried out during the measurement operation.

The operation carried out by the correlator 44 of the post processing section will now be described with the aid of Figures 7, 12 and 13.

Figure 12 shows a graph of amplitude A against position Z to illustrate the correlation function used by the correlator 44. This correlation function consists of two reference wave packets. The reference wave packets WP1 and WP2 have the functional form of a sine wave and a cosine wave, respectively, having a wavelength equal to the mean wavelength of the broadband source bounded by a Gaussian envelope G (shown in dashed lines) so that the Gaussian envelope is modulated by the cosine and sine waves and the correlation function has a length LE. The shape of the correlation function is equivalent to the Fourier transform for a Gaussian distribution broadband source.

Figure 13 shows a functional block diagram of the correlator 44. The correlation processor 45 includes a correlation indices store 45a which stores the

correlation function as an array of pairs of correlation indices a_i, b_i, where a_i represents the amplitude of the sine wavepacket at a point i along with the Z axis and b_i represents the amplitude of the cosine wavepacket at the point i along the Z axis. The reference wave packets WP1 and WP2 shown in Figure 12 are thus digitised into a number of pairs of indices. The actual number of pairs of indices will vary with the scanning interval, mean wavelength and spread or bandwidth of the broadband source. Typically, for a scanning interval of $\lambda/4$ (where λ is the average wavelength of the broadband source and is typically 0.6μm (micrometres)), the number of pairs of indices a_i, b_i will be sixteen, although with increased computing power a greater number of points may be used.

The correlation processor 45 also includes a multiplier 45b that performs the correlation procedure using the indices in the correlation indices store 45a. In order to perform the correlation, the correlator 44 moves a window having a length equal to the number of pairs of correlation indices of the correlation function progressively through the range of intensity values set for a pixel by the discriminator and, at each position of the window, reads in successive ones of the intensity values I_i within the window and multiplies each different intensity value I_i within the window separately by each of a corresponding pair of coefficients a_i, b_i, then sums the results to obtain a pair of correlation elements A_i, B_i for that position of the window and outputs the

resultant correlation elements A_i , B_i to the correlation buffer 46 for storage in a memory area or location allocated to that window position. In this embodiment, the window position is determined as the centre of the window.

In this example, the multiplier steps the window one intensity value at a time through the intensity value data for the pixel, repeating the multiplication process at each step until the window reaches the end of the intensity value data for that pixel at which time the correlation buffer will store a pair of correlation elements A_i , B_i for each intensity value for the pixel apart from the end intensity values corresponding to half the length of the correlation to which the correlation function cannot be fully applied. At this stage the correlator will have produced and stored in corresponding memory areas in the correlation buffer 46 an array of pairs of correlation elements:

$$Ai = \sum_{j=0}^{j=n-1} I_{i-n/2+j}\, a_j,\ Bi = \sum_{j=0}^{j=n-1} I_{i-n/2+j}\, b_j \qquad (2)$$

where I_0 to I_n are the intensity values that fall within the window for the corresponding intensity value and with each pair being associated with a corresponding scan step, that is a corresponding Z position.

As described above, the multiplier step, the window through the data one intensity value at a time. The multiplier may, however, omit some intensity values by using a step size greater than one.

Figure 14 illustrates the steps carried out by the surface topography determiner 35 of the post processing section. Thus when the surface topography determiner 35 is advised, by the correlator 44 that the correlation procedure for the set range of values for a pixel has been completed, then the surface topography determiner 35 determines the sum of squares of cosine and sine wavepacket correlation elements A_i and B_i to obtain squared amplitude data (step S40). At step S40, the surface topography determiner 35 may also accumulate the sum values, then determine the mean of the accumulated sums and compare the mean against a threshold to determine if the signal-to-noise ratio is sufficiently high. If the signal-to-noise ratio is too low then the surface topography determiner causes an indication to be provided to the operator that the measurement operation cannot be completed because the signal-to-noise ratio is too low.

The squared amplitude data may then be smoothed using a box filter at step S41. Then the highest value in the smoothed data is found and a range of values around the highest value selected (step S42).

The square root of each value within the range is then determined at step S43 and, at step S44, the surface topography determiner 35 fits a Gaussian to this data using a least squares fitting procedure by taking the natural logarithm and fitting a quadratic $Ax^2 + Bx + C$ to the $\log_e$ values, from which the height, width and position of the peak can be obtained in accordance with the following formulas:

$$\begin{aligned} Height &= e^{(C - B^2/4A)} \\ Width &= \left(\sqrt{-\frac{1}{A}}\right) \\ Position &= -\frac{B}{2A} \end{aligned} \qquad (3)$$

Then, at step S45, the surface topography determiner 35 sets the Z position associated with the amplitude peak as the height of the surface for that pixel.

The procedure described above with reference to Figure 14 is effected for each pixel within the surface area imaged by the detector 10 in sequence as the correlation procedure is completed for a pixel. The surface topography determiner 35 thus obtains from the correlation element pairs A_i, B_i data indicating the relative heights of different surface pixels in the area imaged by the detector. This data is supplied by the surface topography determiner 35 to the controller 21 which may output the topography data to the operator, for

example by displaying it on the display as a two-dimensional height map and/or by providing a hard copy printout. The controller and/or the operator may also cause the resulting surface topography data to be supplied as a signal over the communications interface to another computing apparatus or downloaded onto a removable medium. The surface topography data may also be supplied to analysis software such as Taylor Hobson's Talymap software which may be installed on the control apparatus or on another computing apparatus to which the data is supplied as a signal over a network or by being downloaded from a removable medium.

Instead of using the position of the amplitude peak (that is the coherence amplitude data) as the height of the surface for that pixel, the data may be further processed after step S45 to determine the Z position at which the phase is zero and to produce a surface topography representation using the zero phase position. Providing the facility to determine the height information using the phase enables the operator to select the surface topography determination most appropriate for the surface being measured with the use of the coherence amplitude data to define the height being more appropriate for surfaces of relatively high roughness and the use of the phase data to define the height being more appropriate for surfaces of relatively low roughness.

A method by which the surface topography determiner 35 may determine the Z position of zero phase for each

surface pixel will now be described with reference to Figure 15. Thus, after steps S40 to S44 shown in Figure 14 have been carried out (step S50), then, at step S51, the surface topography determiner 35 calculates the arctangent of the sine and cosine wavepacket correlation values to obtain the phase.

Because of the sinusoidal nature of the intensity distribution, as is well known in the optical interferometry art, all phase measuring techniques deliver the phase to modulus 2π. The absolute value of the phase angle is thus lost and the phase wraps round at each occurrence of 2π. It is therefore necessary to recover the absolute value of the phase angle by unwrapping the phase. In order to do this in the present case, at step S52, the surface topography determiner 35 determines the datum point (cosine/sine wavepacket correlation value) closest to the determined amplitude peak (which may lie between two datum points) and uses this and the phase gradient determined from the scan speed to estimate the zero phase position. Then, at step S53, the surface topography determiner 35 unwraps the phase by using the phase gradient to calculate the expected phase for a datum point (cosine/sine wavepacket correlation value) and then adds or subtracts 2π to the phase of the datum point until the difference from the expected phase is less than or equal to π.

Once the phase has been unwrapped, then, at step S54, the surface topography determiner 35 performs a linear fit

to the unwrapped phase data, and at step S55 determines the actual zero phase from the zero crossing point of the linear fit.

Then, at step S56, the surface topography determiner 35 sets the height of the surface pixel under consideration as the Z position of the determined zero phase. This procedure is carried out for each of the pixels in the frame data in turn so that the surface topography determiner 35 provides to the controller 21 a two-dimensional zero phase data map representing the surface height variations. The controller 21 may output the data to the operator, for example by displaying it on the display and/or by providing a hard copy printout. The controller and/or the operator may also cause the resulting surface topography data to be supplied as a signal over the communications interface to another computing apparatus or downloaded onto a removable medium. Again, the surface topography data may also be supplied to analysis software such as Taylor Hobson's Talymap software which may be installed on the control apparatus or on another computing apparatus to which the data is supplied as a signal over a network or by being downloaded from a removable medium.

Another form of discriminator that may be used in the correlation determiner 34 shown in Figure 7 will now be described with the aid of the flow chart shown in Figure 16.

As can be seen from the graph representing the correlation function in Figure 12, every other correlation index a_i representing the amplitude of the sine wavepacket and every alternate other index b_i representing the amplitude of the cosine wavepacket is close to zero. Choosing the frame interval (that is the interval between capture of images by the detector) to be an exact integer division of the mean wavelength λ of the broadband source causes some of the indices a_i, b_i to vanish to zero. In this embodiment, the frame interval is $\lambda/4$ and alternate indices a_i and alternate indices b_i vanish to zero. The same would apply for frame intervals of $3/4\ \lambda$, $5/4\ \lambda$ and so on. The fact that these indices vanish to zero means that multiplications for these indices need not be calculated by either the discriminator or the correlator, thereby saving processing time.

The discriminator to be described with reference to Figure 16 has the form of a simplified correlator which consists of two sets of four indices c_i, d_i representing, respectively, one cycle of a simple cosine wave and one cycle of a simple sine wave, wherein the word simple implies that there is no bounding envelope. Thus, the cosine indices will be +1, 0, -1, 0 while the sine indices will be 0, +1, 0, 1.

This discriminator is applied to intensity values in a manner similar to the correlator described above. In principle this would mean multiplying each of a set of

four intensity values i_0 to i_3 by corresponding ones of the cosine indices and summing the results to produce a cosine discrimination element and multiplying each of the intensity values i_0 to i_3 by each of the sine indices and summing these to produce a sine discrimination element. However, because alternate indices are zero and the remaining indices are + or -1, then, as shown at step S61 in Figure 16, the cosine discrimination element can be obtained simply by subtracting the third intensity value i_2 from the first intensity value i_0 of a series of intensity values from four frames for the pixel and the sine discrimination element can be obtained simply by subtracting the fourth intensity value i_3 from the second intensity value i_1.

Then, at step S62 the square of the cosine discrimination element is added to the square of the sine discrimination element to produce a squared amplitude value for the four intensity values. The square of amplitude values may be smoothed over five values using a box filter at step S63 and the smoothed value then passed to the peak finder at step S64 as the discrimination value. Then, at step S65, the discrimination value will be added to the discrimination value sum as described above with reference to Figure 9 and steps S61 to S65 repeated until, at step S66, the discriminator determines that the last frame has been processed in which case the discriminator will proceed to carry out the steps shown in Figure 11.

In this discriminator, the pairs of cosine and sine discrimination elements and the length of the discriminator (that is the length comparable to the length LE of the correlator shown in Figure 12) can be adjusted simply by adding and squaring the cosine discrimination elements, adding and squaring the sine discrimination elements and summing the two. Thus, for example, the length of the discriminator may be increased from four intensity values to eight intensity values by producing the squared amplitude of value SA as follows:

$$SA = (cos_1 + cos_2)^2 + (sin_1 + sin_2)^2$$

where cos_1 and cos_2 are the cosine discrimination elements for the two successive sets of four intensity values and sin_1 and sin_2 are the sine discrimination elements for the two successive sets of four intensity values.

Thus, by storing pairs of cosine and sine discrimination elements for sets of four intensity values, longer discrimination length can easily be calculated to improve the discrimination of the frequency of interest. Also, such pairs can easily be added or subtracted to the box filter as required. To save required memory space, the cosine and sine discrimination element pairs may be stored in a circular buffer of the discriminator or the circular buffer of the correlator.

