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(54) **Title:** BISTATIC INTERFEROMETRIC TERRESTRIAL RADAR WITH TRANSPONDER

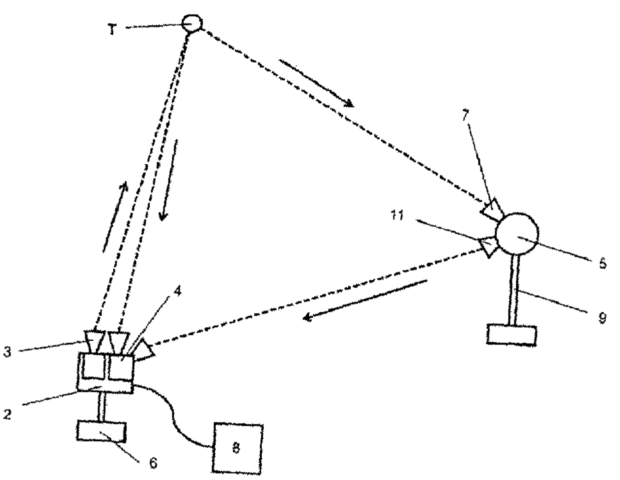

FIG. 1

(57) **Abstract:** Bistatic interferometric terrestrial radar comprising: a main radar unit (2) provided with ground fixing means (6) and provided with at least one transmitting unit (3) and at least one receiving unit (4); at least one amplifier transponder (5, 50) placed far away from said main unit (2), provided with ground fixing means (9) and provided with a receiving antenna (7) and a transmitting antenna (11).

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"BISTATIC INTERFEROMETRIC TERRESTRIAL RADAR WITH TRANSPONDER";

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Field of the Invention

The invention relates to an interferometric radar and in particular an interferometric terrestrial radar of the type used for the remote sensing of landslides, mines, glaciers, avalanches, volcanoes, as well as for detecting movements of large structures such as bridges, dams and building works in general.

State of the Art

A solution is known wherein a bistatic interferometric radar, as described in D. Mecatti, D. Dei, M. Fratini, F. Parrini, M. Pieraccini, F. Coppi, "A novel ground based multi bistatic radar for interferometric measurement of displacement vector." In: Geoscience and Remote Sensing Symposium (IGARSS), 2011 IEEE International (pp. 3983-3986) is able to measure two components of a target displacement.

In this solution, a main radar unit with an on-board transmitter and receiver is provided. The radar signal is irradiated by the main transmission antenna or by one of the two secondary remote antennas that illuminate the same target and are connected to the main unit by RF wiring.

This known solution has some significant drawbacks, due to the need to connect the remote antennas via a cable, which makes it difficult to apply the system to real cases when it is necessary to place or move the secondary antennas at different points of observation, which can also be dozens or hundreds of meters away.

Moreover, within the scope of displacement measurement systems, this solution is not satisfactory because it is unable to provide bidimensional radar images, displacement maps and elevation maps (DEM: Digital Elevation Map) of the visual field.

A technology called GB-SAR (Ground based Synthetic Aperture Radar) is also known, in which a monostatic interferometric radar moves along a mechanical guide to achieve the so-called synthetic opening. In this way, radar images of the visual field are realized and, by means of differential interferometry, it is also possible to measure the displacements of targets. Such technology is of particular interest because it is a radar technique that can provide high-precision displacement maps over an entire field of observation.

An example of a conventional GB-SAR is described in M. Pieraccini, D. Tarchi. H. Rudolf, D. Leva, G. Luzi, C. Atzeni, "Interferometric radar for remote monitoring of building deformations", *Electronics Letters*, Vol. 36, no. 6, pp. 569-570 (2000).

However, GB-SAR systems of the known type have considerable limits as they only detect target displacement along the view direction and not the displacement vector of the side or of the architectural structure observed.

Object of the Invention

The object of the present invention is therefore to propose a bistatic interferometric terrestrial radar free from the above-mentioned drawbacks of the known-type systems and able to measure 2 or more components of the displacement of a target to be monitored, such as a side or other structure.

Summary of the Invention

These and other objects have been achieved with an interferometric terrestrial radar according to one or more of the appended claims, with a main radar unit having a transmitting antenna and a receiving antenna which acquires a first (monostatic) image of its visual field, and which, by using a further receiving antenna (or a rotation of the first receiving antenna), acquires a second (bistatic) image of the same scenario by exploiting the rebound of a signal from an amplifier transponder.

A first advantage of the invention is that the proposed radar is able to obtain radar images taken from multiple points of observation and, by means of differential interferometry, is also able to measure the displacements of targets.

A second advantage is that the interferometric radar of the invention is able to obtain the displacement map in multiple components and, with appropriate arrangements, also the elevation map of the visual field (DEM).

Another advantage is that the radar has a simplified structure with respect to the known solutions of satellite or airplane bistatic radars.

List of Drawings

These and other advantages will be better understood by anyone skilled in the art from the description below and the accompanying drawings, given as a non-limiting example, wherein:

- Fig. 1 shows a first embodiment of a radar according to the invention.

- Fig. 2 shows a preferred example of a radar according to the invention;

- Fig. 3 shows a scheme of an amplifier transponder which can be used in the radar of the invention;

- Fig. 4 schematically shows the operation of the radar of Fig. 2 by highlighting the two components of the displacement (c_1 and c_2) which can be detected by the radar;

- Fig. 5 shows an alternative embodiment, still equivalent to the one shown in Fig. 2;

- Fig. 6 schematically shows the operation of an additional embodiment able to acquire more than two displacement components;

- Fig. 7 shows a further embodiment which can be used when the second point of observation is not with a view of the main unit or too far from the main unit 2;

- Fig. 8 shows a further embodiment equivalent to the one shown in Fig. 7, but with a reversed path of the radar signal;

- Fig. 9 shows a further embodiment based on a movement system along a circle arc (100);

- Fig. 10 shows an alternative embodiment, still equivalent to the one shown in Fig. 9;

- Fig.11 schematically shows an embodiment of a radar according to the invention which allows DEM acquisition of the visual field;

- Fig. 12 shows an alternative embodiment, still equivalent to the one shown in Fig. 11;

- Fig. 13 shows the general geometry of an algorithm for the synthesis of bistatic images using the linear scan radar.

