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- (54) **Title:** A SYNTHETIC APERTURE RADAR SYSTEM WITH AN AIRBORNE REPEATER

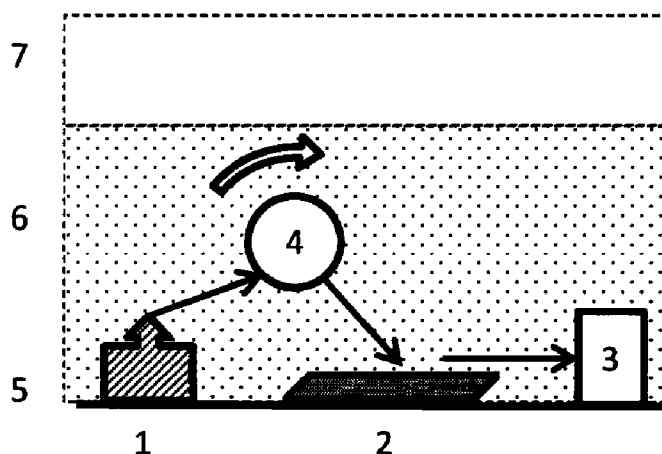


Fig 2

- (57) **Abstract:** A synthetic aperture radar (SAR) apparatus comprising, a ground based transmitter, an airborne analogue repeater, and a ground based radar receiver.

A synthetic aperture radar system with an airborne repeater

The present application is generally concerned with providing low cost and affordable SAR (Synthetic Aperture Radar) systems.

Space based SAR satellite systems have dramatically increased in number over recent years and will continue to do so. There is expected to be more than 50 SAR sensors in orbit by 2017 comprising civil remote sensing and increasingly, military and intelligence collection platforms.

In granted patent GB2501990 it was proposed to use a spaceborne or airborne transmitter to illuminate a ground target, and to use a spaceborne or airborne analogue repeater specifically “downstream” of the target, to bounce the reflected signal from the target back to a receiver on the ground, so that analogue to digital conversion would occur at the ground receiver. This was an advance in the art in terms of cost of the system as the analogue to digital receiver did not need to be certified for use on an aircraft or spacecraft, and as the transmitter was space or air borne this ensures a convenient way to move the viewing angle with respect to the target (generally needing to be moved quickly and in a straight line).

GB2501990 was the first disclosure of a bistatic radar system with a repeater that repeated the analogue signal reflected from the ground target as analogue signals, rather than converting them to digital signals and prior to forwarding them. Conversion to digital at the earliest opportunity and addition of digital checksum bits is the industry standard approach because this prevents further loss in signal quality.

The addition of an analogue repeater is not only contrary to industry standard approach, but carries a penalty typically in terms of transmitted power, but certainly in terms of signal quality (as any analogue amplification to compensate for lost power also amplifies the noise in equal measure). This was therefore a break from standard practice and not likely to be copied in other SAR systems.

It is an object of the present invention to provide a further improved SAR system.

According to a first aspect of the present invention there is provided a synthetic aperture radar (SAR) apparatus comprising:

- A transmitter arranged to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and
- At least one airborne analogue repeater;
- A ground based radar receiver arranged to receive a SAR signal reflected from the ground target, the receiver comprising an analogue to digital converter arranged to digitize the SAR signal to produce raw SAR data;

wherein:

- The transmitter is a ground based radar transmitter; and
- The airborne analogue repeater is adapted to fly along a path so as to vary a viewing angle between the repeater and a ground based target to provide a synthetic radar aperture;

The inventor has identified that a cost reduction is possible by utilizing a ground based transmitter, as this avoids the need to air (or space) certify the transmitter. However, correct operation of the SAR system with a cost-reduced transmitter requires resolution of certain technical challenges.

For correct SAR operation it is necessary to vary the angle from which the target is directly illuminated, and/or from which the radar signal is received directly from the target. This movement needs to be either accurately measured or accurately controlled, in order to minimize blurring in the image.

Generally the analogue SAR signal is a broadband signal, and preferably it has a carrier frequency and a bandwidth, which preferably is at least partially in the Ka band.

These features promote the generation of high quality SAR imagery.

The SAR apparatus comprises means to determine the path of the airborne analogue repeater to at least an accuracy comparable to the wavelength of the highest frequency component of the broadband signal.

This has the advantage of enabling higher quality SAR imagery, in particular coherent SAR imagery. However as an alternative, it is also possible to compare results generated by repetitions of the SAR signal and compensate for deviations in repeater position from the planned positions.