Figure 16a shows a graph of signal S against position Z illustrating the intensity values I and the corresponding signal D produced by this discriminator to illustrate that the discriminator can identify the coherence peak in low signal level data.

In the data processor shown in Figure 7 and described above, discrimination and peak finding procedures are carried out on-the-fly, that is as the measurement operation is proceeding, and correlation is carried out as a post-processing procedure, that is after the measurement operation has been completed.

Figure 17a shows a block diagram of another example of a data processor 320 that may be used in the surface profiling apparatus. As can be seen from a comparison of Figures 7 and 17a, the data receiver 33 is the same as show in Figure 7 and the correlation determiner 340 again has a concurrent processing section and a post processing section. These differ from those shown in Figure 7. Thus, in Figure 17a, the concurrent processing section consists of a correlator 440. The correlator 440 has a correlation processor 450 with a multiplier 450b and a correlation indices store 450a. The correlator 440 also includes a correlation buffer 460 and a correlation buffer status register 461. The concurrent processing section 340 also includes a peak finder 430 and a copy buffer 470 while the post processing section consists simply of the topography determiner 350. Thus, in this

example the discrimination is omitted and the correlation is itself carried out on-the-fly.

The correlator 440 operates in a somewhat different manner from that described above. Thus, although the correlator 440 again steps through the intensity value data and performs a correlation procedure on the intensity data to determine the pair of correlation elements A_i , B_i for each intensity value I_i, the correlator 440 carries out the correlation procedure in parallel for different pixels rather than sequentially as described above and the manner in which the correlation is carried out is somewhat different. This will now be described with the assistance of Figures 17b and 18a to 18g .

Figure 17b shows a diagrammatic representation of the correlation buffer 460. As shown in Figure 17b, the correlation buffer 460 is divided into a number of sections one for each pixel (P1 to P9 are shown). Each section consists of an array of memory locations MO to MN with each memory location being arranged to store a corresponding pair of correlation elements A_i, B_i.

To reduce the amount of memory required to provide the correlation buffer 460, a circular buffer is used wherein, as is known is the art, the oldest entry is overwritten once the buffer becomes full. The size of the correlation buffer 460 is chosen such that data should not be overwritten before a correlation procedure

requiring that data has been completed and, in this example, the correlation buffer provides memory locations for 43 pairs of correlation elements, per pixel. The copy buffer for each pixel may be in a part of memory adjacent the corresponding correlation buffer.

The status register 461 indicates the status of each memory location within the circular correlation buffer 460. Examples of status indicators are: "E" for empty, "F" for filling, "D" for done when that memory location stores the corresponding pair of correlation values A_i ,B_i and W for overwritten to indicate that the data has been overwritten before the correlation procedure requiring the data in that memory location has been completed.

Figures 18a to 18f show diagrammatic representations of part of a portion of the circular correlation buffer 460 allocated to one pixel to illustrate how the correlation procedure is carried out for a pixel. Although the processes for the two indices of a pair of correlation indices are carried out in parallel, for simplicity Figures 18a to 18f show the process for only one, a_i, of the two indices of each pair. Also, again for simplicity, the part of the array shown is represented as memory locations numbered from $M_{n/4-3}$ onwards and the intensity values being processed are represented as intensity values I_n onwards.

In this example, the correlation indices are stored in the correlation indices store 450a (Figure 17a) as four groups:

Group 0:	a_o,	a_4,	a_8,	a_{12}	;	b_o,	b_4,	b_8,	b_{12}
Group 1:	a_1,	a_5,	a_9,	a_{13}	;	b_1,	b_5,	b_9,	b_{13}
Group 2:	a_2,	a_6,	a_{10},	a_{14}	;	b_2,	b_6,	b_{10},	b_{14}
Group 3:	a_3,	a_7,	a_{11},	a_{15}	;	b_3,	b_7,	b_{11},	b_{15}

As shown in Figure 18a, when an intensity value I_n is received by the correlator, the multiplier 450b multiplies it by each of the indices a_o , a_4 , a_8 , a_{12} of Group 0 and adds each result to a corresponding memory location $M_{n/4-3}$, $M_{n/4-2}$, $M_{n/4-1}$, $M_{n/4}$. When the next intensity value I_{n+1} is received the multiplier multiplies it by each of the indices a_1, a_5, a_9, a_{13} of Group 1 and accumulates or adds each result to the corresponding memory location $M_{n/4-3}$, $M_{n/4-2}$, $M_{n/4-1}$, $M_{n/4}$ as shown in Figure 18b.

When the next intensity value I_{n+2} is received the multiplier multiplies it by each of the indices a_2 , a_6, a_{10} , a_{14} of Group 2 and accumulates or adds each result to the corresponding memory location $M_{n/4-3}$, $M_{n/4-2}$, $M_{n/4-1}$, $M_{n/4}$ as shown in Figure 18c. When the next intensity value I_{n+3} is received the multiplier multiplies it by each of the indices a_3, a_7, a_{11}, a_{15} of Group 3 and accumulates or adds each result to the corresponding memory location $M_{n/4-3}$, $M_{n/4-2}$, $M_{n/4-1}$, $M_{n/4}$ as shown in Figure 18d.

Then, as shown in Figure 18e, the correlator moves along one memory location, resets the content of memory location $M_{n/4+1}$ to zero and when the next intensity value I_{n+4} is received the multiplier multiplies it by each of the indices a_o, a_4, a_8, a_{12} of Group 0 and adds each result to a corresponding memory location $M_{n/4+1}$ to $M_{n/4-2}$.

Although not shown, when the next intensity value I_{n+5} is received, the multiplier 450b multiplies it by each of the indices a_1, a_5, a_9, a_{13} of Group 1 and accumulates or adds each result to the corresponding memory location $M_{n/4+1}$ to $M_{n/4-2}$, when the next intensity value I_{n+6} is received the multiplier multiplies it by each of the indices a_2, a_6, a_{10}, a_{14} of Group 2 and accumulates or adds each result to the corresponding memory location $M_{n/4+1}$ to $M_{n/4-2}$ and when the next intensity value I_{n+7} is received the multiplier multiplies it by each of the indices a_3, a_7, a_{11}, a_{15} of Group 3 and accumulates or adds each result to the corresponding memory location $M_{n/4+1}$ to $M_{n/4-2}$.

Then, as shown in Figure 18f, the correlator moves along one memory location, resets the content of memory location $M_{n/4+2}$ to zero and, when the next intensity value I_{n+8} is received, by the correlator, the multiplier 450b multiplies it by each of the indices a_o, a_4, a_8, a_{12} of Group 0 and adds each result to a corresponding memory location $M_{n/4+2}$ to $M_{n/4-1}$.

Although the above refers only to one index of each pair of indices, it will be appreciated that the same

multiplication process is carried out in parallel for the indices b_0 to b_{15}.

This procedure continues as intensity values are received with the group of indices used for the multiplication being changed each time a new intensity value is received (so that Groups 0, 1, 2, and 3 are used in sequence) and with the memory locations being advanced by one after receipt of every fourth intensity value. As the process proceeds successive memory locations (ignoring the first and last eight memory location (that is half the correlator length at each end)) will become filled with corresponding correlation elements A_i, B_i having the form set out in equation (2) above for every fourth received intensity value I_n, I_{n+4}, I_{n+8}, ... The correlation is thus effected only for every fourth intensity value.

The status of a memory location in the correlation buffer status register 461 changes from "E" or empty to "F" or filling when the value obtained by multiplying a value by a first coefficient is stored in that memory location and from "F" to "D" or done when that memory location stores the corresponding pair of correlation elements A_i, B_i. Figure 18g shows entries in the correlation buffer status register 461 after 18f. Figure 18g shows that the memory locations $M_{n/4-3}$,$M_{n/4-2}$, are done ("D"), the memory locations $M_{n/4-1}$,$M_{n/4}$,$M_{n/4+1}$,$M_{n/4+2}$ are being filled ("F") and are not ready and the memory location $M_{n/4+3}$ is empty ("E"). When a memory location for a pixel becomes

filled, then that memory locations will have the status "D", that is done or filled.

This correlation procedure has the advantage that it is not necessary to access intensity values more than once because all calculations requiring a particular intensity value are carried out at the same time, so facilitating correlation as the intensity values are received, that is correlation on-the-fly.

Changing the status of a memory location with status done ("D") in the correlation buffer status register 461 causes the peak finder 430 to use the correlation elements in that memory location in a peak finding procedure to determine the coherence peak as will now be described with reference to Figures 19a to 19f.

The peak finder 430 operates on the pair of correlation elements stored at a particular memory location when the correlation procedure has been completed for a number, in this case two, of memory locations ahead of that memory location. The peak finder 430 operates in a manner similar to the peak finder 43 discussed above in that it has a number of states. These states differ somewhat from those of the peak finder 43.

Thus, the peak finder 430 has an initial state that exists, for a given surface pixel, for a first amplitude value derived from a first pair of correlation elements, a low state that exists before the amplitude value rises

above a threshold value, a rising state that exists when the amplitude value is rising, a falling state that exists when the amplitude value is falling, a found state that exists after the amplitude value falls to a fraction of the maximum, a saturated state that exists if the light level is too high and so the discrimination value is out-of-range, that exists if a maximum detected value is above the permissible highest maximum and an early state that exists if the amplitude value starts above the threshold. In addition, the peak finder has a late state that exists where the correlation buffer is a circular buffer and peak data has been overwritten.

Figure 19a shows the overall operation of the peak finder 430. As set out at step S70, the peak finder carries out the peak finding procedure for the correlation element data for each surface pixel in parallel. Steps S71 to S74 show the steps carried out for each pixel in parallel. When, at step S71, the peak finder 430 determines that the status of a memory location is done, that is the pair of correlation elements have been calculated, then the peak finder determines the sum of squares combination of the correlation elements to obtain an amplitude value and at step S72 sets the state as initial and sets the current amplitude value as the current maximum. As will be appreciated this amplitude value is actually a squared amplitude value.

Then at step S73, the peak finder 430 sets the state as low if the amplitude value is below a threshold or as

early if the amplitude value is equal to or greater than the threshold. As indicated by step S74 the peak finder continues to check the amplitude data in accordance with the status by, each time, the status of a memory location becomes "done", determining the sum of squares combination of the pair of correlation elements to obtain an amplitude value and checking the amplitude value in accordance with the set state until all amplitude values for a pixel have been checked.

Figure 19b shows the steps carried out by the peak finder when the current state is low. Thus, at step S75, the peak finder determines the amplitude value as set out in step S71 in Figure 19a. Then, the peak finder checks at step S76 whether the current value is greater than the stored maximum and, if not, returns to step S75. If the answer at step S76 is yes, then the peak finder stores, at step S77, the current value as the maximum. Then the peak finder checks at step S78 if the current value is above the threshold and, if so, sets the state as rising at step S78. If the current value is not above the threshold, then the peak finder returns to step S75.

Figure 19c shows steps carried out by the peak finder when the state is set at rising at step S81 in Figure 19b.

Step S82 in Figure 19c corresponds to step S75 in Figure 19b. However, in this case, the peak finder checks at step S85 whether the current value is greater than the

stored maximum and if the answer is yes, stores the current value as the maximum at step S86 and returns to step S82. If, however, the answer at step S85 is no, then at step S87, the peak finder 430 sets the state as falling.