- Fig. 14 shows the general geometry of an algorithm for the synthesis of bistatic images using the movement radar along a circumferential arc.

- Fig. 15 shows a bistatic synthetic radar image of a target acquired by the radar of the invention.

Detailed Description

With reference to the accompanying drawings, Figure 1 shows a first embodiment, Figures 2-6 illustrate a preferred embodiment of the radar of the invention.

In the preferred example, the radar is a bistatic interferometric terrestrial radar of the synthetic opening type comprising a movement system, e.g. a straight linear guide 1 provided with ground fixing means 6 on which a main radar unit 2 having at least a first transmitting unit 3 and a receiving unit 4 can slide; the latter must be able to acquire, simultaneously or at different times, from at least two different directions. This can be accomplished in several ways: through two antennas and a single acquisition channel; through two antennas and two separate acquisition channels; through a single antenna able to rotate and a single acquisition channel.

The radar further comprises an amplifier transponder 5 placed far away from said main unit 2, e.g. at a distance between 10 m and 500 m, provided with ground fixing means 9, with a signal amplification unit 12 and further provided, in turn, with a receiving unit 7 and a transmitting unit 11.

According to the invention, the transmitting unit 3 and the receiving unit 4 of the main radar unit are respectively arranged to transmit and receive a signal towards and from a target T to be monitored. Furthermore, the receiving unit 4 is arranged to also receive from the amplifier transponder 5.

In the amplifier transponder 5, the receiving unit 7 and the transmitting unit 11 are, in turn, oriented to receive a radar signal from the target T to be monitored and to transmit towards the main unit 2, respectively.

For the acquisition and processing of the radar signals, an electronic unit 8 connected to the main radar unit 2 is provided.

During operation, the electronic unit 8 acquires a monostatic synthetic radar image of target T by exploiting the main unit movement along the guide 1.

Subsequently or simultaneously, the unit 8 acquires a bistatic synthetic radar image of target T by exploiting the main unit movement along the guide 1 and using the amplifier transponder.

Thanks to the invention, by means of the radar signal bouncing through the transponder 5, it is possible to realize a bistatic synthetic image of the scenery in the visual field of the radar head transmission antenna and of the transponder receiving antenna. From the synthetic image, by means of *per se* known methods of radar interferometry, it is possible to measure the c_1 component of the displacement in the direction between radar and target and a second displacement component c_2 in the direction of the bisector between radar - target and target - transponder, thus obtaining at least two components (Figure 4).

Preferably, the unit 8 processes the second synthetic radar image of target T by means of an algorithm having as parameters at least the position of the main unit 2 along the guide 1, the distance d_1 between the main unit 2 and the amplifier transponder 5, the distance d_2 between the amplifier transponder 5 and the target T and the distance d_3 between the main unit 2 and the target T.

In more detail, with reference to the general geometry shown in Figures 13 and 14, the result of a measurement is a matrix $N_f \times N_p$ of complex numbers

$$E_{i,k} = I_{i,k} + jQ_{i,k}$$

where $I_{i,k}$ and $Q_{i,k}$ are the in-phase and in-quadrature components acquired at the i^{th} frequency f_i ($1 < i < N_f$) in the k^{th} position along the guide ($1 < k < N_p$).

Synthesizing the image in a generic point identified by the polar coordinates (r,ϕ) means compensating for the path phase among an image generic point, the amplifier transponder 5 and the radar unit 2.

With reference to Figures 13 and 14, the base formula is:

$$I(r,\phi) = \frac{1}{N_f N_p} \sum_{i,k} E_{i,k} e^{j\frac{2\pi}{c} f_i(R(r,\phi,k))}$$

with

$$R(r,\phi,k) = d_1(k) + d_2(r,\phi) + d_3(r,\phi,k)$$

and where:

c is the speed of light

$d_1(k)$ is the distance between the transponder and the k^{th} position of the radar unit 2 along the guide 1,

$d_2\,(r,\phi,)$ is the distance between the observed target of coordinates (r,ϕ) and the transponder 5,

$d_3(r,\phi,k)$ is the distance between the observed target of coordinates (r,ϕ) and the k^{th} position of the radar unit 2 along the guide 1.

In an exemplary embodiment of the of the radar schematized in Figures 2 and 4,

the transmitting unit 3 of the main unit 2 comprises an antenna oriented to transmit a signal towards said target T,

the receiving unit 4 of the main unit 2 comprises an antenna oriented to receive a signal from said target T and an antenna to receive a signal from said amplifier transponder 5,

the receiving unit 7 of the amplifier transponder 5 comprises an antenna oriented to receive a signal from said target T, and

the transmitting unit 11 of the transponder unit 7 comprises an antenna oriented to transmit the signal towards said main unit 2.

In this case (Figure 4), the radar measures the displacement component c_1 of the target T along the direction between target and radar, and the displacement component c_2 of the target T along the bisector direction between the radar - target T and target T - amplifier transponder directions.

In a further embodiment schematized in Figure 5:

the receiving unit 4 of the main unit 2 comprises an antenna oriented to receive a signal from said target T,

the transmitting unit 3 of the main unit 2 comprises an antenna oriented to transmit a signal towards said target T and an antenna to transmit a signal towards the amplifier transponder 5,

the receiving unit 7 of the amplifier transponder 5 comprises an antenna oriented to receive a signal from said main unit 2,

the transmitting unit 11 of the amplifier transponder 7 comprises an antenna oriented to transmit the signal towards said target T.

Also in this case the radar measures the displacement component c_1 of the target T along the direction between target and radar, and the displacement component c_2 of the target T along the bisector direction between the radar - target T and target T - amplifier transponder directions.

In a further embodiment schematized in Figure 6, the radar comprises a second transponder unit 50.

In this case the radar measures

the displacement component c_1 of the target T along the direction between target and radar,

the displacement component c_2 of the target T along the bisector direction between radar - target T and target T - first amplifier transponder 5, and

the displacement component c_3 of the target T along the bisector direction between the directions radar - target T and target T - second amplifier transponder 50.

Advantageously, in case of use of multiple transponders, if the amplifier transponders are at different heights, by means of at least two amplifier transponders it is possible to obtain the three components in the displacement vector space (x, y, z).