Measuring the trajectory of an aircraft sufficiently accurately for Ka band (i.e. short wavelengths) SAR imagery without excessive blurring is particularly challenging, as compared to when performing long wavelength SAR imagery. Given this challenge it would normally be preferable for the transmitter to be airborne, and generally it would be arranged on the same platform as the receiver, as this avoids the need to have sophisticated equipment operating together at two locations.

Even determining the trajectory of an airborne analogue repeater is expensive compared to doing this with a satellite (which is trivial because the orbital trajectory is generally known with extreme precision). The industry standard approach is to use a satellite.

Determining the trajectory of an airborne analogue repeater does not necessarily reduce the cost of the system compared to using an airborne transmitter because instead of having to air-certify the transmitter aircraft, it is now necessary to implement sophisticated equipment aboard or in relation to the airborne repeater, so to the person skilled in the art this simply transfers the cost from one problem to another, whilst also increasing the distance travelled by the signal from transmitter to receiver which generally compromises image quality.

In the approach suggested by GB2501990 a satellite or airborne transmitter is available and it would be straightforward to use the movement of the transmitter to provide the required variation in illumination angle. Movement of the transmitter is the accepted standard choice used wherever possible in the field. The moving position of a satellite is widely and generally used as the part of the SAR system giving rise to the Synthetic Aperture, because their trajectory is generally easily ascertainable with extreme precision.

Even in the embodiment in GB2501990 where an airborne transmitter is used, the skilled person would select to use variation in the position of the transmitter to create the SAR aperture, as this is the component with the one with the more sophisticated equipment aboard.

Therefore the present invention differs from GB2501990 by relying on the movement of the repeater to provide variation in the transmitter-receiver geometry and thence the synthetic aperture, and also differs from GB2501990 by requiring a ground based transmitter, which is contrary to the teaching GB2501990.

The use of a ground based transmitter is a bold departure from the teaching of GB2501990 and differs from most prior art, and indeed differs from the industry standard approach to SAR imaging of ground targets.

In view of the numerous disadvantages of the use of a ground based transmitter, and the use of movement of an airborne analogue repeater to provide the synthetic aperture, it was not obvious that this approach is advantageous.

According to a second aspect of the invention there is provided a method of performing synthetic aperture radar (SAR) comprising the steps of:

- Providing a transmitter to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and
- Controlling at least one airborne analogue repeater;
- Providing a ground based radar receiver arranged to receive said SAR signal reflected from the ground target, the receiver comprising an analogue to digital converter arranged to digitize the SAR signal to produce raw SAR data;

And:

- Arranging the transmitter as a ground based radar transmitter;
- Controlling the transmitter to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and

- Controlling the airborne analogue repeater to fly along a path so as to vary a viewing angle between the repeater and a ground based target to provide a synthetic radar aperture.

Further embodiments

Optionally the apparatus comprises at least one airborne upstream analogue repeater arranged to receive said SAR signal from the transmitter, and arranged to transmit it as an analogue signal to a ground based target.

This has the disadvantage that the power with which the target is illuminated is limited by the ability of the repeater to collect, amplify and transmit the signal from the ground based transmitter. Although it may be feasible to use a more powerful ground transmitter, the amount collected by the repeater is typically a very small fraction, and despite amplification (which also amplifies noise) it is more challenging to provide a high illumination power to the target, which will either cause a reduction in signal to noise ratio (and thence reduction in image quality) and/or require a longer illumination time which both causes moving objects in the target to be more blurred, and makes accurate tracking of the repeater(s) more difficult with consequent reduction in image quality.

Optionally the apparatus comprises at least one airborne downstream analogue repeater arranged to receive said SAR signal reflected from the ground target, and arranged to output it as an analogue signal to a ground based receiver.

This has the advantage that it is possible to obtain a SAR image of a ground target which lacks even one suitably overlooking ground location, so it is not necessary for either the ground based transmitter or ground based receiver to be in line of sight of the imaging target. There is however a significant disadvantage, which is that the use of two analogue repeaters further decreases the signal strength and/or signal quality and thus limits the possible image quality available.

Preferably there is an airborne downstream analogue repeater, and an airborne upstream analogue repeater. This has the problem of increasing the length of the SAR signal transmission journey, yet allows elevated viewing/receiving angles from/to the target,

without the need for convenient hillside viewing points at different angles around the target.