Figure 19d shows steps carried out by the peak finder when the state is set as falling. Step S90 corresponds to step S75 in Figure 19b. In this case, the peak finder checks at step S93 whether the current value is greater than the stored maximum and, if so, stores the current value as the maximum at step S94 and sets the state as rising. If, however, the answer at step S93 is no, then the peak finder checks at step S95 whether the current amplitude is less than one quarter of the stored maximum. If the answer is no, the peak finder 430 returns to step S90. If, however, the answer is yes, then this provides a peak trigger to the peak finder. Thus, the peak finder 430 determines that a peak has been found and, at step S96, records the Z position determined by the Z logger and copies a range of correlation elements encompassing the position of the determined peak to corresponding memory locations in the copy buffer 470. The peak finder 430 also sets the state as found at step S96.

Figure 19e shows steps carried out by the peak finder when the state is set as found. Step S100 corresponds to step S75 in Figure 19b. At step S103, the peak finder 430 checks whether the current value is greater than the stored maximum and, if not, returns to step S100. If,

however, the answer is yes, then the peak finder determines that the currently identified peak may not be the correct peak, stores the current value as the maximum and sets the state as rising at step S104.

Figure 19f shows steps carried out by the peak finder 430 when the state is set at early at step S73 in Figure 19a. At step S105, the peak finder 430 again determines the amplitude value for a pair of correlation elements and then at step S106 checks whether the current value is greater than the currently stored maximum and, if so, stores the current value as the maximum at step S106. Then at step S107, the peak finder checks whether the current amplitude value is below the threshold and, if not, returns to step S105. If, however, the answer at step S107 is yes, then, at step S108, the peak finder 430 sets the state as low and, when the next pair of correlation elements is ready for that pixel, returns to step S75 in Figure 19b.

Thus, as explained above with reference to Figure 19d each time the current amplitude value falls to less than, in this example, one quarter of the stored maximum, the peak finder determines that a peak has been found and copies a range of correlation elements including the correlation elements corresponding to the position of the peak to corresponding memory locations in the copy buffer 470. In this example, the range of pairs of correlation elements extends from thirteen before to two after the pair of correlation elements corresponding to the

position of the peak trigger (as described at step S95 in Figure 19d). The data in the copy buffer may be overwritten if, after correlation elements have been copied to the copy buffer, the peak finder subsequently finds a higher peak.

Although not shown, the copy buffer 470 is also divided into a number of sections one for each pixel. Each section again consists of an array of pairs of memory locations with each pair of locations being provided to store a corresponding pair of correlation elements A_i, B_i with in this case the number of pairs of memory locations per pixel being equal to four times the correlation function length (which again is sixteen).

At the end of the measurement procedure, the copy buffer 470 should contain, for each surface pixel, the sub-range of correlation elements containing the coherence peak. The post processing can then be carried out by surface topography determiner 350 as will be explained below so that the correlation data for each pixel in turn is processed and the surface profile or topography obtained and supplied to the operator or another piece of software as described above.

The post-processing by the surface topography determiner can be carried out once the peak finder has completed the peak finding procedure. The surface topography determination may be commenced immediately or the data stored for subsequent processing. In this embodiment,

the steps carried out by the surface topography determiner corresponds to steps S40 to S45 described above with reference to Figure 14 or steps S50 to S56 described above with reference to Figure 15.

Figures 20a to 20f are graphs of signal strength S against position Z with graphs 20a and 20b showing results obtained using the data processor shown in Figure 7 with the discriminator operating as explained with reference to Figures 16 and with Figures 20a showing determination of the Z position of the peak and 20b determining the Z position of zero phase. In Figure 20a line 200 represents the intensity values provided by the detector, lines 201 and 202 represent the sine and cosine wavepacket correlation elements A_i, B_i, dashed line 203 represents the amplitude determined from the correlation elements and line 204 represents the Gaussian fitted to the amplitude data. In Figure 20b lines 200, 201 and 202 again represent the intensity values and the sine and cosine wavepacket correlation elements while dashed line 205 represents the unwrapped phase and line 206 represents the results of the linear fitting procedure carried out at step S54 in Figure 15 and shows the position of zero phase as the zero crossing point on the Z axis.

Figures 20c and 20d shows results obtained using the data processor shown in Figure 17a and 17b with Figure 20c showing determination of the Z position of the peak and Figure 20 showing determination of the zero phase

position. In Figure 20c, line 200a represents the intensity values, lines 201a and 202a represent the sine and cosine wavepacket correlation elements, dashed line 203a represents the amplitude values derived from the sine and cosine wavepacket correlation elements and line 204a represents the Gaussian fitted to the amplitude values. In Figure 20d, lines 200a, 201a and 202a again represent the intensity values and sine and cosine wavepacket correlation elements, dashed line 205a represents the unwrapped phase and line 206a represents the result of the linear fitting procedure showing determination of the Z position of zero phase, that is the zero crossing point on the Z axis.

Figures 20e and 20f show the results of carrying out the processing described above with reference to Figures 17a to 19f (that is concurrent correlation) across a 100 nanometre grating where the X axis in Figures 20e and 20f represents the direction perpendicular to the grating lines. Figure 20e shows the results obtained where the surface height is set as the Z position of the peak while Figure 20f shows the results obtained where the surface height is set as the Z position of the actual zero phase. In addition to showing the grating steps, Figures 20e and 20f show a slight overall tilt in the grating surface.

In the embodiment described with reference to Figure 6, a specially designed piezoelectric Z mover is used. As another possibility, a commercially available Z mover may be used. Also a motor may be used.

In the above described embodiments, the Z mover 15 is driven at a largely constant rate either with a servo control or open loop with respect to the Z position sensor 15a. The Z position sensor 15a feeds the scan position to the trigger generator 60 and, each time a predetermined interval has been covered, the trigger generator produces a trigger for the detector 10. The detector must be capable of external asynchronous trigger. In this manner, images are taken at a constant position interval based only on the Z position sensor 15a and trigger generator 60 and not on the errors in the servo-control or largely constant scan speed. This is especially useful where the Z mover is a motor but can also be used where the Z mover is a piezo-electric mover.

As another possibility, the Z mover 15 may be servo-controlled with respect to the Z position sensor 15a and a series of command positions sent to the servo-controller at the desired frame interval so that the Z mover steps between the positions. The detector 10 can then be triggered by a time-based trigger generator and at a constant time interval. The scan then steps in between the exposure times of the detector. This is useful where the Z mover is a piezo-electric mover.

In the above described embodiments, it is assumed that the areal pixel resolution (that is effectively the sensing element pitch of the detector 10) is the same as the number of resolvable positions that can pass through the objective lens 14. However, often in interferometry,

the areal pixel resolution of the camera or detector is not as great as the number of resolvable positions that can pass through the objective lens. Therefore, in order to cover the range from maximum field of view to maximum lateral resolution, a zoom lens or the option of extra lenses may be provided to enable the image to be magnified or reduced. As another possibility, the detector 10 may comprise a camera that has a larger areal pixel resolution than will normally be required and a smaller areal pixel resolution can then be achieved by taking only selected pixels, for example every other pixel, or by adding together the intensity data acquired by groups of adjacent pixels thus forming "super pixels". These super pixels may consist of, for example, 2 x 2, 4 x 4 or 8 x 8 square arrays of individual sensing elements. Also, a smaller areal pixel resolution may be achieved by selecting the sensing elements of only a portion of the overall array. These approaches enable the same areal pixel resolution to cover different fields of view and lateral resolutions, so providing an electronic zoom function.

A disadvantage of using a detector comprising a large areal pixel resolution camera is that the frame readout rate is reduced, typically proportionally to the number of lines of sensing elements, that is number of lines in the image. However, the detector may comprise a commercially available CCD camera such as the Vosskühler GmbH:CCD 1300B CCD camera having a vertical binning function in which groups of pixels over a number of lines

are added together reducing the number of lines that need to be read and therefore increasing the read out rate and/or having a partial scanning function in which only some of the lines in the frame are read out, again increasing the read out rate. Both of functions enable electronic zoom to be achieved with high readout rates.

In the above described embodiments, the correlation function has a Gaussian envelope. Other peaked envelope forms such as a Lorentzian may be used. It is, however, desirable for the envelope used to be a smoothly varying function.

The discriminator 42 described with reference to Figure 7 may carry out a correlation procedure in a similar manner to the correlator 440 shown in Figure 16, but at a coarser scale, that is with the reference wave packets of the correlation function being digitized as a smaller number of points, for example, 4 points for each reference function. Also, such a discriminator may use an interval larger or smaller than four between the intensity values for which the correlation procedure is carried out. Also the concurrent correlator described with reference to Figures 17a and 17b may use an interval other than four. The correlators described above may, like the discriminator described with reference to Figure 16, be configured not to carry out the multiplication steps where the indices a_i, b_i are zero or substantially zero.

It may also be possible to use a discriminator that simply looks for the highest intensity value in the intensity value data for a pixel.

In the embodiments where correlation is a post processing procedure, then other methods of carrying out the correlation than that described may be used. For example, each set of intensity values may be multiplied by each index a_i (and each index b_i) in turn and the sums or accumulated values stored in the corresponding memory locations before the next set of intensity values is processed by the correlator 44. As another possibility, the correlation procedure described above with reference to Figures 18a to 18g may be used.

In the embodiments described with reference to Figure 14, the data for each surface pixel is processed in sequence by the correlator and the surface topographer. As another possibility, the correlator 44 may repeat the above process for each pixel in turn so that, at the end of the correlation process, the correlation buffer 46 stores, for each pixel, a corresponding array of pairs of correlation elements with each pair being associated with a corresponding scan step, that is a corresponding Z position logged by the Z logger and the surface topography determiner may then determine the surface topography.

A different frame interval for the correlation procedure than described above may be used with the frame interval

being increased to speed up processing or reduced to increase accuracy. The frame interval may be selectable by the operator. As described in the paper entitled: "Three-Dimensional Imaging by Sub-Nyquist Sampling of White-Light Interferograms" by Peter de Groot and Leslie Deck published in Optics Letters Volume 18, No. 17, September 1, 1993 at pages 1462 to 1464, undersampling or sub-Nyquist sampling may be used for increased speed, that is the frame interval may be greater than the mean wavelength. In this case, the bandwidth of the broadband source may be reduced to attain an interference signature similar to that described above so that the Gaussian fit remains appropriate. As examples of frame intervals that may be used are $n\lambda \pm \lambda_{/4}$ for example $\lambda_{/4}$, $3/4\lambda$, $5/4\lambda$, $n\lambda \pm \lambda_{/3}$ for example $\lambda_{/3}$, $n\lambda \pm \lambda_{/5}$, for example $\lambda_{/5}$.

If processing power is a consideration and speed is not an issue, then at any one or more point where data for different pixels is processed in parallel in the embodiments described above, that data may instead be processed serially for each pixel in turn. Alternatively, if processing power is not a consideration and speed is an issue, then at any one or more point where data for different pixels is processed in series in the embodiments described above, that data may instead be processed in parallel.

In the embodiments described above, the frame buffer stores all of the frames of data acquired during a measurement operation. This does, however, require a

considerable amount of memory, especially if a relatively large number of frames of intensity data are to be processed and the number of pixels per frame is high, for example 1024 by 1024. In the embodiment described with reference to Figures 17a and 17b where the correlation is carried out concurrently, the frame buffer may be a circular buffer, so reducing the size of buffer required. A circular buffer may also be used where the correlation is a post-processing procedure.

