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(54) **HELIOSTAT CALIBRATION**

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(52) **U.S. Cl.** **126/573**

(57) **ABSTRACT**

Embodiments relate to solar energy systems and methods of operating the same. In some embodiments, the solar energy system comprising: a plurality of heliostats configured to reflect sunlight to a target mounted on a tower, each heliostat including a respective heliostat controller, the target, the target being selecting from the group consisting of an energy conversion target and/or a secondary reflector; and a macro-array of light-intensity sensors characterized by a maximum sensor-sensor distance and mounted on the tower such that when any heliostat of the plurality of heliostats reflects a beam of light onto the macro-array of light-intensity sensors, the maximum dimension of the reflected beam's projection on the macro-array is at most twice the maximum sensor-sensor distance, wherein each heliostat controller is operative to control its respective heliostat so that the light beam reflected by the heliostat traverses the macro-array of light-intensity sensors.

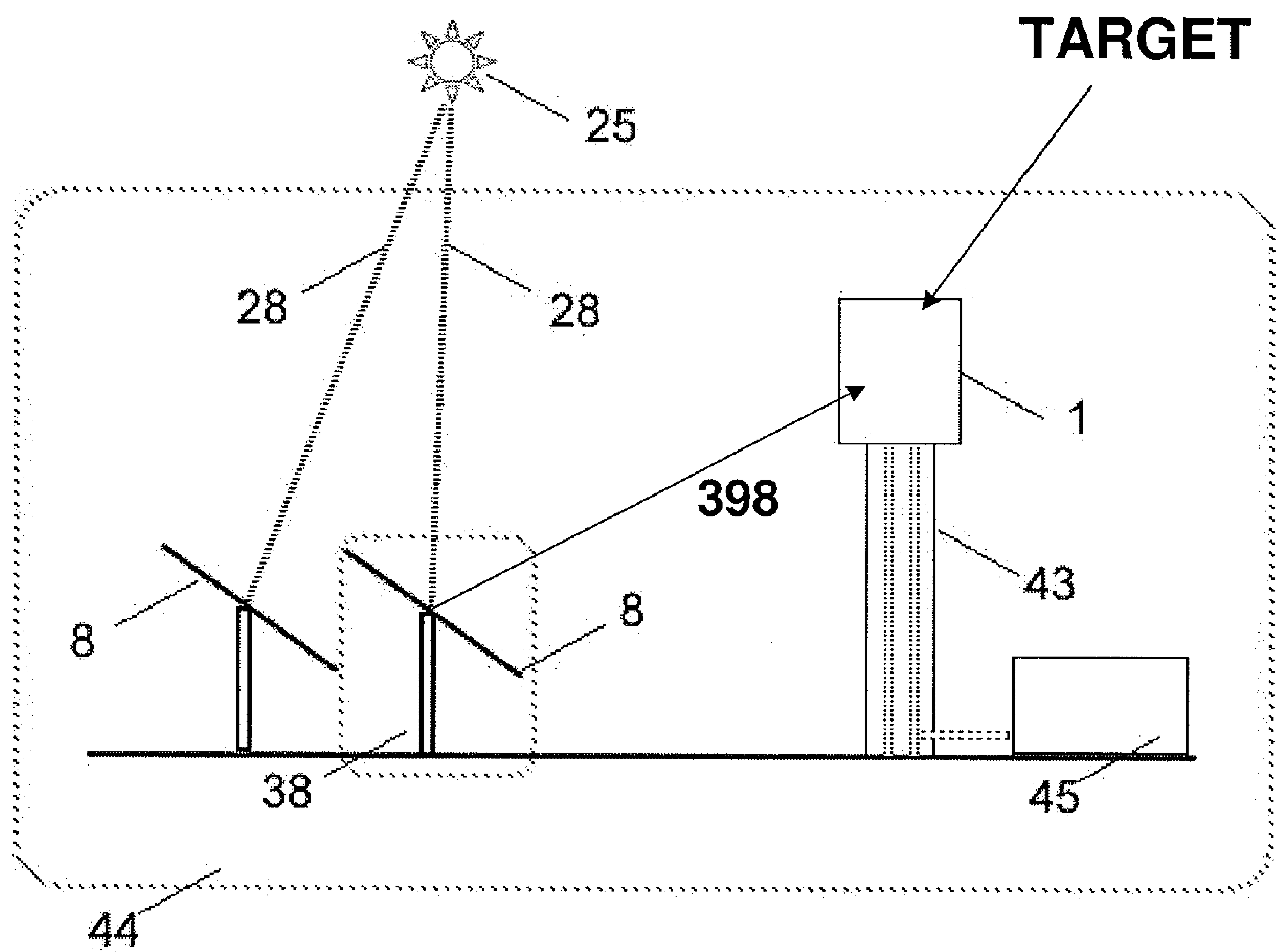


FIG. 1

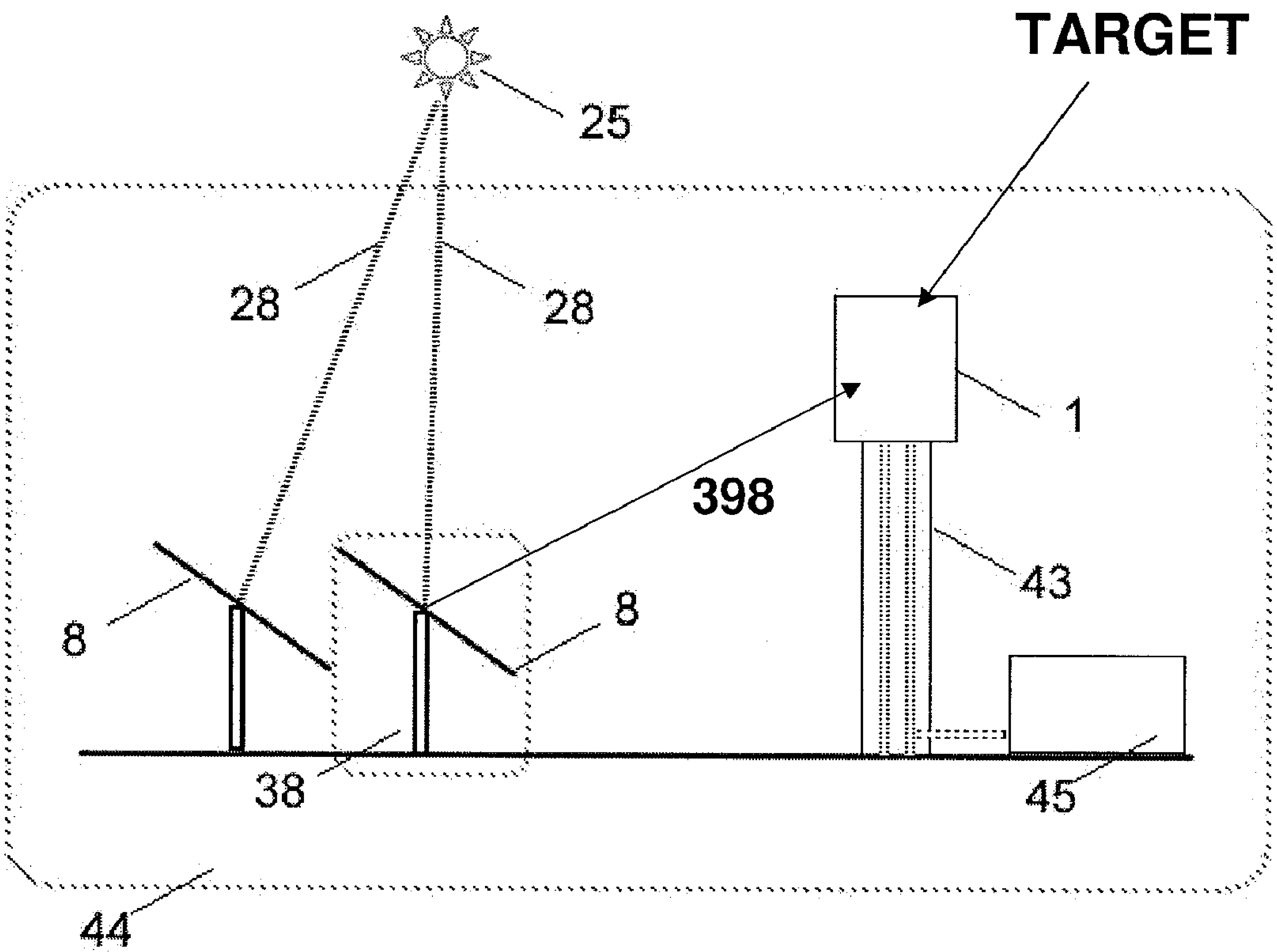


FIG. 2

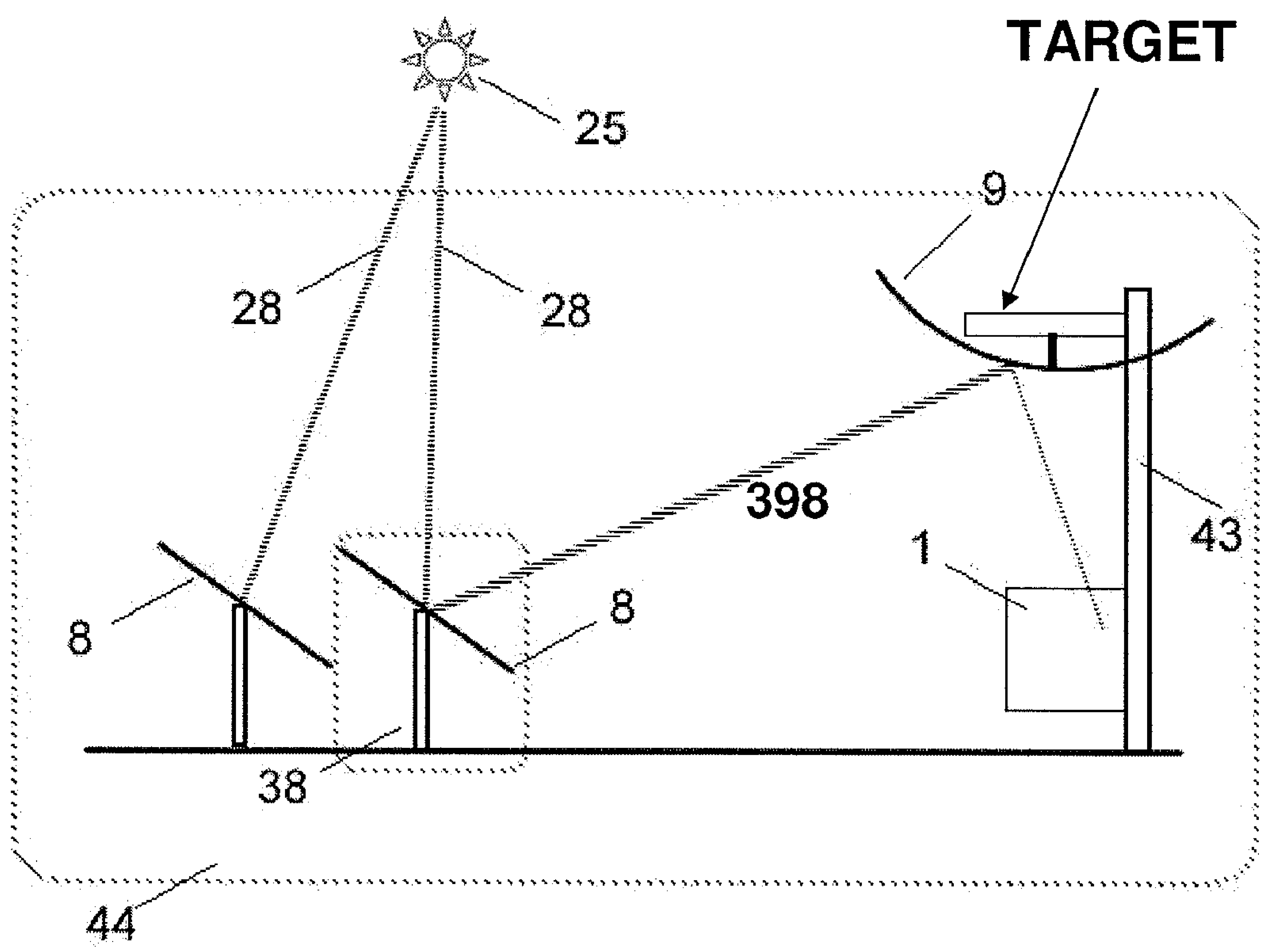
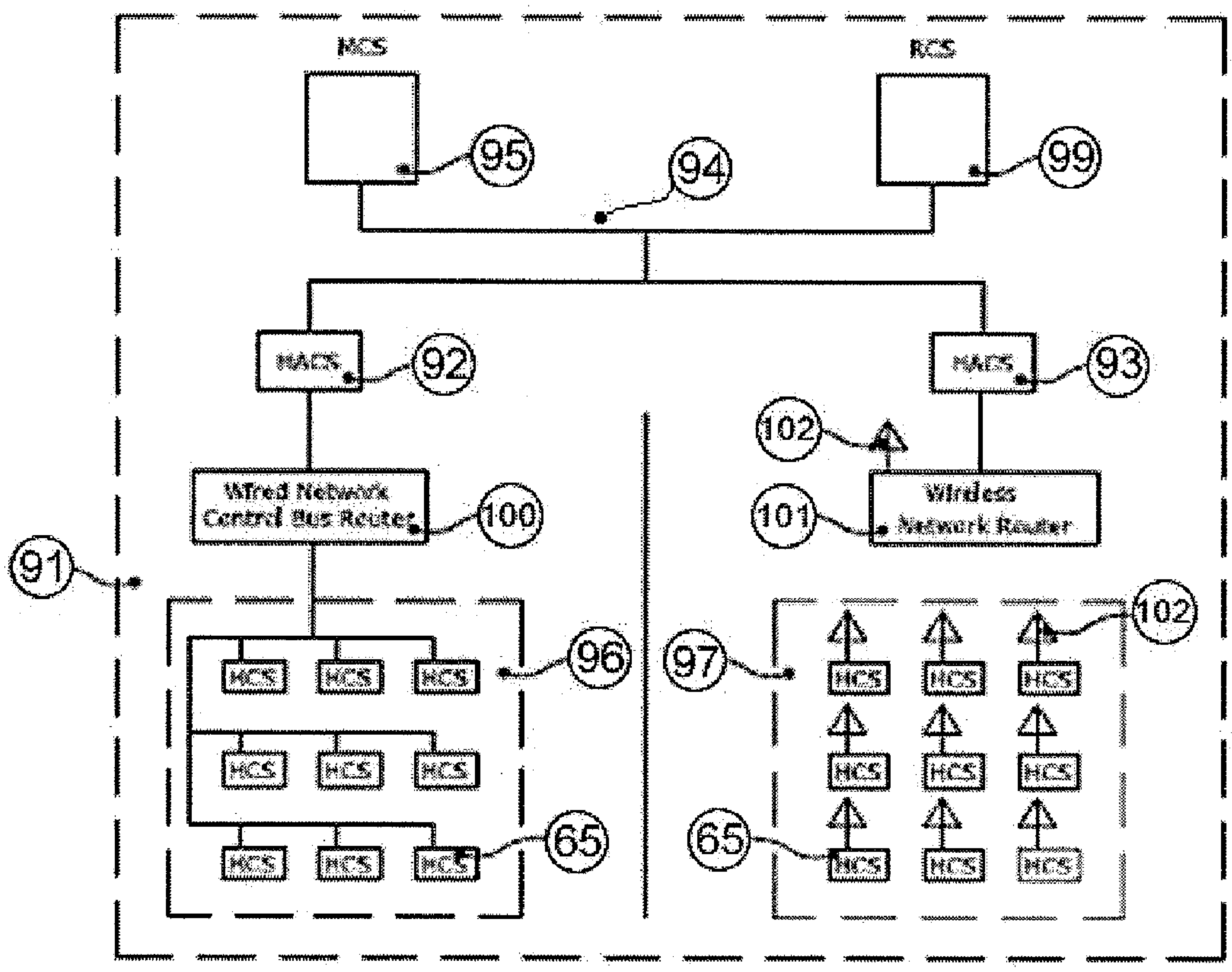
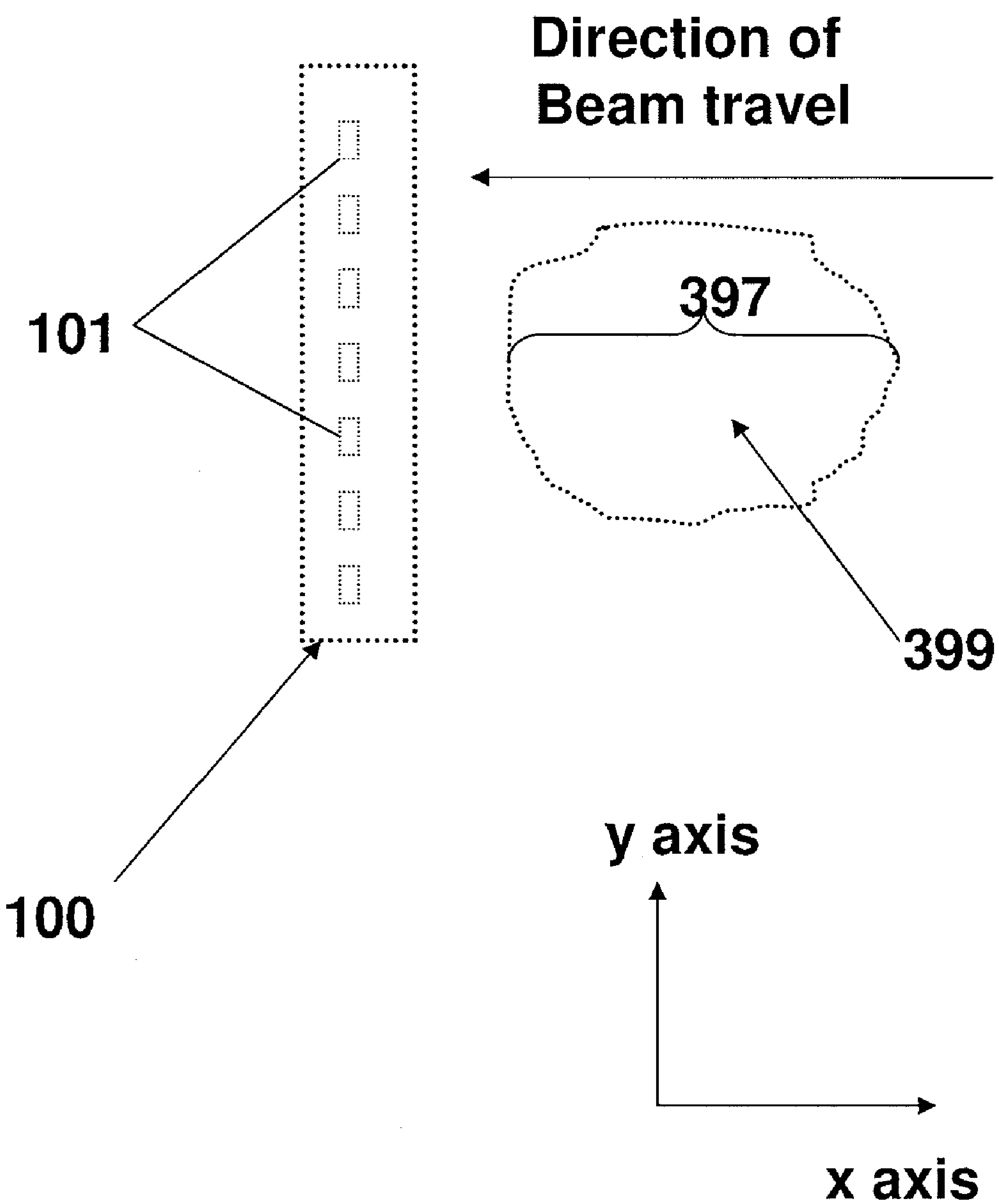