In a further embodiment schematized in Figure 7, the radar comprises a second amplifier transponder 50.

In this case

the transmitting unit 3 comprises an antenna oriented to transmit a signal towards the target T,

the receiving unit 4 comprises an antenna oriented to receive a signal from said target T and an antenna to receive a signal from the first amplifier transponder 5,

the receiving unit 7 of the first amplifier transponder 5 comprises an antenna oriented to receive the signal from the second amplifier transponder 50,

the transmitting unit 11 of the first amplifier transponder 5 comprises an antenna oriented to transmit the signal towards the main unit 2, the receiving unit 7 of the second amplifier transponder 50 comprises an antenna oriented to receive a signal from the target T, the transmitting unit 11 of the second amplifier transponder 50 comprises an antenna oriented to transmit the signal towards the first amplifier transponder 5.

Advantageously, in the case of use of multiple transponders arranged as in Fig. 7, if the radar and a transponder with a view of the target do not have a view free from obstacles, or they are too far to get a good signal, it is possible to use another transponder which acts as a sort of radio link.

In a further embodiment, schematized in Figure 8, the radar signal path is reverse with respect to the embodiment described above.

Referring to Figures 9-10, a radar according to the invention is shown, in which the movement system of the main unit 2 is a rotating arm on a circumferential arc 100.

In such embodiment, the antenna connecting the unit 3 to the amplifier transponder 5 will preferably be of the omnidirectional type.

In Figure 11 a further embodiment example is shown, in which the ground fixing means 9 of the amplifier transponder comprise height adjustment means 13.

Advantageously, in this case, the radar of the invention can also be used to get the target altitude in the visual field, i.e. DEM (Digital Elevation Model). With reference to Figure 11, two bistatic measurements are in fact performed, which differ only because the transponder has been moved at a certain height (e.g. raised or lowered).

From the interferogram between the two images, it is thus possible to obtain the heights of the target in the field of observation of the radar.

Fig. 12 shows an embodiment equivalent to the one shown in Fig. 11.

The present invention has been described according to preferred embodiments; however, equivalent variants can be conceived without departing from the scope of the present invention.

CLAIMS

1. Bistatic interferometric terrestrial radar comprising

a main radar unit (2) provided with ground fixing means (6) and provided with at least one first transmitting unit (3) and at least one first receiving unit (4)

at least one amplifier transponder (5, 50) placed far away from said main unit (2), provided with ground fixing means (9) and also provided with a second receiving unit (7) and a second transmitting unit (11),

at least one first transmitting unit (3) and at least one first receiving unit (4) being respectively arranged to transmit and receive a signal towards and from a target (T) to be monitored or said amplifier transponder (5, 50),

said second receiving unit (7) and second transmitting unit (11) being respectively arranged to receive and transmit a signal towards and from said target (T) to be monitored or said main unit (2),

an acquisition and processing unit (8) of radar signals operatively connected to said main radar unit (2) to acquire in succession or simultaneously

at least one monostatic radar image obtained by using the signal received from said target (T),

at least one bistatic radar image of the target (T) obtained by using the signal passing through said amplifier transponder (5), and

to process said monostatic and bistatic images by interferometry to measure two components (c_1, c_2) of the displacement of the target (T) corresponding to said monostatic and bistatic images.

2. Radar according to the preceding claim, comprising a movement system of said main radar unit (2) wherein said acquisition and processing unit (8) of radar signals acquires in succession or simultaneously at least one monostatic synthetic radar of the target (T) realized by exploiting the movement of the main unit (2) and at least one bistatic synthetic radar image of the target (T) realized by exploiting the movement of the main radar unit (2) and using the signal which passes through said amplifier transponder (5) to process said bistatic and monostatic synthetic images by interferometry to measure two components (c_1, c_2) of the displacement of the target (T) corresponding to said bistatic and

monostatic images.

3. Radar according to claim 2, wherein said movement system of the main unit comprises a straight guide (1).

4. Radar according to claim 2, wherein said movement system comprises a circumferential arc guide (100).

5. Radar according to one of claims 2 to 4, wherein said unit (8) processes said bistatic image of the target (T) by means of an algorithm having at least

the distance (d_1) between the main unit (2) and the amplifier transponder (5),

the distance (d_2) between the amplifier transponder (5) and the target (T), and

the distance (d_3) between the main unit (2) and the target (T),

6. Radar according to one of the preceding claims, wherein

said first receiving unit (4) of the main unit (2) comprises an antenna oriented to receive a signal from said target (T) and an antenna to receive a signal from said amplifier transponder (5),

said first transmitting unit (3) of the main unit (2) comprises an antenna oriented to transmit a signal towards said target (T),

said second receiving unit (7) of the amplifier transponder (5) comprises an antenna oriented to receive a signal from said target (T),

said second transmitting unit (11) of the amplifier transponder (7) comprises an antenna oriented to transmit the signal towards said main unit (2).

7. Radar according to one of claims 1 to 5, wherein

said first receiving unit (4) of the main unit (2) comprises an antenna oriented to receive a signal from said target (T),

said first transmitting unit (3) of the main unit (2) comprises an antenna oriented to transmit a signal towards said target (T) and an antenna to transmit a signal towards said amplifier transponder (5),

said second receiving unit (7) of the amplifier transponder (5) comprises an antenna oriented to receive a signal from said main unit (2)

said second transmitting unit (11) of the amplifier transponder (7) comprises an antenna oriented to transmit the signal towards said target (T).

8. Radar according to one of the claims 1 to 5, comprising a first and a second transponder unit (5, 50), wherein

said first receiving unit (4) of the main unit (2) comprises an antenna oriented to receive a signal from said target (T) and an antenna to receive a signal from a first transponder unit (5),

said first transmitting unit (3) of the main unit (2) comprises an antenna oriented to transmit a signal towards said target (T),

and wherein in the first transponder unit (5),

said second receiving unit (7) comprises an antenna oriented to receive a signal from said second transponder unit (50),

said second transmitting unit (11) comprises an antenna oriented to transmit the signal towards said main unit (2),

and wherein in the second transponder unit (50)

said second receiving unit (7) comprises an antenna oriented to receive a signal from said target (T),

said second transmitting unit (11) comprises an antenna oriented to transmit the signal towards said first transponder unit (2).