In the embodiments described where the correlation is carried out concurrently, a circular buffer is used for the correlation buffer. As another possibility, the correlation buffer may be sufficiently large to store all correlation elements.

Surface topography determination may be made for different areas of the sample surface. Surface height representations for these different areas may be supplied separately to the operator. As another possibility, the surface height determinations for different areas may be combined. This may be achieved by ensuring that the surface areas overlap and relating the surface height data in the overlap region determined from one area to the surface height data in the overlap region obtained for another area so as to ensure that the surface height data for the combined areas is all referred to a common reference. As another possibility the Z position data acquired by the controller 21 from the coarse Z position sensor 20a and the Z logger 24 may be used to provide a

Z or height reference datum enabling the surface height data obtained for the different areas to be referenced to a common height datum.

In the examples described above, the post processing section is arranged to carry out processing as soon as the results from the concurrent processing section are available. This need not necessarily be the case and, for example, the post processing may be deferred until a later time or date, if desired. Thus, the concurrent processing may be carried out for a number of different regions of the surface or for a number of different surfaces and then stored on a removable medium 29 or on the mass storage device 27 and the post processing carried out only after all these have been completed.

In the example described above with reference to Figure 7 the step of the window in the correlation procedure carried out by the correlator of the post-processing section is one, it may however be two or more, if potentially higher accuracy is less important than speed.

As described above, where the height is determined from the amplitude data it is determined to be the position of the peak. This need not necessarily be the case and the height may be determined to be another predetermined position on the Gaussian fit, such as the half height position on one side or the other. Also, as described above, where the height is determined from the phase data it is determined to be the position of zero phase. This

need not necessarily be the case and the height may be determined to be at the position corresponding to a predetermined phase other than zero.

At step S53 in Figure 15, the surface topography determiner 35 unwraps the phase by using the phase gradient to calculate the expected phase for a datum point (cosine/sine wavepacket correlation value)and then adding or subtracting 2π to the phase of the datum point until the difference from the expected phase is less than π. As another possibility the actual phase may be determined by scanning through the phase data, detecting where the phase jumps, considering the direction of the jump and integrating the phase by adding or subtracting 2π at such jumps or discontinuities. Any other conventional phase unwrapping procedure may be used.

In the embodiments described above, the beam splitter 5 may have a reflectance of about 20% to reduce or avoid the possibility of light reflected by the sample being swamped by light reflected by the reference mirror. As another possibility the reference mirror 6, rather than the beam splitter 5, may be so tailored and may have a reflectance of about 20%. This would however, be less efficient because of the loss of light.

In the embodiments described above, the frame interval and width of the Gaussian envelope of the correlator may be selected so that the correlation indices add up to zero which enables correlation to be carried out for very

low intensity value signal levels because there is no resultant offset.

In the embodiments described above with reference to Figure 19d, the range of correlation elements is copied to a copy buffer. As another possibility this range may be frozen.

In the above described embodiments, the surface profiling apparatus is used to determine the surface profile or topography of a surface area. The present invention may, however, also be used to determine a step height, that is the relative height distance between two individual points or surface pixels on a surface or to determine the height of a single surface pixel relative to a fixed reference.

CLAIMS:

1. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light source providing means for providing broadband spatially incoherent light;

light directing means for directing light from the light source providing means along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a scan path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values, said data processing means comprising:

receiving means for receiving intensity values from the sensing means during a measurement operation;

first processing means for carrying out processing on intensity values as the intensity values are received by the receiving means during a measurement operation to produce data indicating the position of a coherence peak; and

second processing means for, after completion of a measurement operation, using the data produced by the first processing means to obtain data indicative of a height of the surface region, wherein one of the first and second processing means comprises:

correlating means for correlating intensity values with correlation function data representing a correlation function to provide correlation data for that sample surface region to enable a position of a coherence peak in the intensity values for a sample surface region to be identified; and

the second processing means comprises surface height determining means for determining a height of a sample surface region from data related to the position of the coherence peak.

2. Apparatus according to claim 1, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function having first and second periodically varying wave functions with the first and second wave functions being of different phase and being bounded by an envelope.

3. Apparatus according to claim 2, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function in which the envelope is a smoothly varying peaked function.

4. Apparatus according to claim 3, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function in which the envelope is a Gaussian.

5. Apparatus according to claim 2, 3 or 4, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function in which the first and second wave functions are sine and cosine wave functions.

6. Apparatus according to claim 1, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function consisting of sine and cosine wave functions bounded by a Gaussian envelope.

7. Apparatus according to any one of the preceding claims, wherein the first processing means comprises the correlating means.

8. Apparatus according to claim 7, wherein the correlating means comprises:

correlation processing means for correlating intensity values with correlation function data to produce correlation data;

peak finding means for finding a position related to a coherence peak in the correlation data, the peak finding means being operable to copy a range of the correlation data including the correlation data for the position related to the coherence peak into a copy buffer or to freeze the range of correlation data in the correlation buffer, for subsequent processing by the second processing means.

9. Apparatus according to any one of claims 1 to 6, wherein the second processing means comprises the correlating means and the first processing means comprises determining means for determining a range of the intensity values that includes an intensity value representing a coherence peak and for identifying that range of intensity values to the correlating means.

10. Apparatus according to claim 9, wherein the determining means comprises discriminating means for determining discrimination values for successive sets of received intensity values and peak finding means for finding a peak in the discrimination values and for identifying the peak as representing the coherence peak.

11. Apparatus according to claim 10, wherein the discriminating means is arranged to determine

discrimination values for sets consisting of spaced-apart received intensity values.

12. Apparatus according to claim 11, wherein the discriminating means is arranged to determine discrimination values for sets consisting of every second received intensity value.

13. Apparatus according to claim 10, 11 or 12, wherein the discriminating means is arranged to determine discrimination values for successive sets of received intensity values wherein each successive set consists of intensity values from the previous set and at least one further intensity value.

14. Apparatus according to claim 10, wherein the discriminating means is arranged to determine discrimination values by multiplying a set of intensity values by corresponding pairs of discrimination values.

15. Apparatus according to claim 10, wherein the control means is arranged to provide a scan interval such that certain discrimination values are zero.

16. Apparatus according to claim 14, wherein the control means is arranged to provide a scan interval such that one of each pair of discrimination values is alternately zero.

17. Apparatus according to claim 16, wherein the discriminating value pairs are: 0,1; 1,0; 0,-1; -1,0.

18. Apparatus according to any one of claims 10 to 17, wherein the discriminating means is arranged to identify the range of intensity values in accordance with whether or not the peak in the discrimination values is higher than a predetermined threshold.

19. Apparatus according to claim 18, wherein the discriminating means is arranged to use as the predetermined threshold a value related to the mean of the discrimination values.

20. Apparatus according to claim 18 or 19, wherein the discriminating means is arranged to set the range as all of the intensity values supplied by the sensing means for the sample surface region when the peak of the discrimination values does not exceed the predetermined threshold.

21. Apparatus according to any one of the preceding claims, wherein the correlating means is arranged to correlate intensity values with correlation function data comprising a set of pairs of first and second indices to produce pairs of correlation elements.

22. Apparatus according to any one of claims 9 to 20, wherein the correlating means is arranged to correlate intensity values with correlation function data

comprising a set of pairs of first and second indices and is arranged to produce a pair of correlation elements for a given intensity value by multiplying each of a range of intensity values including the given intensity value by a corresponding one of the first indices and summing the results to produce a first one of the pair of correlation elements and by multiplying each of the range of intensity values by a corresponding one of the second indices and summing the results to produce the other one of the pair of correlation elements, the correlation means being operable to store the pair of correlation elements in a memory area of a correlation buffer of the correlating means.

23. Apparatus according to claim 7, 8, 9 or 10, wherein:

the correlating means has correlation function providing means providing the correlation function data as a number of groups each consisting of a number of pairs of first and second indices and has a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating means is arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first group of said pairs of indices to produce, for each of said pairs of indices, corresponding pairs of first and second multiplication elements and to accumulate each pair of multiplication

elements in a corresponding different one of a series of the memory areas;

to carry out a second step of repeating the first step for each of a succession of said intensity values using a different group of said pairs of indices at each repetition;

to carry out a third step by moving the series of memory areas by a predetermined number of memory areas along the array and then repeating the first and second steps; and

to carry out a fourth step by repeating the third step moving the series of memory areas by a predetermined number of memory areas along the array at each repetition until, at least for each of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of the multiplication elements resulting from multiplying each of a sequence of said intensity values by a corresponding different one of the first and second indices, respectively.

24. Apparatus according to claim 7, 8, 9 or 10, wherein:

the correlating means has correlation function providing means providing the correlation function data as four groups each having four pairs of first and second indices and has a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating means is arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first one of said groups of pairs of indices to produce four pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of four of the memory areas;

to carry out a second step of repeating the first step for the next three intensity values using the second, third and fourth groups of said pairs of indices, respectively;

to carry out a third step by moving the series of memory areas by one and then repeating the first step for the next intensity value and the second step for the three following intensity values; and

to carry out a fourth step by repeating the third step moving the series of memory areas by one memory area along the array at each repetition until, for every fourth one of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of multiplication elements resulting from multiplying each of a sequence of sixteen of said intensity values by a corresponding different one of the first and second indices, respectively.

25. Apparatus according to claim 22, 23 or 24, wherein the correlation buffer is a circular buffer and

correlation buffer control means are provided for overwriting an oldest entry in the buffer when the buffer is full.

26. Apparatus according to any one of claims 9 to 15, 20 or 22, wherein the determining means comprises further correlating means.

27. Apparatus according to claim 26, wherein the further correlating means is arranged to use a coarser correlation function than the correlating means.

28. Apparatus according to claim 26 or 27, wherein the further correlating means is arranged to function in the manner set out in any one of claims 22, 23 or 24.

29. Apparatus according to any one of claims 21 to 28, wherein the control means is arranged to provide a scan interval such that certain of the correlation function data is zero.

30. Apparatus according to any one of claims 21 to 25 or 28, wherein the control means is arranged to provide a scan interval such that certain correlation indices are zero.

31. Apparatus according to any one of claims 21 to 25 or 28, wherein the control means is arranged to provide a scan interval such that one of each pair of correlation indices is alternately zero.

32. Apparatus according to any one of the preceding claims, wherein the peak finding means is arranged to function in a number of different states with the switch from one state to the next being determined by the relationship of an intensity value, discrimination value or correlation element to a previous intensity value, discrimination value or correlation element or threshold.

33. Apparatus according to claim 32, wherein the peak finding means has an optional initial state which exists for a first value, a low state which exists when the value is below a threshold value, a found state which exists when the value is above the threshold value, and an optional early state which exists if the first value is above the threshold value.

34. Apparatus according to claim 32, wherein the peak finding means has an optional initial state that exists for a first value, a low state that exists before the value rises above a threshold value, a rising state that exists when the value is rising, a falling state that exists when the value is falling, a found state that exists if the value falls below a predetermined proportion of a previous maximum value, and an optional state that exists if the first value is above the threshold.