Optionally the apparatus further comprises optical detection means (E.g. Lidar) for measuring the position and trajectory of one of the airborne analogue repeaters (e.g. the upstream one, or if only one is moving then that one). The apparatus may further comprise a second optical detection means for measuring at least the position (and trajectory if any) of another airborne analogue repeater (E.g. a downstream one).

The optical range and position detection means may comprise a range finder aboard the analogue airborne repeater(s), utilizing at least two, preferably at least three ground based references (E.g. optical retro-reflectors) to measure it's position. Optical range and position detection may alternatively comprise at least one (preferably two or more, or preferably three or more) ground based apparatus. Such ground based optical apparatus may be arranged to detect the position of the (or each) airborne analogue repeater, by means of an optical retroreflector aboard the (or each) airborne analogue repeater.

Optionally the apparatus further comprises first inertial acceleration detection means for determining the trajectory of one of the airborne analogue repeaters (e.g. the upstream one, or if only one is moving then that one). The apparatus may further comprise second inertial acceleration detection means for determining the trajectory of at least the position of another airborne analogue repeater (E.g. a downstream one).

An inertial acceleration detection means comprises an inertial acceleration sensor aboard the relevant airborne analogue repeater(s) and may include additional sensors such as rotation sensors and GPS sensors. It may not be required to determine the absolute trajectory of the airborne analogue sensor, but rather a precise relative trajectory combined with a less precise absolute position measurement may suffice to provide much of the image quality benefit expected of coherent SAR imaging without all of the complexity or cost of generating precise absolute measurements.

Optionally both inertial acceleration measurements are combined with optical position detection (e.g. Lidar) to precisely measure the position and trajectory of the (or each)

moving analogue airborne repeater. Preferably this includes measuring rotation of the (or each) airborne repeater in multiple axes, so as to calculate the position of both a re-transmitter and a receiver (if any) comprised in the repeater.

Preferably the ground based transmitter, and/or the ground based receiver are 'portable', meaning vehicle based and/or suitable for being conveniently carried or moved by a person (e.g. a unit with a handle and typically wheels and a case), but preferably vehicle based.

Preferably the (or any) travelling airborne analogue repeater (i.e. that or those arranged to fly with a substantial direction component that both is horizontal and is tangential to the direction of the ground target from that repeater, during repeating of the analogue radar signal) is an aeroplane (as opposed to a purely vertical rotor aircraft). Preferably such aircraft are arranged to fly during the transmission of the analogue radar signal, at a flying speed over ground of at least 100mph, more preferably 200mph, more preferably 300mph as this minimizes the flight time required to traverse a required angle with respect to the ground target. Preferably such aircraft are arranged to fly during the transmission of the analogue radar signal, at an airspeed of at least 100 knots, more preferably 200 knots, more preferably 300 knots. Optionally both an upstream and a downstream airborne repeater have such properties.

Additional simplification and cost saving is synergistically achieved via use of unmanned aircraft to provide the airborne repeater(s). Additional simplification is achieved by processing the image at the site of receiving the raw (i.e. unprocessed) SAR data, and then sending the image which will be a much smaller electronic data file than the raw SAR data.

Preferably the upstream airborne analogue repeater is a UAV. Preferably the downstream airborne analogue repeater (if present) is also a UAV. Preferably there is both an upstream analogue repeater and a downstream analogue repeater.

Preferably the upstream airborne analogue repeater is a UAV operating during SAR imaging at an altitude greater than flight level 600 (approximately 60,000 feet which is 5500 metres) and less than 100 kilometres. This has the advantage of avoiding some of the air

certification requirements associated with use in commercial airspace. Preferably all the airborne analogue repeaters have this property.

Optionally the UAVs are adapted to be solar powered. Optionally the UAVs are maintained at operational altitude for more than 24 hours (or are adapted to be).

Preferably there is both an upstream analogue repeater and a downstream analogue repeater and both are UAVs and both are operated above 60,000 feet but below 100 kilometers. Preferably both are maintained at operational altitude for more than 24 hours, and preferably more than one week, being preferably solar powered. Preferably at least one has a standard cruising speed over ground of at least 100mph more preferably at least 200mph, and preferably both upstream and downstream UAVs do.

The use of two UAVs provides for repeated SAR imaging of an area of concern (e.g. regarding disaster management such as in case of flooding, or for policing) for monitoring changes, and can enable high quality imaging at a lower cost than previously possible. The use of Ka band is synergistic with this approach because Ka band is absorbed by atmospheric water vapour and thus benefits from the shorter path lengths than using conventional satellite SAR imaging.