9. Radar according to one of the preceding claims, but with a reversed path of the bistatic signal, i.e. the radar signal instead of proceeding from the radar to the target, from the target to the transponder and from the transponder to the radar, proceeds from the radar to the transponder, from the transponder to the target and, finally, from the target to the radar.

10. Radar according to one of the preceding claims, wherein at least one of said receiving or transmitting units of the main unit (2) comprises an orientable antenna to be alternately oriented toward said target (T) or said transponder (5).

11. Radar according to one of the preceding claims, wherein said ground fixing means (9) of the amplifier transponders (5, 50) comprise height adjustment means (13) of the amplifier transponder (5, 50).

12. Method for measuring the displacements of a target (T) by means of a bistatic interferometric terrestrial radar comprising

a main radar unit (2) provided with ground fixing means (6) and provided with at least one first transmitting unit (3) and at least one first receiving unit (4)

at least one amplifier transponder (5, 50) placed far away from said main unit (2), provided with ground fixing means (9) and provided also with a second receiving unit (7) and a second transmitting unit (11),

said at least one first transmitting unit (3) and at least one first receiving unit (4) being respectively arranged to transmit and receive a signal towards and from a target (T) to be monitored or said transponder unit (5),

said second receiving unit (7) and second transmitting unit (11) being respectively arranged to receive and transmit a signal towards and from said target (T) to be monitored or said main unit (2),

an acquisition and processing unit (8) operatively connected to said main radar unit (2)

wherein said acquisition and processing unit (8) performs a phase of

acquisition, in succession or simultaneously, of at least one monostatic radar image of the target (T) and at least one bistatic radar image of the target (T) realized using the signal which passes through at least one amplifier transponder (5), and

an interferometric processing phase of said bistatic and monostatic images to measure at least two components (c_1, c_2) of the displacement of the target (T) corresponding to said monostatic and bistatic images.

13. Method according to claim 12, wherein said main radar unit (2) is movable by means of a movement system (1, 100) and said acquisition and processing unit (8) performs an acquisition phase, in succession or simultaneously, of at least one monostatic synthetic radar image of the target (T) realized by exploiting the movement of the main unit (2) and at least one bistatic synthetic radar image of the target (T) realized by exploiting the movement of the main unit and using the signal passing through at least one amplifier transponder (5), and

an interferometric processing phase of said bistatic and monostatic synthetic images to measure at least two components (c_1, c_2) of the displacement of the target (T) corresponding to said monostatic and bistatic synthetic images.