35. Apparatus according to any one of the preceding claims, wherein the surface height determining means is arranged to determine a height of a sample region by

fitting a Gaussian to values provided by the correlating means and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

36. Apparatus according to any one of claims 21 to 34, wherein the surface height determining means is arranged to determine amplitude values from the pairs of correlation elements and to determine a height of a sample region by fitting a Gaussian to amplitude values and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

37. Apparatus according to claim 36, wherein the surface height determining means is arranged to obtain the amplitude values by determining the sum of the square of the correlation elements of each pair to obtain a squared amplitude value for each pair of correlation elements, to find a range of squared amplitude values including a highest value, to determine a square root value for each of said range of squared amplitude values and to fit the Gaussian to said square root values.

38. Apparatus according to any one of claims 35 to 37, wherein the surface height determining means is arranged to carry out a smoothing procedure before fitting the Gaussian.

39. Apparatus according to claim 36 or 37, wherein the surface height determining means is arranged to smooth the squared amplitude values using a box filter.

40. Apparatus according to any one of the preceding claims, wherein the surface height determining means is arranged to determine a signal-to-noise ratio for the values provided by the correlating means and to abort the height determination if the signal-to-noise ratio is too low.

41. Apparatus according to any one of claims 36 to 39, wherein the surface height determining means is arranged to accumulate the squared amplitude values and to abort the height determination if the ratio between a maximum squared amplitude value and a mean of the accumulated squared amplitude values is below a threshold.

42. Apparatus according to any one of the preceding claims, wherein the surface height determining means further comprises phase determining means for determining the intensity value having a predetermined phase and for determining a height of a sample surface region using a position on the scan path corresponding to the determined intensity value.

43. Apparatus according to claim 42, wherein the phase determining means is operable to determine an estimate of the predetermined phase position using the intensity value closest to the coherence peak, then to unwrap the

phase of the correlation values, and to determine the actual position corresponding to the predetermined phase using a linear fitting procedure.

44. Apparatus according to any one of the preceding claims, wherein position determining means are provided for determining the position of said one of the sample surface and the reference surface on the scan path and triggering means are provided for triggering the sensing means to sense light intensity to provide a set of intensity data signals in accordance with position data obtained by the position determining means.

45. Apparatus according to any one of the preceding claims, wherein the sensing means comprises a two-dimensional array of sensing elements and control means are provided for controlling the field of view of the sensing means by controlling combining or selecting of intensity data signals produced by sensing elements.

46. Apparatus according to any one of the preceding claims, wherein the light directing means comprises beam splitting means for splitting light from the light source providing means into reference light directed along the reference path and sample light directed along the sample path.

47. Apparatus according to claim 46, wherein at least one of the reference surface and the beam splitting means

is configured such that less than 50% of the light is directed along the reference path.

48. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light source providing means for providing broad band spatially incoherent light;

light directing means for directing light from the light source providing means along the sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a scan path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values to obtain data indicative of a height of the surface region;

wherein the light directing means comprises beam splitting means for splitting light from the light source providing means into reference light directed along the reference path and sample light directed along sample path such that less than 50% of the light is directed along the reference path.

49. Apparatus according to claim 47 or 48, wherein the beam splitting means is arranged to direct about 20% of the light along the reference path.

50. Apparatus according to claim 47, 48 or 49, wherein the beam splitting means comprises a Herpin filter or a neutral density partially reflective metal filter.

51. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light source providing means for providing broad band spatially incoherent light;

light directing means for directing light from the light source providing means along the sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a scan path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values to obtain data indicative of a height of the surface region;

wherein position determining means are provided for determining the position of said one of the sample surface and the reference surface on the scan path and triggering means are provided for triggering the sensing means to sense light intensity to provide a set of intensity data signals in accordance with position data obtained by the position determining means.

52. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light source providing means for providing broad band spatially incoherent light;

light directing means for directing light from the light source providing means along the sample path towards a region of a sample surface and along a reference path towards a reference surface such that

light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a scan path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values to obtain data indicative of a height of the surface region;

wherein the sensing means comprises a two-dimensional array of sensing elements and control means are provided for controlling the field of view of the sensing means by controlling combining or selecting of intensity data signals produced by sensing elements.

53. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light source providing means for providing broadband spatially incoherent light;

light directing means for directing light from the light source providing means along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a scan path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values, said data processing means comprising:

receiving means for receiving intensity values from the sensing means during a measurement operation; and

surface height determining means for determining a height of a sample region by fitting a Gaussian to data derived from the received intensity values and identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

54. Apparatus according to claim 53, wherein the surface height determining means is arranged to carry out a smoothing procedure before fitting the Gaussian.

55. A method of obtaining surface profile data for a sample surface, the method comprising:

directing light from a broadband spatially incoherent source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

effecting relative movement along a scan path between the sample surface and the reference surface;

sensing light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

processing the intensity values by:

receiving intensity values from the sensing means during a measurement operation;

carrying out a first processing step on intensity values as the intensity values are received by the receiving means during a measurement operation to produce data indicating the position of a coherence peak; and

in a second processing step, after completion of a measurement operation, using the data produced by the first processing step to obtain data indicative of a height of the surface region, wherein one of the first and second processing steps comprises:

a correlating step correlating intensity values with correlation function data representing a correlation function to provide correlation data for that sample surface region to enable a position of a coherence peak in the intensity values for a sample surface region to be identified; and

the second processing step comprises a surface height determining step determining a height of a sample surface region from data related to the position of the coherence peak.

56. A method according to claim 55, wherein the correlating step correlates intensity values with correlation function data representing a correlation function having first and second periodically varying wave functions with the first and second wave functions being of different phase and being bounded by an envelope.

57. A method according to claim 56, wherein the correlating step correlates intensity values with correlation function data representing a correlation function in which the envelope is a smoothly varying peaked function.

58. A method according to claim 57, wherein the correlating step correlates intensity values with correlation function data representing a correlation function in which the envelope is a Gaussian.

59. A method according to claim 56, 57 and 58, wherein the correlating step correlates intensity values with correlation function data representing a correlation function in which the first and second wave functions are sine and cosine wave functions.

60. A method according to claim 55, wherein the correlating step correlates intensity values with correlation function data representing a correlation function consisting of sine and cosine wave functions bounded by a Gaussian envelope.

61. A method according to any one of claims 55 to 60, wherein the first processing step comprises the correlating step.

62. A method according to claim 61, wherein the correlating step comprises:

a correlation processing step correlating intensity values with correlation function data to produce correlation data;

a peak finding step finding a position related to a coherence peak in the correlation data, the peak finding step copying a range of the correlation data including the correlation data for the position related to the coherence peak into a copy buffer or freezing the range of correlation data in the correlation buffer, for subsequent processing in the second processing step.

63. A method according to any one of claims 55 to 60, wherein the second processing step comprises the correlating step and the first processing step comprises determining a range of the intensity values that includes an intensity value representing a coherence peak and identifying that range of intensity values for use in the correlating step.

64. A method according to claim 63, wherein the determining step comprises a discriminating step determining discrimination values for successive sets of received intensity values and a peak finding step finding a peak in the discrimination values and identifying the peak as representing the coherence peak.

65. A method according to claim 64, wherein the discriminating step determines discrimination values for sets consisting of spaced-apart received intensity values.

66. A method according to claim 65, wherein the discriminating step determines discrimination values for sets consisting of every second received intensity value.

67. A method according to claim 64, 65 or 66, wherein the discriminating step determines discrimination values for successive sets of received intensity values wherein each successive set consists of intensity values from the previous set and at least one further intensity value.

68. A method according to claim 64, wherein the discriminating step determines discrimination values by multiplying a set of intensity values by corresponding pairs of discrimination values.

69. A method according to claim 64, wherein a scan interval is such that certain discrimination values are zero.

70. A method according to claim 68, wherein a scan interval is such that one of each pair of discrimination values is alternately zero.

71. A method according to claim 70, wherein the discriminating value pairs are: 0,1; 1,0; 0,-1; -1,0.

72. A method according to any one of claims 64 to 71, wherein the discriminating step identifies the range of intensity values in accordance with whether or not the peak in the discrimination values is higher than a predetermined threshold.

73. A method according to claim 72, wherein the discriminating step uses as the predetermined threshold a value related to the mean of the discrimination values.

74. A method according to claim 72 or 73, wherein the discriminating step sets the range as all of the intensity values supplied for the sample surface region

when the peak of the discrimination values does not exceed the predetermined threshold.

75. A method according to any one of claims 55 to 74, wherein the correlating step correlates intensity values with correlation function data comprising a set of pairs of first and second indices to produce pairs of correlation elements.

76. A method according to any one of claims 63 to 74, wherein the correlating step correlates intensity values with correlation function data comprising a set of pairs of first and second indices and produces a pair of correlation elements for a given intensity value by multiplying each of a range of intensity values including the given intensity value by a corresponding one of the first indices and summing the results to produce a first one of the pair of correlation elements and by multiplying each of the range of intensity values by a corresponding one of the second indices and summing the results to produce the other one of the pair of correlation elements, the pair of correlation elements being stored in a memory area of a correlation buffer of the correlating means.

77. Apparatus according to claim 61, 62, 63 or 64, wherein:

the correlating step uses correlation function data having a number of groups each consisting of a number of pairs of first and second indices and a correlation

buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating step comprises:

a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first group of said pairs of indices to produce, for each of said pairs of indices, corresponding pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of a series of the memory areas;

a second step of repeating the first step for each of a succession of said intensity values using a different group of said pairs of indices at each repetition;

a third step of moving the series of memory areas by a predetermined number of memory areas along the array and then repeating the first and second steps; and

a fourth step of repeating the third step moving the series of memory areas by a predetermined number of memory areas along the array at each repetition until, at least for each of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of the multiplication elements resulting from multiplying each of a sequence of said intensity values

by a corresponding different one of the first and second indices, respectively.

78. A method according to claim 61, 62, 63 or 64, wherein:

the correlating step uses correlation function data having four groups each having four pairs of first and second indices and a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating step comprises:

a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first one of said groups of pairs of indices to produce four pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of four of the memory areas;

a second step of repeating the first step for the next three intensity values using the second, third and fourth groups of said pairs of indices, respectively;

a third step of moving the series of memory areas by one and then repeating the first step for the next intensity value and the second step for the three following intensity values; and

a fourth step of repeating the third step moving the series of memory areas by one memory area along the array at each repetition until, for every fourth one of a number of the intensity values, a memory location

corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of multiplication elements resulting from multiplying each of a sequence of sixteen of said intensity values by a corresponding different one of the first and second indices, respectively.

79. A method according to claim 76, 77 or 78, wherein the correlation buffer is a circular buffer and for an oldest entry in the buffer is overwritten when the buffer is full.

80. A method according to any one of claims 63 to 69, 74 or 76, wherein the determining step comprises another correlating step.

81. A method according to claim 80, wherein the other correlating step uses a coarser correlation function than the correlating step.

82. A method according to claim 80 or 81, wherein the other correlating step functions in the manner set out in any one of claims 76, 77 or 78.

83. A method according to any one of claims 75 to 82, wherein a scan interval is such that certain of the correlation function data is zero.

84. A method according to any one of claims 75 to 79 or 82, wherein a scan interval is such that certain correlation indices are zero.

85. A method according to any one of claims 75 to 79 or 82, wherein a scan interval is such that one of each pair of correlation indices is alternately zero.

86. A method according to any one of claims 55 to 85, wherein the peak finding step functions in a number of different states with the switch from one state to the next being determined by the relationship of an intensity value, discrimination value or correlation element to a previous intensity value, discrimination value, or correlation element or threshold.