Optionally the SAR method is repeated at two different times, and the two digital images are digitally aligned and compared to identify changes that have occurred in the ground target between those two times. Preferably the comparison is performed by implementing a digital image comparison algorithm in a computer system.

Preferably the analogue signal is at least partially in the Ka band. Preferably it at least spans the Ka band. Preferably it has a bandwidth of at least 10GHz, more preferably at least 20GHz, more preferably at least 30GHz.

Preferably the receiver comprises a SAR image processor arranged to process the raw SAR data to generate a digital image, and preferably it also comprises means for sending the digital image via a data connection for remote use.

While tangential movement of the upstream analogue repeater can be used to form the varying aperture of the SAR system, in the case that a downstream analogue repeater is also provided, either of the analogue repeaters can be moved tangentially (with respect to the ground target) or both can be moved in a jointly coordinated fashion.

Optionally the frequency referred to is the lowest frequency of the broadband signal, but preferably the midpoint of a frequency span of the broadband signal, and optionally is the highest frequency thereof.

More generally, the invention provides a SAR apparatus comprising, a ground based transmitter, one or more airborne analogue repeaters and a ground based radar receiver. The apparatus operates with a broadband signal at least partially in the Ka band, and the airborne analogue repeater(s) is/are adapted to fly with their path controlled or measured with an accuracy corresponding to a wavelength of the broadband signal.

Optionally the SAR is bistatic (which term is used to encompass multistatic SAR). Bistatic requires that the SAR signal is sent to the ground target at one angle, and collected from the ground target at another, different angle, however as the SAR signal is redirected by at least one airborne repeater, the initial transmission and eventual recording of the signal by the ground based transmitter and ground based receiver may be performed at substantially the same ground based location. Typically however they are performed at different locations.

The term "ground based" includes being mounted on a ground based tower or similar arrangement. Preferably the transmitter, receiver or both are portable, such as being vehicle mounted. Generally SAR signal decoding means are provided substantially at the location of the receiver, for generating a SAR image substantially at the location of the receiver.

While optionally the analogue repeater is a reflector, preferably it comprises a collector and retransmitter, preferably with an amplifier arranged to amplify the collected SAR signal for retransmission. Optionally the analogue repeater comprises two collectors, and two retransmitters. The term 'retransmitter' is used to distinguish from the transmitter which converts digital code to generate the analogue SAR signal.

The terms 'upstream' and 'downstream' refer to the position of a repeater relative to the target with respect to the direction of flow of SAR signals from the transmitter to the target and on to the receiver.

In the term "an accuracy comparable to the highest frequency component of the broadband signal" the highest frequency component corresponds to the highest frequency of a continuous band of frequencies used. The inclusion of extraneous (i.e. irrelevant or unrelated to the subject matter being dealt with) higher frequencies is to be disregarded as such frequencies would not be those that contribute usefully to the resolution of the resulting SAR image.

However where the broadband signal is required to be at least in the Ka band, the highest frequency component of the broadband signal will be at least comparable to the lower frequency boundary of the Ka band, i.e. at least 26.5GHz. Thus the accuracy of the determination referred to should therefore be an accuracy comparable to 11.1 cm (which is 4.37 inches), which preferably is at least an accuracy of 8cm (which is 3.15 inches), more preferably at least an accuracy of 2cm (which is 0.787 inches), more preferably an accuracy of at least 1cm (which is 0.394 inches), and most preferably an accuracy of at least 0.5cm (which is 0.197 inches).

Preferably the SAR apparatus comprises means to determine the path of the airborne analogue repeater to at least an accuracy of substantially the wavelength of the highest frequency component of the broadband signal.

Further embodiments are set out in the claims.

A preferred embodiments of the invention will now be described by way of reference only to the accompanying drawings in which:

Figure 1 shows two known SAR approaches;

Figure 2 shows one preferred embodiment of the invention;

Figure 3 shows a second preferred embodiment

Figure 4 shows a third preferred embodiment; and

Figure 5 shows a fourth preferred embodiment.

Turning to figure 1, a first known SAR approach is shown on the left, being the preferred approach taught by GB2501990. Here a satellite transmitter 1 orbits in space 7 above a ground based 5 target 2, and the reflected SAR signal is repeated by a repeater 4 which is airborne 6, to a ground based receiver 3. As discussed above, it would be easiest for the transmitter 1 to move (curved arrow) and for its trajectory to be controlled or monitored, as this is either in space (with a well-known trajectory) or already has sophisticated equipment aboard and thus would normally be selected as the component who's trajectory is carefully controlled or monitored.