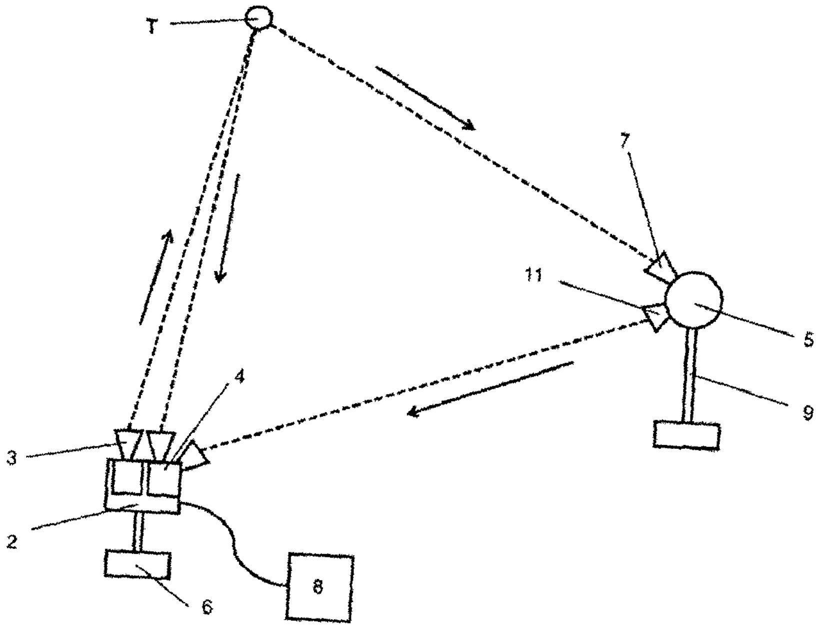

FIG. 1

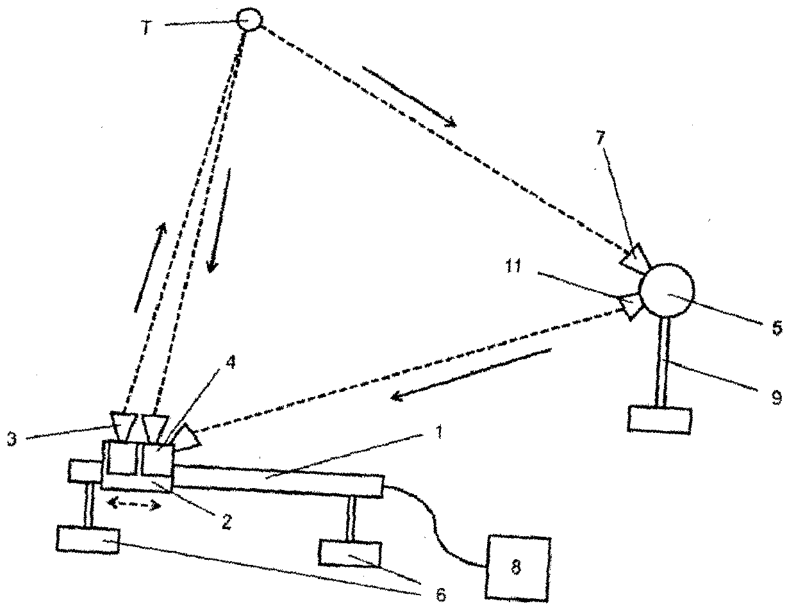

FIG. 2

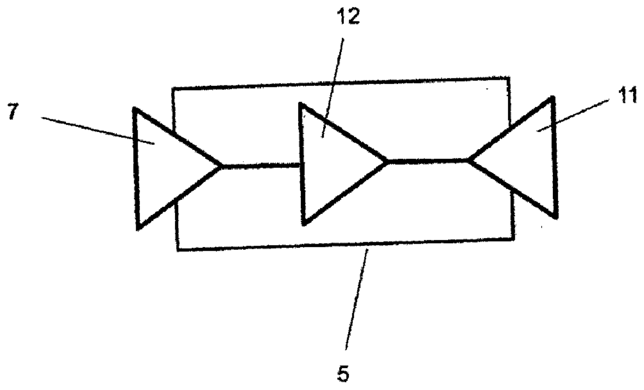

FIG. 3

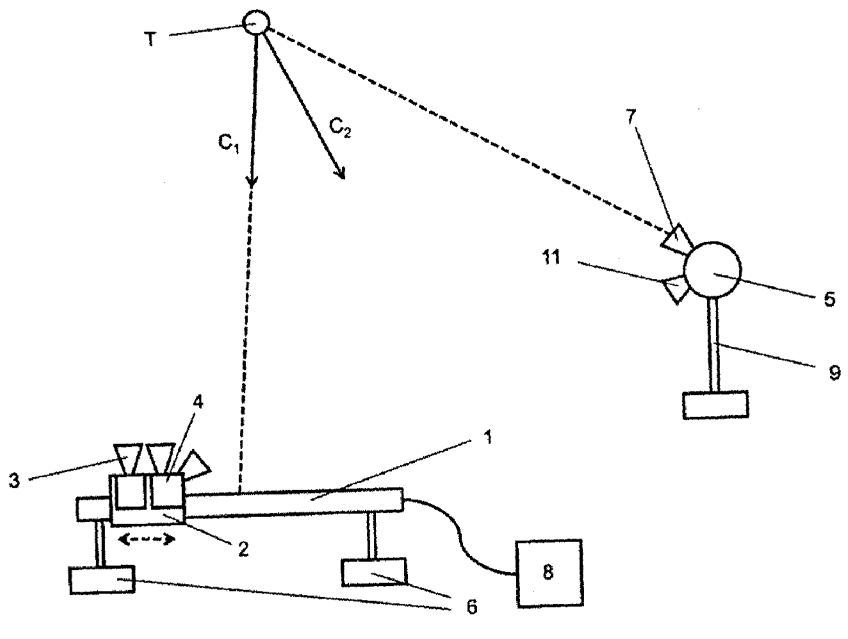

FIG. 4

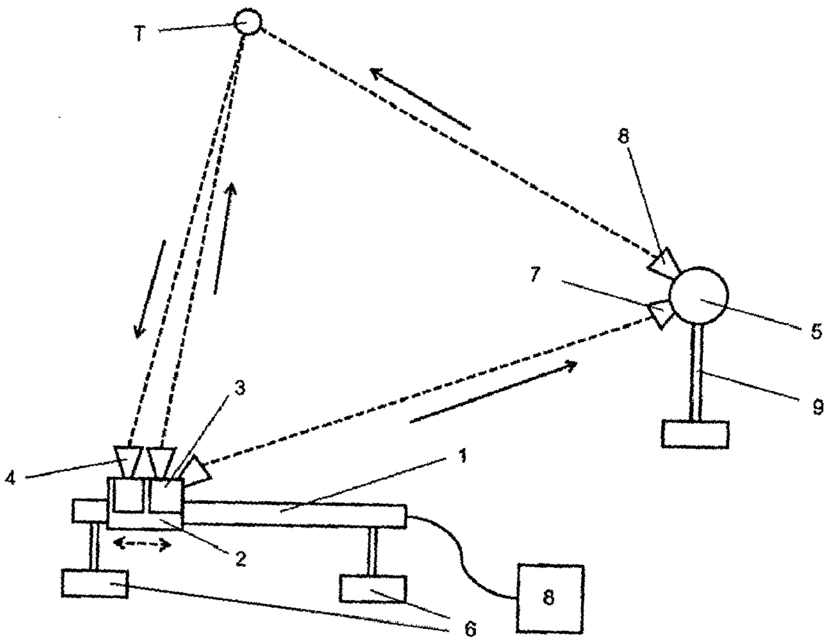

FIG. 5

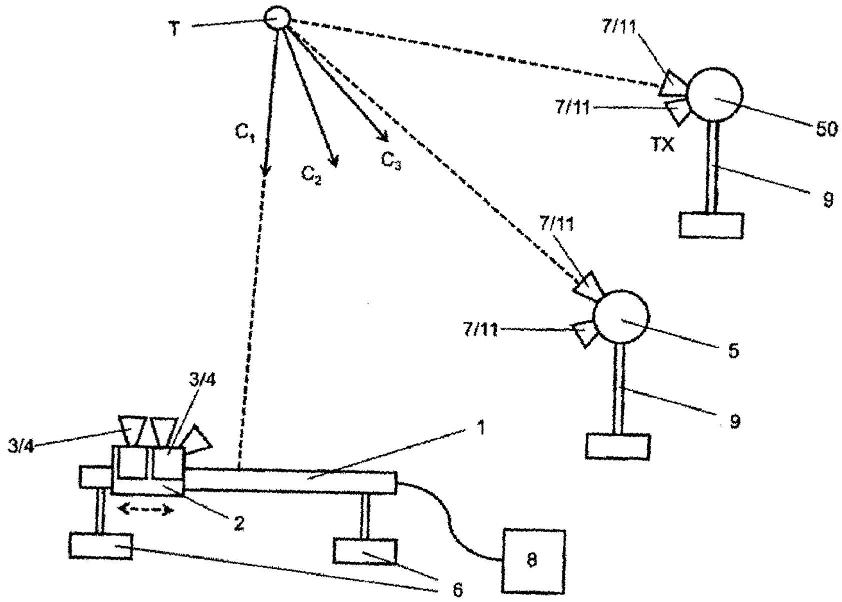

FIG. 6

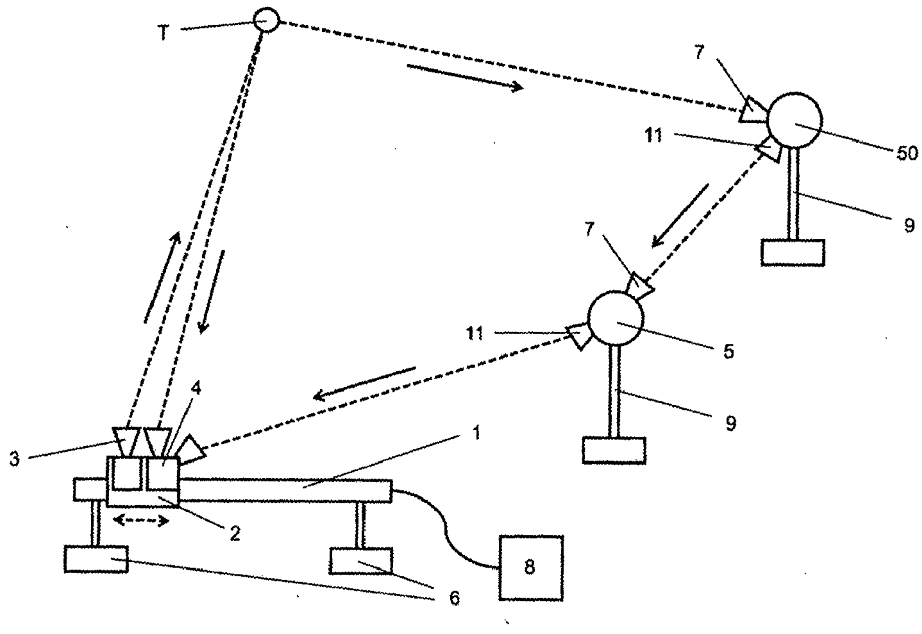

FIG. 7

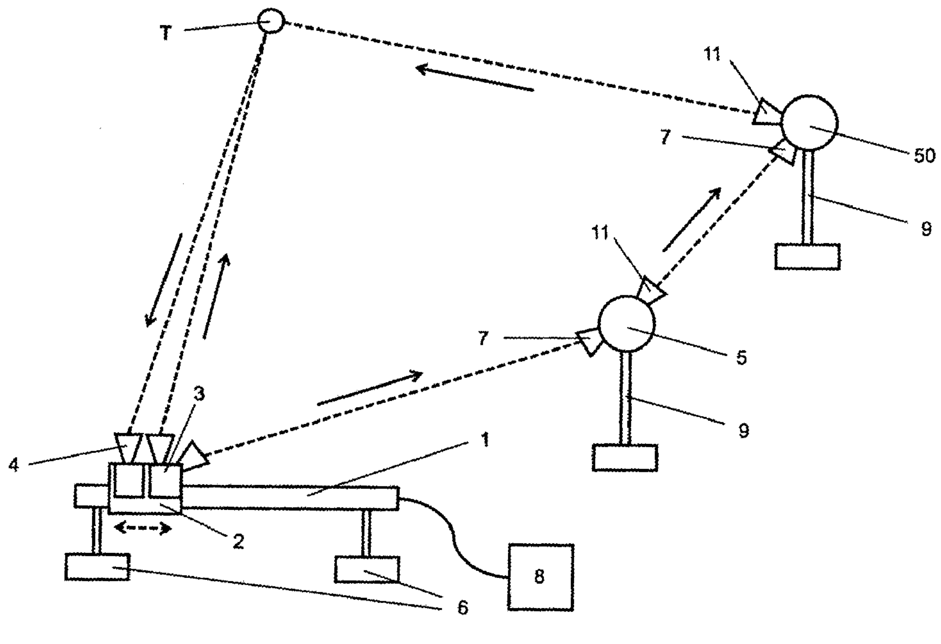

FIG. 8

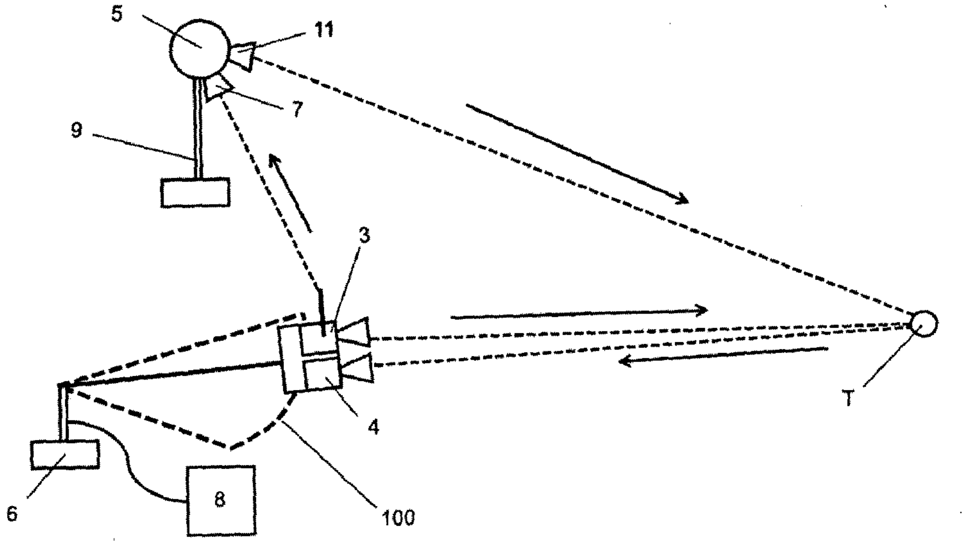

FIG. 9

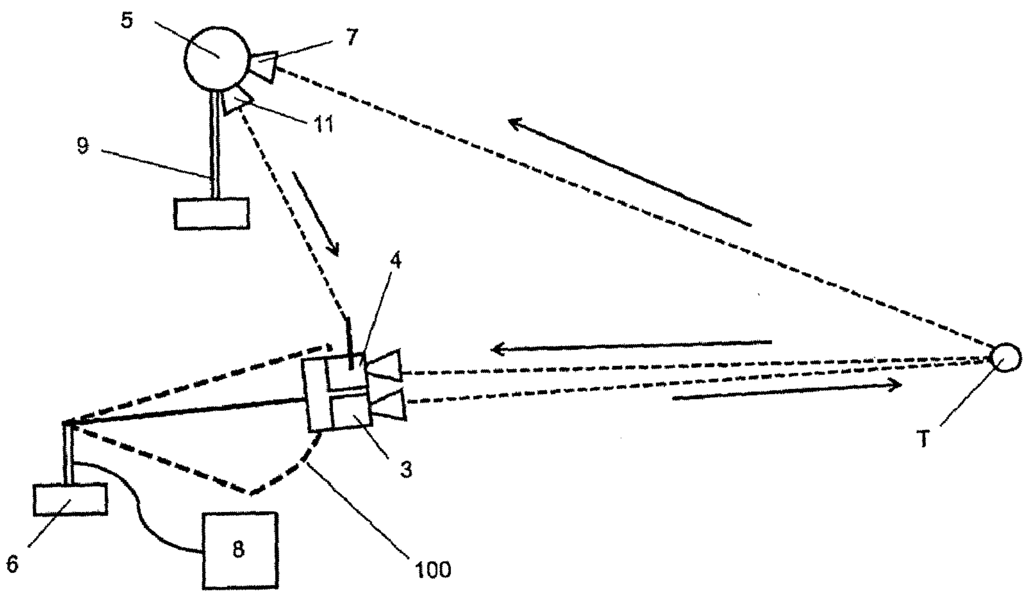