87. A method according to claim 86, wherein the peak finding step has an optional initial state which exists for a first value, a low state which exists when the value is below a threshold value, a found state which exists when the value is above the threshold value, and an optional early state which exists if the first value is above the threshold value.

88. A method according to claim 86, wherein the peak finding step has an optional initial state that exists for a first value, a low state that exists before the value rises above a threshold value, a rising state that exists when the value is rising, a falling state that exists when the value is falling, a found state that

exists if the value falls below a predetermined proportion of a previous maximum value, and an optional state that exists if the first value is above the threshold.

89. A method according to any one of claims 55 to 88, wherein the surface height determining step determines a height of a sample region by fitting a Gaussian to values provided by the correlating means and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

90. A method according to any one of claims 75 to 88, wherein the surface height determining step determines amplitude values from the pairs of correlation elements and determines a height of a sample region by fitting a Gaussian to amplitude values and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

91. A method according to claim 90, wherein the surface height determining step obtains the amplitude values by determining the sum of the square of the correlation elements of each pair to obtain a squared amplitude value for each pair of correlation elements, finds a range of squared amplitude values including a highest value, determines a square root value for each of said range of

squared amplitude values and to fit the Gaussian to said square root values.

92. A method according to any one of claims 89 to 91, wherein the surface height determining step carries out a smoothing procedure before fitting the Gaussian.

93. A method according to claim 90 or 91, wherein the surface height determining step smooths the squared amplitude values using a box filter.

94. A method according to any one of claims 55 to 93, wherein the surface height determining step determines a signal-to-noise ratio for the values provided by the correlating step and aborts the height determination if the signal-to-noise ratio is too low.

95. A method according to any one of claims 90 to 93, wherein the surface height determining step accumulates the squared amplitude values and aborts the height determination if the ratio between a maximum square amplitude value and a mean of the accumulated squared amplitude values is below a threshold.

96. A method according to any one of claims 55 to 95, wherein the surface height determining step further comprises a phase determining step determining the intensity value having a predetermined phase and determining a height of a sample surface region using a

position on the scan path corresponding to the determined intensity value.

97. A method according to claim 96, wherein the phase determining step determines an estimate of the predetermined phase position using the intensity value closest to the coherence peak, then unwraps the phase of the correlation values, and determines the actual position corresponding to the predetermined phase using a linear fitting procedure.

98. A method according to any one of claims 55 to 97, further comprising a position determining step determining the position of said one of the sample surface and the reference surface on the scan path and a triggering step triggering sensing of light intensity to provide a set of intensity data signals in accordance with position data obtained in the position determining step.

99. A method according to any one of claims 55 to 98, wherein the sensing step uses a sensing means having a two-dimensional array of sensing elements and the field of view of the sensing means is controlled by controlling combining or selecting of intensity data signals produced by sensing elements.

100. A method according to any one of claims 55 to 99, wherein the light directing step uses beam splitting means splitting light from the light source providing

means into reference light directed along the reference path and sample light directed along the sample path.

101. A method according to claim 100, wherein at least one of the reference surface and the beam splitting means is configured such that less than 50% of the light is directed along the reference path.

102. A method of obtaining surface profile data for a sample surface, the method comprising:

directing light from a broadband spatially incoherent source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

effecting relative movement along a scan path between the sample surface and the reference surface;

sensing light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

processing the intensity values;

further comprising the steps of determining the position of said one of the sample surface and the reference surface on the scan path and triggering sensing of light intensity to provide a set of intensity data signals in accordance with position data obtained by the position determining step.

103. A method of obtaining surface profile data for a sample surface, the method comprising:

directing light from a broadband spatially incoherent source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

effecting relative movement along a scan path between the sample surface and the reference surface;

sensing light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

processing the intensity values;

wherein the sensing step uses a two-dimensional array of sensing elements and the field of view is controlled by controlling combining or selecting of intensity data signals produced by sensing elements.

104. A method of obtaining surface profile data for a sample surface, the method comprising:

directing light from a broadband spatially incoherent source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the

region of the sample surface and light reflected by the reference surface interfere;

effecting relative movement along a scan path between the sample surface and the reference surface;

sensing light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

processing the intensity values;

further comprising determining a height of a sample by fitting a Gaussian to data derived from the received intensity values and identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

105. A method according to claim 104, wherein the surface height determining step carries out a smoothing procedure before fitting the Gaussian.

106. Data processing apparatus for processing intensity values, said data processing apparatus comprising:

first processing means for carrying out processing on intensity values as the intensity values are received by receiving means during a measurement operation to

produce data indicating the position of a coherence peak; and

second processing means for, after completion of a measurement operation, using the data produced by the first processing means to obtain data indicative of a height of the surface region, wherein one of the first and second processing means comprises:

correlating means for correlating intensity values with correlation function data representing a correlation function to provide correlation data for that sample surface region to enable a position of a coherence peak in the intensity values for a sample surface region to be identified; and

the second processing means comprises surface height determining means for determining a height of a sample surface region from data related to the position of the coherence peak.

107. Apparatus according to claim 106, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function consisting of sine and cosine wave functions bounded by a Gaussian envelope.

108. Apparatus according to claim 106 or 107, wherein the first processing means comprises the correlating means.

109. Apparatus according to claim 108, wherein the correlating means comprises:

correlation processing means for correlating intensity values with correlation function data to produce correlation data;

peak finding means for finding a position related to a coherence peak in the correlation data, the peak finding means being operable to copy a range of the correlation data including the correlation data for the position related to the coherence peak into a copy buffer or to freeze the range of correlation data in the correlation buffer, for subsequent processing by the second processing means.

110. Apparatus according to claim 106 to 107, wherein the second processing means comprises the correlating means and the first processing means comprises determining means for determining a range of the intensity values that includes an intensity value representing a coherence peak and for identifying that range of intensity values to the correlating means.

111. Apparatus according to claim 110, wherein the determining means comprises discriminating means for determining discrimination values for successive sets of received intensity values and peak finding means for

finding a peak in the discrimination values and for identifying the peak as representing the coherence peak.

112. Apparatus according to claim 111, wherein the discriminating means is arranged to determine discrimination values for sets consisting of spaced-apart received intensity values.

113. Apparatus according to claim 112, wherein the discriminating means is arranged to determine discrimination values for sets consisting of every second received intensity value.

114. Apparatus according to claim 111, 112 or 113, wherein the discriminating means is arranged to determine discrimination values for successive sets of received intensity values wherein each successive set consists of intensity values from the previous set and at least one further intensity value.

115. Apparatus according to claim 111, wherein the discriminating means is arranged to determine discrimination values by multiplying a set of intensity values by corresponding pairs of discrimination values.

116. Apparatus according to claim 111, wherein the control means is arranged to provide a scan interval such that certain discrimination values are zero.

117. Apparatus according to claim 115, wherein the control means is arranged to provide a scan interval such that one of each pair of discrimination values is alternately zero.

118. Apparatus according to claim 117, wherein the discriminating value pairs are: 0,1; 1,0; 0,-1; -1,0.

119. Apparatus according to any one of claims 111 to 118, wherein the discriminating means is arranged to identify the range of intensity values in accordance with whether or not the peak in the discrimination values is higher than a predetermined threshold.

120. Apparatus according to claim 119, wherein the discriminating means is arranged to use as the predetermined threshold a value related to the mean of the discrimination values.

121. Apparatus according to any one of claims 110 to 120, wherein the correlating means is arranged to correlate intensity values with correlation function data

comprising a set of pairs of first and second indices and is arranged to produce a pair of correlation elements for a given intensity value by multiplying each of a range of intensity values including the given intensity value by a corresponding one of the first indices and summing the results to produce a first one of the pair of correlation elements and by multiplying each of the range of intensity values by a corresponding one of the second indices and summing the results to produce the other one of the pair of correlation elements, the correlation means being operable to store the pair of correlation elements in a memory area of a correlation buffer of the correlating means.

122. A correlator for use in apparatus in accordance with claim 106, comprising:

correlation function providing means providing the correlation function data as a number of groups each consisting of a number of pairs of first and second indices and having a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

correlation processing means arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the

second index of each of a first group of said pairs of indices to produce, for each of said pairs of indices, corresponding pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of a series of the memory areas;

to carry out a second step of repeating the first step for each of a succession of said intensity values using a different group of said pairs of indices at each repetition;

to carry out a third step by moving the series of memory areas by a predetermined number of memory areas along the array and then repeating the first and second steps; and

to carry out a fourth step by repeating the third step moving the series of memory areas by a predetermined number of memory areas along the array at each repetition until, at least for each of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of the multiplication elements resulting from multiplying each of a sequence of said intensity values by a corresponding different one of the first and second indices, respectively.

123. A correlator for use in apparatus in accordance with claim 106, comprising:

correlation function providing means providing the correlation function data as four groups each having four pairs of first and second indices and having a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

correlation processing means arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first one of said groups of pairs of indices to produce four pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of four of the memory areas;

to carry out a second step of repeating the first step for the next three intensity values using the second, third and fourth groups of said pairs of indices, respectively;

to carry out a third step by moving the series of memory areas by one and then repeating the first step for the next intensity value and the second step for the three following intensity values; and

to carry out a fourth step by repeating the third step moving the series of memory areas by one memory area along the array at each repetition until, for every fourth one of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of multiplication elements resulting from multiplying each of a sequence of sixteen of said intensity values by a corresponding different one of the first and second indices, respectively.

124. A signal carrying program instructions for programming processing means to carry out a method in accordance with any one of claims 55 to 105.

125. A storage medium carrying program instructions for programming processing means to carry out a method in accordance with any one of claims 55 to 105.

Amendments to the claims have been filed as follows

CLAIMS:

1. Surface profiling apparatus for obtaining surface profile data for a sample surface, the apparatus comprising:

light directing means for directing light from a broadband source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

moving means for effecting relative movement along a measurement path between the sample surface and the reference surface;

sensing means for sensing light representing the interference fringes produced by a sample surface region during said relative movement;

control means for carrying out a measurement operation by causing said moving means to effect said relative movement while said sensing means senses light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

data processing means for processing the intensity values, said data processing means comprising:

receiving means for receiving intensity values from the sensing means during a measurement operation;

first processing means for carrying out processing on intensity values as the intensity values are received

by the receiving means during a measurement operation to produce data indicating the position of a coherence peak; and

second processing means for, after completion of a measurement operation, using the data produced by the first processing means to obtain data indicative of a height of the surface region, wherein one of the first and second processing means comprises:

correlating means for correlating intensity values with correlation function data representing a correlation function to provide correlation data for that sample surface region to enable a position of a coherence peak in the intensity values for a sample surface region to be identified; and

the second processing means comprises surface height determining means for determining data relating to a height of a sample surface region from data related to the position of the coherence peak.

2. Apparatus according to claim 1, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function having first and second periodically varying wave functions with the first and second wave functions being of different phase and being bounded by an envelope.

3. Apparatus according to claim 2, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a

correlation function in which the envelope is a smoothly varying peaked function.

4. Apparatus according to claim 3, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function in which the envelope is a Gaussian.

5. Apparatus according to claim 2, 3 or 4, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function in which the first and second wave functions are sine and cosine wave functions.

6. Apparatus according to claim 1, wherein the correlating means is arranged to correlate intensity values with correlation function data representing a correlation function consisting of sine and cosine wave functions bounded by a Gaussian envelope.

7. Apparatus according to any one of the preceding claims, wherein the first processing means comprises the correlating means.