A second known SAR approach is shown on the right of figure 1 which is representative of the conventional approach used in the field of SAR radar. A satellite transmitter 1 orbits above the atmosphere 6 in space 7 above a ground target 2. A SAR signal transmitted to the ground based 5 target 2 is reflected to a receiver 3 which is also a satellite. Here both transmitter and receiver move in precisely defined and accurately known orbits (curved arrows).

Turning to figures 2 and 3 two preferred embodiments are shown. Figure 2 shows a ground based 5 transmitter 1 transmitting a SAR signal to an airborne 6 repeater 4, which redirects the signal to a ground based 5 target 2, which reflects the signal to a ground based 5 receiver 3.

Figure 3 shows a different embodiment where the airborne 6 repeater 4 is 'downstream' of the ground based 5 target 2, to redirect the signal from the ground based 5 target 2 to the ground based 5 receiver 3.

Figure 4 shows another embodiment where there are two airborne repeaters 4. Both of these are analogue repeaters. One or both of these move (curved arrows) so as to form a varying synthetic aperture and the position of the one or more moving repeaters is accurately determined by being accurately tracked or controlled. Generally, even if one of them does not move, it's position is preferably accurately determined.

Typically the airborne repeaters are both aeroplanes, although they could be aeroplane and a vertical shaft rotorcraft (e.g. quadcopter) respectively. To limit the reduction in image

quality caused by passing the SAR signal along three or four journeys, the length of each journey is minimised, preferably being less than substantially 30km each, preferably less than 10km each, and is preferably less than 30km in total, preferably less than 10km total.

Figure 5 shows a monostatic preferred embodiment where the signal is passed from the ground based 5 transmitter 1 to the analogue repeater 4 to the ground based 5 target 2 and back to the analogue repeater 4 and back to the ground based 5 receiver 3. Thus the analogue repeater is adapted both to repeat SAR signals from the transmitter to the target, and also from the target to the same location as the transmitter.

Claims:**1. A synthetic aperture radar (SAR) apparatus comprising:**

- A transmitter arranged to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and
- At least one airborne analogue repeater;
- A ground based radar receiver arranged to receive said SAR signal reflected from the ground target, the receiver comprising an analogue to digital converter arranged to digitize the SAR signal to produce raw SAR data;

wherein:

- The transmitter is a ground based radar transmitter; and
- The airborne analogue repeater is adapted to fly along a path so as to vary a viewing angle between the repeater and a ground based target to provide a synthetic radar aperture.

2: The SAR apparatus of claim 1 comprising at least one airborne upstream analogue repeater arranged to receive said SAR signal from the transmitter, and arranged to transmit it as an analogue signal to a ground based target.

3: The SAR apparatus of claim 1 or 2 comprising at least one airborne downstream analogue repeater arranged to receive said SAR signal from the ground target, and arranged to output it as an analogue signal to a ground based receiver.

4. The SAR apparatus of any preceding claim wherein the analogue SAR signal is a broadband signal which is at least partially in the Ka band.

5. The SAR apparatus of any preceding claim wherein the SAR apparatus comprises means to determine the path of the airborne analogue repeater to at least an accuracy comparable to the wavelength of the highest frequency component of the broadband signal.

6: The SAR apparatus of any preceding claim, comprising optical position detection means for measuring the position and trajectory of at least one airborne analogue repeater.

7: The SAR apparatus of any preceding claim, comprising inertial acceleration detection means for determining the trajectory of at least one airborne analogue repeater.

8: The SAR apparatus of any preceding claim wherein the or each upstream airborne analogue repeater is an unmanned aerial vehicle (UAV) arranged at an altitude greater than flight level 600.

9. The SAR apparatus of any preceding claim wherein the SAR apparatus is a monostatic SAR apparatus, and the airborne analogue repeater is both adapted to repeat SAR signals from the ground based transmitter to the ground target, and adapted to repeat SAR signals from the ground target to the ground based receiver.

10. A method of performing synthetic aperture radar (SAR) comprising the steps of:

- Providing a transmitter to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and
- Controlling at least one airborne analogue repeater;
- Providing a ground based radar receiver arranged to receive said SAR signal as a - reflection from a ground target, the receiver comprising an analogue to digital converter arranged to digitize the SAR signal to produce raw SAR data;

And:

- Arranging the transmitter as a ground based radar transmitter;
- Controlling the transmitter to convert a digital code to an analogue SAR signal and to transmit the analogue SAR signal; and
- Controlling the airborne analogue repeater to fly along a path so as to vary a viewing angle between the repeater and a ground based target to provide a synthetic radar aperture.