FIG. 10

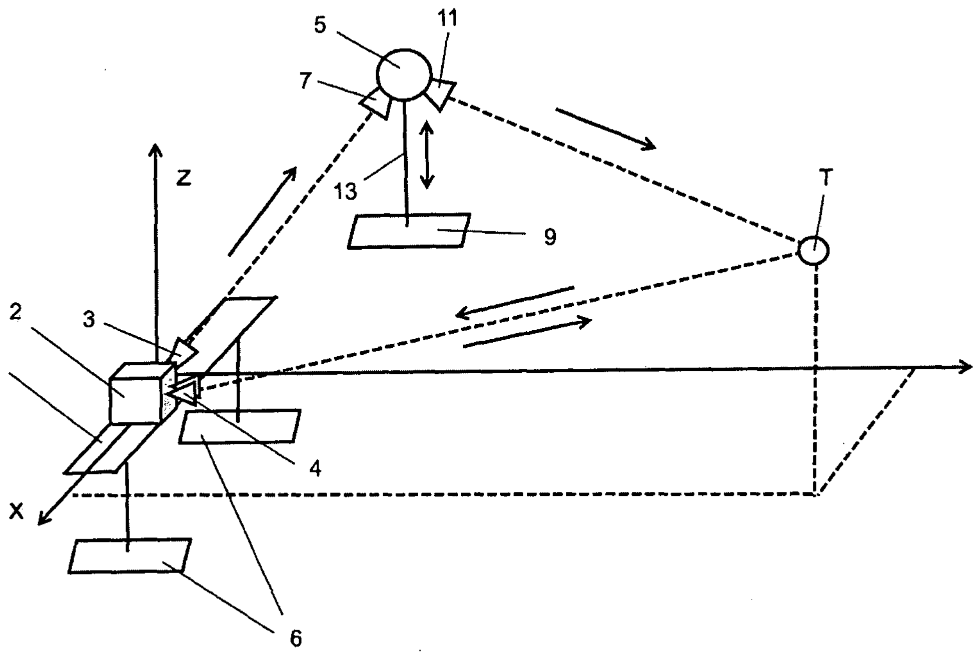

FIG. 11

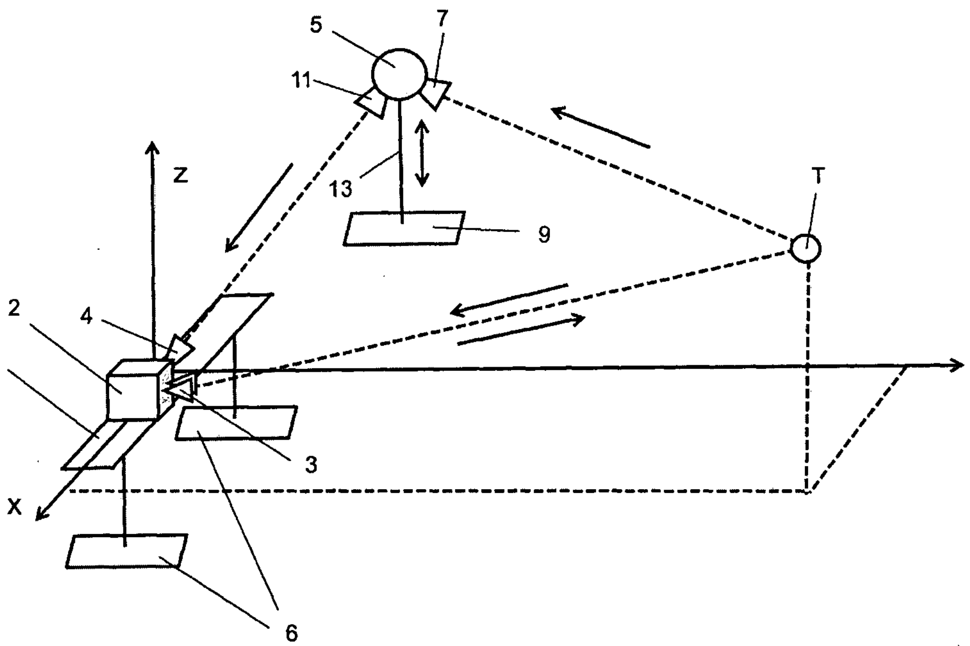

FIG. 12

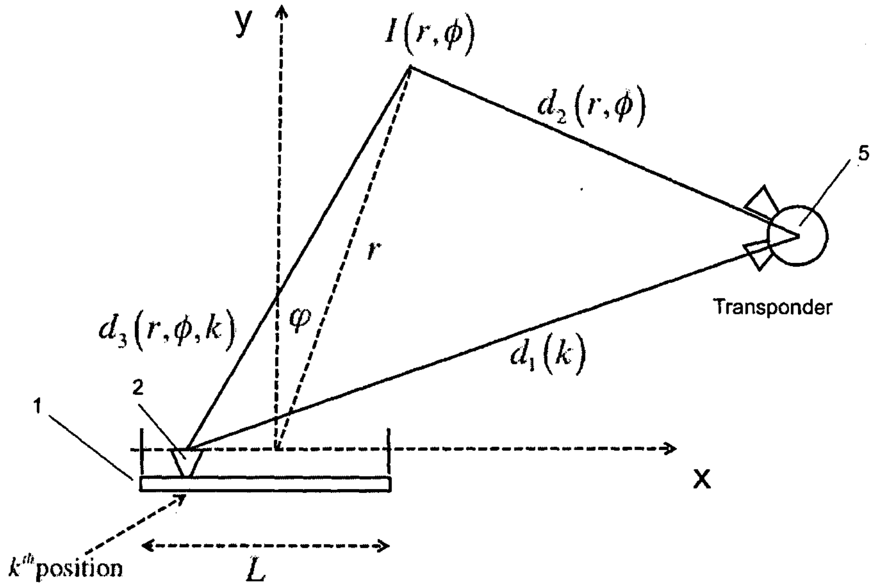
y
$I(r,\phi)$
$d_2(r,\phi)$
5
r
$d_3(r,\phi,k)$
φ
Transponder
$d_1(k)$
1
2
x
k^{th}position
L

FIG. 13

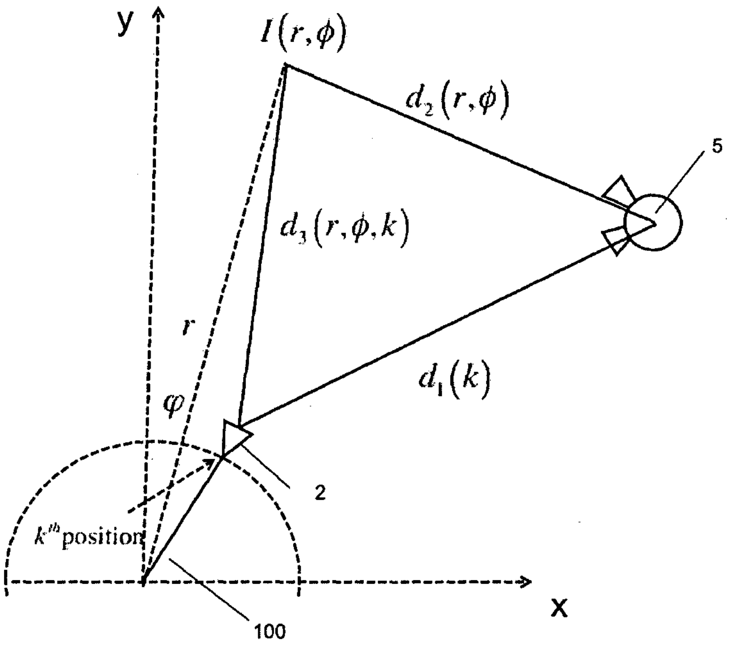
y
$I(r,\phi)$
$d_2(r,\phi)$
5
$d_3(r,\phi,k)$
r
$d_1(k)$
φ
2
k^{th}position
x
100

FIG. 14

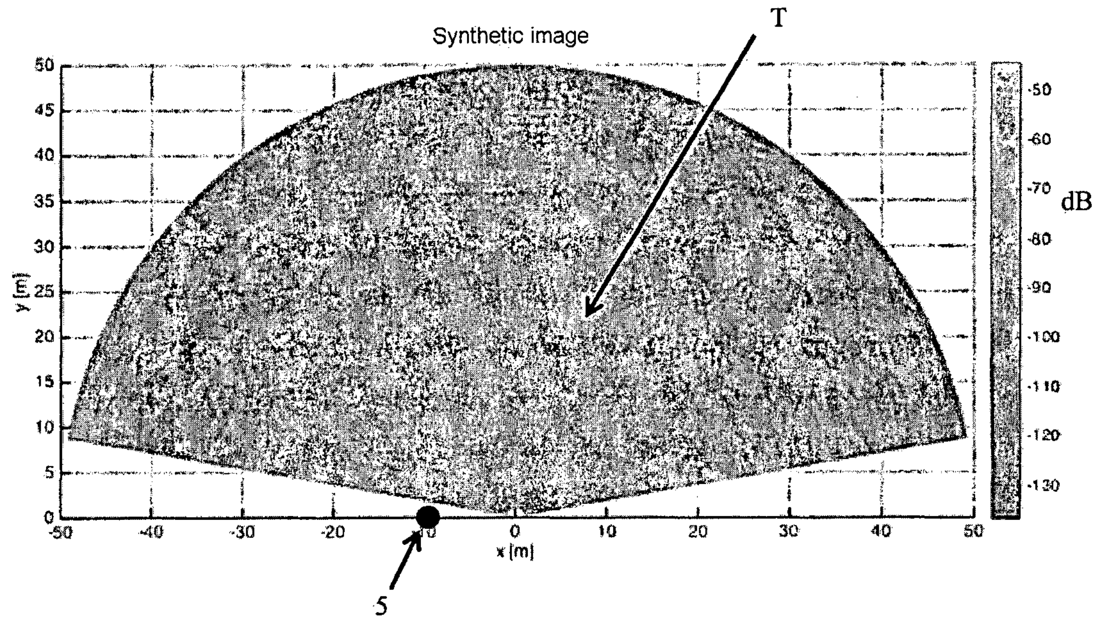

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2017/001238

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S13/90 G01S13/74
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 163 231 A (BANKS DONALD S [US] ET AL) 31 July 1979 (1979-07-31) figures 2, 4 -----	1-13
A	US 5 826 819 A (OXFORD STEPHEN C [US]) 27 October 1998 (1998-10-27) figure 2 -----	1-13
A	US 2009/051585 A1 (KRIKORIAN KAPRIEL V [US] ET AL) 26 February 2009 (2009-02-26) paragraph [0013]; figure 3a -----	1-13
A	US 2002/135505 A1 (KLAUSING HELMUT [DE] ET AL) 26 September 2002 (2002-09-26) figure 1 -----	1-13
A	US 6 724 340 B1 (CARLOS JOHN DON [US] ET AL) 20 April 2004 (2004-04-20) figure 1 -----	1-13

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 January 2018	22/01/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Rudolf, Hans

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2017/001238

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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US 6724340	B1	20-04-2004	NONE			