8. Apparatus according to claim 7, wherein the correlating means comprises:

correlation processing means for correlating intensity values with correlation function data to produce correlation data;

a correlation buffer for receiving correlation data produced by the correlation processing means;

peak finding means for finding a position related to a coherence peak in the correlation data, the peak finding means being operable to copy a range of the correlation data including the correlation data for the position related to the coherence peak into a copy buffer or to freeze the range of correlation data in the correlation buffer, for subsequent processing by the second processing means.

9. Apparatus according to any one of claims 1 to 6, wherein the second processing means comprises the correlating means and the first processing means comprises determining means for determining a range of the intensity values that includes an intensity value representing a coherence peak and for identifying that range of intensity values to the correlating means.

10. Apparatus according to claim 9, wherein the determining means comprises discriminating means for determining discrimination values for successive sets of received intensity values and peak finding means for finding a peak in the discrimination values and for identifying the peak as representing the coherence peak.

11. Apparatus according to claim 10, wherein the discriminating means is arranged to determine discrimination values for sets consisting of spaced-apart received intensity values.

12. Apparatus according to claim 11, wherein the discriminating means is arranged to determine discrimination values for sets consisting of every second received intensity value.

13. Apparatus according to claim 10, 11 or 12, wherein the discriminating means is arranged to determine discrimination values for successive sets of received intensity values wherein each successive set consists of intensity values from the previous set and at least one further intensity value.

14. Apparatus according to claim 10, wherein the discriminating means is arranged to determine discrimination values by multiplying a set of intensity values by corresponding pairs of discrimination values.

15. Apparatus according to claim 10, wherein the control means is arranged to provide a measurement interval such that certain discrimination values are zero.

16. Apparatus according to claim 14, wherein the control means is arranged to provide a measurement interval such that one of each pair of discrimination values is alternately zero.

17. Apparatus according to claim 16, wherein the discriminating value pairs are: 0,1; 1,0; 0,-1; -1,0.

18. Apparatus according to any one of claims 10 to 17, wherein the discriminating means is arranged to identify the range of intensity values in accordance with whether or not the peak in the discrimination values is higher than a predetermined threshold.

19. Apparatus according to claim 18, wherein the discriminating means is arranged to use as the predetermined threshold a value related to the mean of the discrimination values.

20. Apparatus according to claim 18 or 19, wherein the discriminating means is arranged to set the range as all of the intensity values supplied by the sensing means for the sample surface region when the peak of the discrimination values does not exceed the predetermined threshold.

21. Apparatus according to any one of the preceding claims, wherein the correlating means is arranged to correlate intensity values with correlation function data comprising a set of pairs of first and second indices to produce pairs of correlation elements.

22. Apparatus according to any one of claims 9 to 20, wherein the correlating means is arranged to correlate intensity values with correlation function data comprising a set of pairs of first and second indices and is arranged to produce a pair of correlation elements for a given intensity value by multiplying each of a range

of intensity values including the given intensity value by a corresponding one of the first indices and summing the results to produce a first one of the pair of correlation elements and by multiplying each of the range of intensity values by a corresponding one of the second indices and summing the results to produce the other one of the pair of correlation elements, the correlation means being operable to store the pair of correlation elements in a memory area of a correlation buffer of the correlating means.

23. Apparatus according to claim 7, 8, 9 or 10, wherein:

the correlating means has correlation function providing means providing the correlation function data as a number of groups each consisting of a number of pairs of first and second indices and has a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating means is arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first group of said pairs of indices to produce, for each of said pairs of indices, corresponding pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of a series of the memory areas;

to carry out a second step of repeating the first step for each of a succession of said intensity values using a different group of said pairs of indices at each repetition;

to carry out a third step by moving the series of memory areas by a predetermined number of memory areas along the array and then repeating the first and second steps; and

to carry out a fourth step by repeating the third step moving the series of memory areas by a predetermined number of memory areas along the array at each repetition until, at least for each of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of the multiplication elements resulting from multiplying each of a sequence of said intensity values by a corresponding different one of the first and second indices, respectively.

24. Apparatus according to claim 7, 8, 9 or 10, wherein:

the correlating means has correlation function providing means providing the correlation function data as four groups each having four pairs of first and second indices and has a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating means is arranged:

to carry out a first step of multiplying a first intensity value of a series of intensity values for a

surface region separately by the first index and by the second index of each of a first one of said groups of pairs of indices to produce four pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of four of the memory areas;

to carry out a second step of repeating the first step for the next three intensity values using the second, third and fourth groups of said pairs of indices, respectively;

to carry out a third step by moving the series of memory areas by one and then repeating the first step for the next intensity value and the second step for the three following intensity values; and

to carry out a fourth step by repeating the third step moving the series of memory areas by one memory area along the array at each repetition until, for every fourth one of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of multiplication elements resulting from multiplying each of a sequence of sixteen of said intensity values by a corresponding different one of the first and second indices, respectively.

25. Apparatus according to claim 22, 23 or 24, wherein the correlation buffer is a circular buffer and correlation buffer control means are provided for

overwriting an oldest entry in the buffer when the buffer is full.

26. Apparatus according to any one of claims 9 to 15, 20 or 22, wherein the determining means comprises further correlating means.

27. Apparatus according to claim 26, wherein the further correlating means is arranged to use a coarser correlation function than the correlating means.

28. Apparatus according to claim 26 or 27, wherein the further correlating means is arranged to function in the manner set out in any one of claims 22, 23 or 24.

29. Apparatus according to any one of claims 21 to 28, wherein the control means is arranged to provide a measurement interval such that certain of the correlation function data is zero.

30. Apparatus according to any one of claims 21 to 25 or 28, wherein the control means is arranged to provide a measurement interval such that certain correlation indices are zero.

31. Apparatus according to any one of claims 21 to 25 or 28, wherein the control means is arranged to provide a measurement interval such that one of each pair of correlation indices is alternately zero.

32. Apparatus according to any one of the preceding claims, wherein the peak finding means is arranged to function in a number of different states with the switch from one state to the next being determined by the relationship of an intensity value, discrimination value or correlation element to a previous intensity value, discrimination value or correlation element or threshold.

33. Apparatus according to claim 32, wherein the peak finding means has an optional initial state which exists for a first value, a low state which exists when the value is below a threshold value, a found state which exists when the value is above the threshold value, and an optional early state which exists if the first value is above the threshold value.

34. Apparatus according to claim 32, wherein the peak finding means has an optional initial state that exists for a first value, a low state that exists before the value rises above a threshold value, a rising state that exists when the value is rising, a falling state that exists when the value is falling, a found state that exists if the value falls below a predetermined proportion of a previous maximum value, and an optional state that exists if the first value is above the threshold.

35. Apparatus according to any one of the preceding claims, wherein the surface height determining means is arranged to determine a height of a sample region by

fitting a Gaussian to values provided by the correlating means and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

36. Apparatus according to any one of claims 21 to 34, wherein the surface height determining means is arranged to determine amplitude values from the pairs of correlation elements and to determine a height of a sample region by fitting a Gaussian to amplitude values and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

37. Apparatus according to claim 36, wherein the surface height determining means is arranged to obtain the amplitude values by determining the sum of the square of the correlation elements of each pair to obtain a squared amplitude value for each pair of correlation elements, to find a range of squared amplitude values including a highest value, to determine a square root value for each of said range of squared amplitude values and to fit the Gaussian to said square root values.

38. Apparatus according to any one of claims 35 to 37, wherein the surface height determining means is arranged to carry out a smoothing procedure before fitting the Gaussian.

39. Apparatus according to claim 36 or 37, wherein the surface height determining means is arranged to smooth the squared amplitude values using a box filter.

40. Apparatus according to any one of the preceding claims, wherein the surface height determining means is arranged to determine a signal-to-noise ratio for the values provided by the correlating means and to abort the height determination if the signal-to-noise ratio is too low.

41. Apparatus according to any one of claims 36 to 39, wherein the surface height determining means is arranged to accumulate the squared amplitude values and to abort the height determination if the ratio between a maximum squared amplitude value and a mean of the accumulated squared amplitude values is below a threshold.

42. Apparatus according to any one of the preceding claims, wherein the surface height determining means further comprises phase determining means for determining the intensity value having a predetermined phase and for determining a height of a sample surface region using a position on the measurement path corresponding to the determined intensity value.

43. Apparatus according to claim 42, wherein the phase determining means is operable to determine an estimate of the predetermined phase position using the intensity value closest to the coherence peak, then to unwrap the

phase of the correlation values, and to determine the actual position corresponding to the predetermined phase using a linear fitting procedure.

44. Apparatus according to any one of the preceding claims, wherein position determining means are provided for determining the position of said one of the sample surface and the reference surface on the measurement path and triggering means are provided for triggering the sensing means to sense light intensity to provide a set of intensity data signals in accordance with position data obtained by the position determining means.

45. Apparatus according to any one of the preceding claims, wherein the sensing means comprises a two-dimensional array of sensing elements and control means are provided for controlling the field of view of the sensing means by controlling combining or selecting of intensity data signals produced by sensing elements.

46. Apparatus according to any one of the preceding claims, wherein the light directing means comprises beam splitting means for splitting light into reference light directed along the reference path and sample light directed along the sample path.

47. Apparatus according to claim 46, wherein at least one of the reference surface and the beam splitting means is configured such that less than 50% of the light is directed along the reference path.

48. Apparatus according to claim 47, wherein the beam splitting means is arranged to direct 20% of the light along the reference path.

49. Apparatus according to claim 47 or 48, wherein the beam splitting means comprises a Herpin filter or a neutral density partially reflective metal filter.

50. A method of obtaining surface profile data for a sample surface, the method comprising:

directing light from a broadband source along a sample path towards a region of a sample surface and along a reference path towards a reference surface such that light reflected by the region of the sample surface and light reflected by the reference surface interfere;

effecting relative movement along a measurement path between the sample surface and the reference surface;

sensing, using sensing means, light intensity at intervals to provide a series of intensity values representing interference fringes produced by a region of a sample surface during said relative movement; and

processing the intensity values by:

receiving intensity values from the sensing means during a measurement operation;

carrying out a first processing step on intensity values as the intensity values are received during a measurement operation to produce data indicating the position of a coherence peak; and

in a second processing step, after completion of a measurement operation, using the data produced by the

first processing step to obtain data indicative of a height of the surface region, wherein one of the first and second processing steps comprises:

a correlating step correlating intensity values with correlation function data representing a correlation function to provide correlation data for that sample surface region to enable a position of a coherence peak in the intensity values for a sample surface region to be identified; and

the second processing step comprises a surface height determining step determining data relating to a height of a sample surface region from data related to the position of the coherence peak.

51. A method according to claim 50, wherein the correlating step correlates intensity values with correlation function data representing a correlation function having first and second periodically varying wave functions with the first and second wave functions being of different phase and being bounded by an envelope.

52. A method according to claim 51, wherein the correlating step correlates intensity values with correlation function data representing a correlation function in which the envelope is a smoothly varying peaked function.

53. A method according to claim 52, wherein the correlating step correlates intensity values with

correlation function data representing a correlation function in which the envelope is a Gaussian.

54. A method according to claim 51, 52 or 53, wherein the correlating step correlates intensity values with correlation function data representing a correlation function in which the first and second wave functions are sine and cosine wave functions.

55. A method according to claim 50, wherein the correlating step correlates intensity values with correlation function data representing a correlation function consisting of sine and cosine wave functions bounded by a Gaussian envelope.