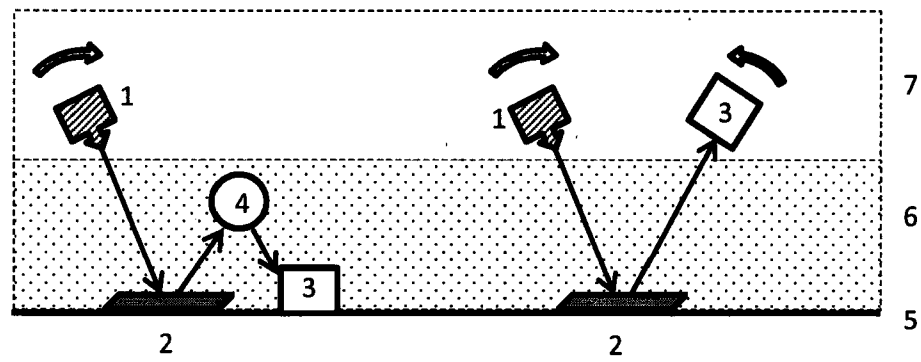


Fig 1. Prior Art

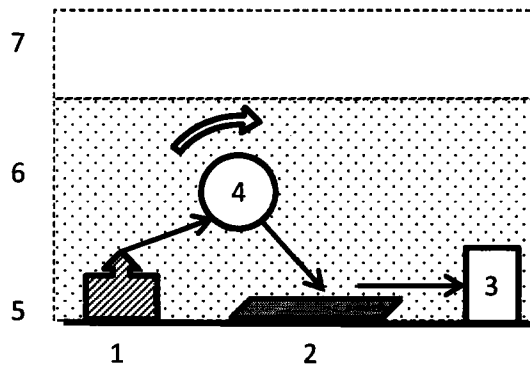


Fig 2

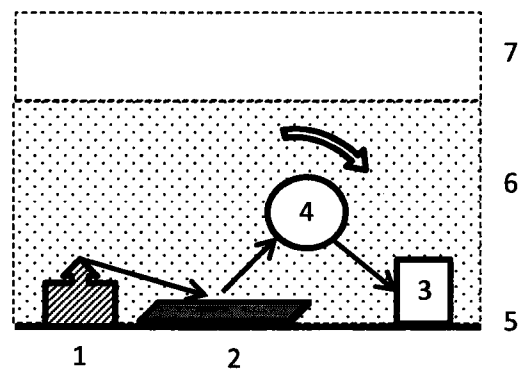


Fig 3

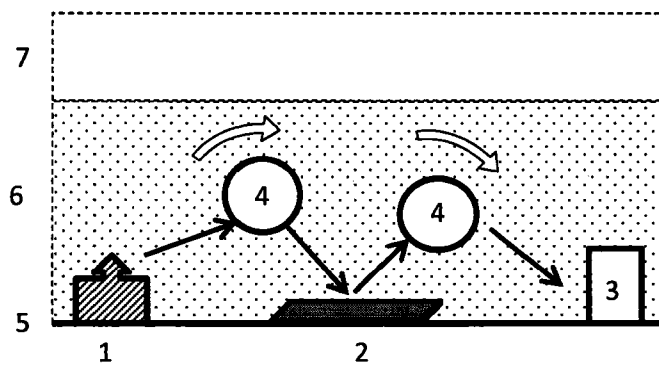


Fig 4

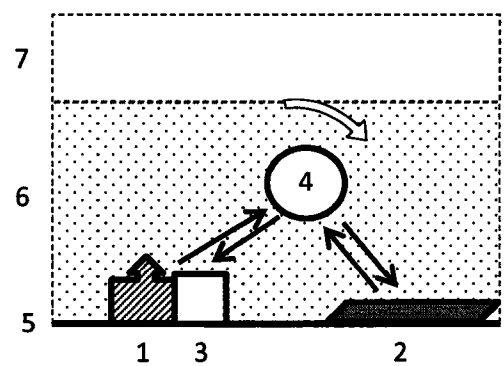


Fig 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2017/000019

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S7/00 G01S13/90 H04B7/185
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, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 60 170777 A (NATL SPACE DEV AGENCY JAPAN) 4 September 1985 (1985-09-04) figure 4 the whole document -----	1-10



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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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

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Date of the actual completion of the international search

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Metz, Carsten

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2017/000019

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 60170777	A	04-09-1985	NONE