56. A method according to any one of claims 50 to 55, wherein the first processing step comprises the correlating step.

57. A method according to claim 56, wherein the correlating step comprises:

a correlation processing step correlating intensity values with correlation function data to produce correlation data which is received by a correlation buffer;

a peak finding step finding a position related to a coherence peak in the correlation data, the peak finding step copying a range of the correlation data including the correlation data for the position related to the coherence peak into a copy buffer or freezing the

range of correlation data in the correlation buffer, for subsequent processing in the second processing step.

58. A method according to any of claims 50 to 55, wherein the second processing step comprises the correlating step and the first processing step comprises determining a range of the intensity values that includes an intensity value representing a coherence peak and identifying that range of intensity values for use in the correlating step.

59. A method according to claim 58, wherein the determining step comprises a discriminating step determining discrimination values for successive sets of received intensity values and a peak finding step finding a peak in the discrimination values and identifying the peak as representing the coherence peak.

60. A method according to claim 59, wherein the discriminating step determines discrimination values for sets consisting of spaced-apart received intensity values.

61. A method according to claim 60, wherein the discriminating step determines discrimination values for sets consisting of every second received intensity value.

62. A method according to claim 59, 60 or 61, wherein the discriminating step determines discrimination values for successive sets of received intensity values wherein

each successive set consists of intensity values from the previous set and at least one further intensity value.

63. A method according to claim 59, wherein the discriminating step determines discrimination values by multiplying a set of intensity values by corresponding pairs of discrimination values.

64. A method according to claim 59, wherein a measurement interval is such that certain discrimination values are zero.

65. A method according to claim 63, wherein a measurement interval is such that one of each pair of discrimination values is alternately zero.

66. A method according to claim 65, wherein the discriminating value pairs are: 0,1; 1,0; 0,-1; -1,0.

67. A method according to any of claims 59 to 66, wherein the discriminating step identifies the range of intensity values in accordance with whether or not the peak in the discrimination values is higher than a predetermined threshold.

68. A method according to claim 67, wherein the discriminating step uses as the predetermined threshold a value related to the mean of the discrimination values.

69. A method according to claim 67 or 68, wherein the discriminating step sets the range as all of the intensity values supplied for the sample surface region when the peak of the discrimination values does not exceed the predetermined threshold.

70. A method according to any one of claims 50 to 69, wherein the correlating step correlates intensity values with correlation function data comprising a set of pairs of first and second indices to produce pairs of correlation elements.

71. A method according to any one of claims 58 to 69, wherein the correlating step correlates intensity values with correlation function data comprising a set of pairs of first and second indices and produces a pair of correlation elements for a given intensity value by multiplying each of a range of intensity values including the given intensity value by a corresponding one of the first indices and summing the results to produce a first one of the pair of correlation elements and by multiplying each of the range of intensity values by a corresponding one of the second indices and summing the results to produce the other one of the pair of correlation elements, the pair of correlation elements being stored in a memory area of a correlation buffer.

72. A method according to claim 56, 57, 58 or 59, wherein:

the correlating step uses correlation function data having a number of groups each consisting of a number of pairs of first and second indices and a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating step comprises:

a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first group of said pairs of indices to produce, for each of said pairs of indices, corresponding pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of a series of the memory areas;

a second step of repeating the first step for each of a succession of said intensity values using a different group of said pairs of indices at each repetition;

a third step of moving the series of memory areas by a predetermined number of memory areas along the array and then repeating the first and second steps; and

a fourth step of repeating the third step moving the series of memory areas by a predetermined number of memory areas along the array at each repetition until, at least for each of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the

sum of the multiplication elements resulting from multiplying each of a sequence of said intensity values by a corresponding different one of the first and second indices, respectively.

73. A method according to claim 56, 57, 58 or 59, wherein:

the correlating step uses correlation function data having four groups each having four pairs of first and second indices and a correlation buffer having an array of memory areas each for storing a pair of correlation elements for a corresponding intensity value; and

the correlating step comprises:

a first step of multiplying a first intensity value of a series of intensity values for a surface region separately by the first index and by the second index of each of a first one of said groups of pairs of indices to produce four pairs of first and second multiplication elements and to accumulate each pair of multiplication elements in a corresponding different one of four of the memory areas;

a second step of repeating the first step for the next three intensity values using the second, third and fourth groups of said pairs of indices, respectively;

a third step of moving the series of memory areas by one and then repeating the first step for the next intensity value and the second step for the three following intensity values; and

a fourth step of repeating the third step moving the series of memory areas by one memory area along the array

at each repetition until, for every fourth one of a number of the intensity values, a memory location corresponding to the intensity value contains first and second correlation elements with the first and second correlation elements representing the sum of multiplication elements resulting from multiplying each of a sequence of sixteen of said intensity values by a corresponding different one of the first and second indices, respectively.

74. A method according to claim 71, 72 or 73, wherein the correlation buffer is a circular buffer and for an oldest entry in the buffer is overwritten when the buffer is full.

75. A method according to any one of claims 58 to 64, 69 or 71, wherein the determining step comprises another correlating step.

76. A method according to claim 75, wherein the other correlating step uses a coarser correlation function than the correlating step.

77. A method according to claim 75 or 76, wherein the other correlating step functions in the manner set out in any one of claims 71, 72 or 73.

78. A method according to any one of claims 70 to 77, wherein a measurement interval is such that certain of the correlation function data is zero.

79. A method according to any one of claims 70 to 74 or 77, wherein a measurement interval is such that certain correlation indices are zero.

80. A method according to any one of claims 70 to 74 or 77, wherein a measurement interval is such that one of each pair of correlation indices is alternately zero.

81. A method according to any one of claims 50 to 80, wherein the peak finding step functions in a number of different states with the switch from one state to the next being determined by the relationship of an intensity value discrimination value or correlation element to a previous intensity value, discrimination value, or correlation element or threshold.

82. A method according to claim 81, wherein the peak finding step has an optional initial state which exists for a first value, a low state which exists when the value is below a threshold value, a found state which exists when the value is above the threshold value, and an optional early state which exists if the first value is above the threshold value.

83. A method according to claim 81, wherein the peak finding step has an optional initial state that exists for a first value, a low state that exists before the value rises above a threshold value, a rising state that exists when the value is rising, a falling state that exists when the value is falling, a found state that

exists if the value falls below a predetermined proportion of a previous maximum value, and an optional state that exists if the first value is above the threshold.

84. A method according to any one of claims 50 to 83, wherein the surface height determining step determines a height of a sample region by fitting a Gaussian to values provided by the correlating step and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

85. A method according to any one of claims 70 to 83, wherein the surface height determining step determines amplitude values from the pairs of correlation elements and determines a height of a sample region by fitting a Gaussian to amplitude values and by identifying the position of the coherence peak with a predetermined feature of the Gaussian fit such as the position of the peak of the Gaussian.

86. A method according to claim 85, wherein the surface height determining step obtains the amplitude values by determining the sum of the square of the correlation elements of each pair to obtain a squared amplitude value for each pair of correlation elements, finds a range of squared amplitude values including a highest value, determines a square root value for each of said range of

squared amplitude values and to fit the Gaussian to said square root values.

87. A method according to any one of claims 84 to 86, wherein the surface height determining step carries out a smoothing procedure before fitting the Gaussian.

88. A method according to claim 85 or 86, wherein the surface height determining step smooths the squared amplitude values using a box filter.

89. A method according to any one of claims 50 to 88, wherein the surface height determining step determines a signal-to-noise ratio for the values provided by the correlating step and aborts the height determination if the signal-to-noise ratio is too low.

90. A method according to any one of claims 85 to 88, wherein the surface height determining step accumulates the squared amplitude values and aborts the height determination if the ratio between a maximum square amplitude value and a mean of the accumulated squared amplitude values is below a threshold.

91. A method according to any one of claims 50 to 90, wherein the surface height determining step further comprises a phase determining step determining the intensity value having a predetermined phase and determining a height of a sample surface region using a

position on the measurement path corresponding to the determined intensity value.

92. A method according to claim 91, wherein the phase determining step determines an estimate of the predetermined phase position using the intensity value closest to the coherence peak, then unwraps the phase of the correlation values, and determines the actual position corresponding to the predetermined phase using a linear fitting procedure.

93. A method according to any one of claims 50 to 92, further comprising a position determining step determining the position of said one of the sample surface and the reference surface on the measurement path and a triggering step triggering sensing of light intensity to provide a set of intensity data signals in accordance with position data obtained in the position determining step.

94. A method according to any one of claims 50 to 93, wherein the sensing step uses a sensing means having a two-dimensional array of sensing elements and the field of view of the sensing means is controlled by controlling combining or selecting of intensity data signals produced by sensing elements.

95. A method according to any one of claims 50 to 94, wherein the light directing step directs light to beam splitting means which splits light from the light source

into reference light directed along the reference path and sample light directed along the sample path.

96. A method according to claim 95, wherein at least one of the reference surface and the beam splitting means is configured such that less than 50% of the light is directed along the reference path.

97. A signal carrying program instructions for programming processing means to carry out a method in accordance with any one of claims 50 to 94.

98. A storage medium carrying program instructions for programming processing means to carry out a method in accordance with any one of claims 50 to 94.

Application No: GB 0206023.4 **Examiner:** Bob Clark
Claims searched: 1 **Date of search:** 7 June 2002

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G1A (ACEW, ACEX)

Int Cl (Ed.7): G01B 9/02, 11/24, 11/30

Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	EP 0244781 A2	(KLA INSTRUMENTS) Pages 9 to 18	
A	US 6195168	(DE LEGA et al.) Line 62 col.7 to line 8 col.10	
A	US 5953124	(DECK) Line 8 col.7 to line 41 col.8	
A	US 5706085	(BLOSSEY et al.) Line 59 col.4 to line 31 col.5, and line 61 col.5 to line 24 col.6	
A	US 5402234	(DECK) Columns 5 to 8	
A	US 5398113	(de GROOT) Line 56 col.8 to line 57 col.11	
A	US 5194918	(KINI et al.) Line 22 col.3 to line 25 col.4	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

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Application No: GB 0206023.4 **Examiner:** Bob Clark
Claims searched: 51 and 102 **Date of search:** 12 July 2002

Patents Act 1977
Further Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G1A (ACEW, ACEX)

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Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	WO 95/33970 A1	(MIT)	
A	US 5615011	(BOISROBERT et al.)	
A	US 5469261	(HELLMUTH et al.)	
X	US 5459570	(SWANSON et al.) Line 33 col.4 to line 62 col.5, and lines 47-64 col.8	51,102

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

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INVESTOR IN PEOPLE

Application No: GB 0206023.4 **Examiner:** Bob Clark
Claims searched: 52 and 103 **Date of search:** 12 July 2002

Patents Act 1977
Further Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G1A (ACEW, ACEX)

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Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	US 5953124	(DECK)	
A	US 5402234	(DECK)	
A	US 5398113	(de GROOT)	
A	US 5194918	(KINO et al.)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

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INVESTOR IN PEOPLE

Application No: GB 0206023.4
Claims searched: 53 and 104

Examiner: Bob Clark
Date of search: 12 July 2002

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Further Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

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Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	WO 98/50779 A1	(HOLCOMB)	
X	WO 93/24805 A1	(ZYGO) Particularly pages 22 and 23	53,104
X	US 5706085	(BLOSSEY et al.) Particularly lines 20 to 23 in column 6	53,104

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.