FIG. 3


MCS
RCS
95
99
94
NACS
92
NACS
93
102
Wired Network Control Bus Router
100
Wireless Network Router
101
91
HCS
96
97
65
102

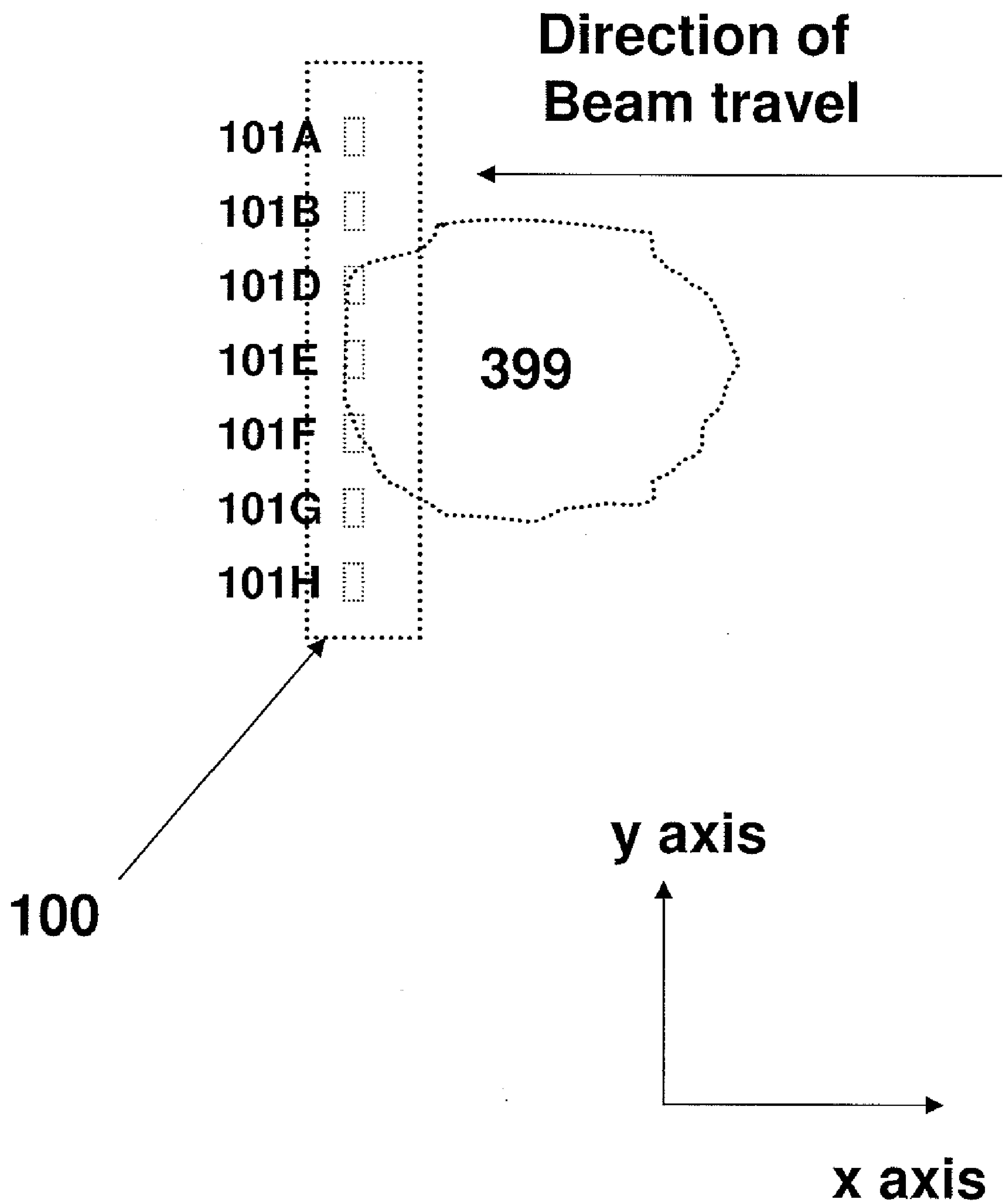
Time = t0

FIG. 4A



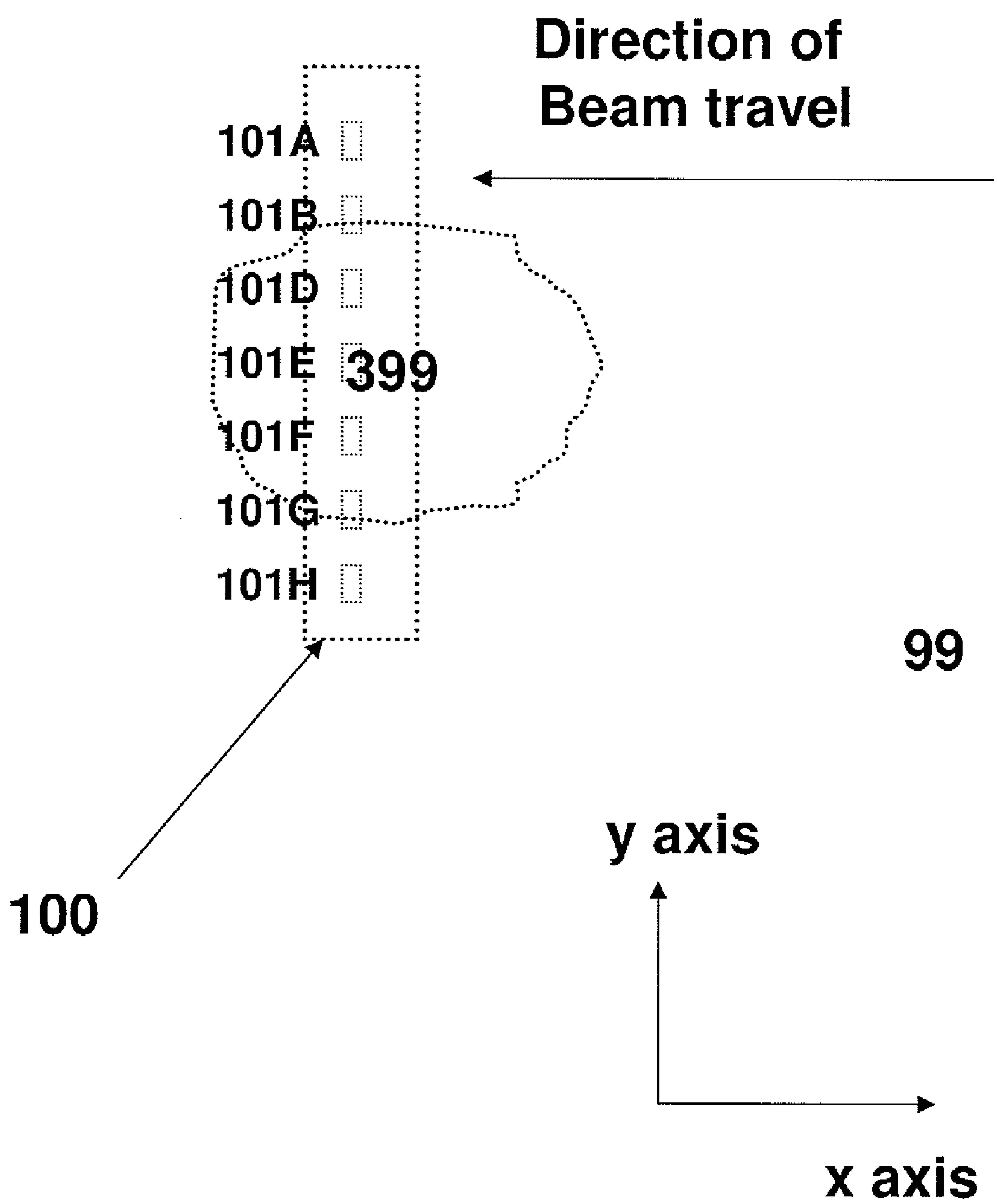
Time = t1

FIG. 4B



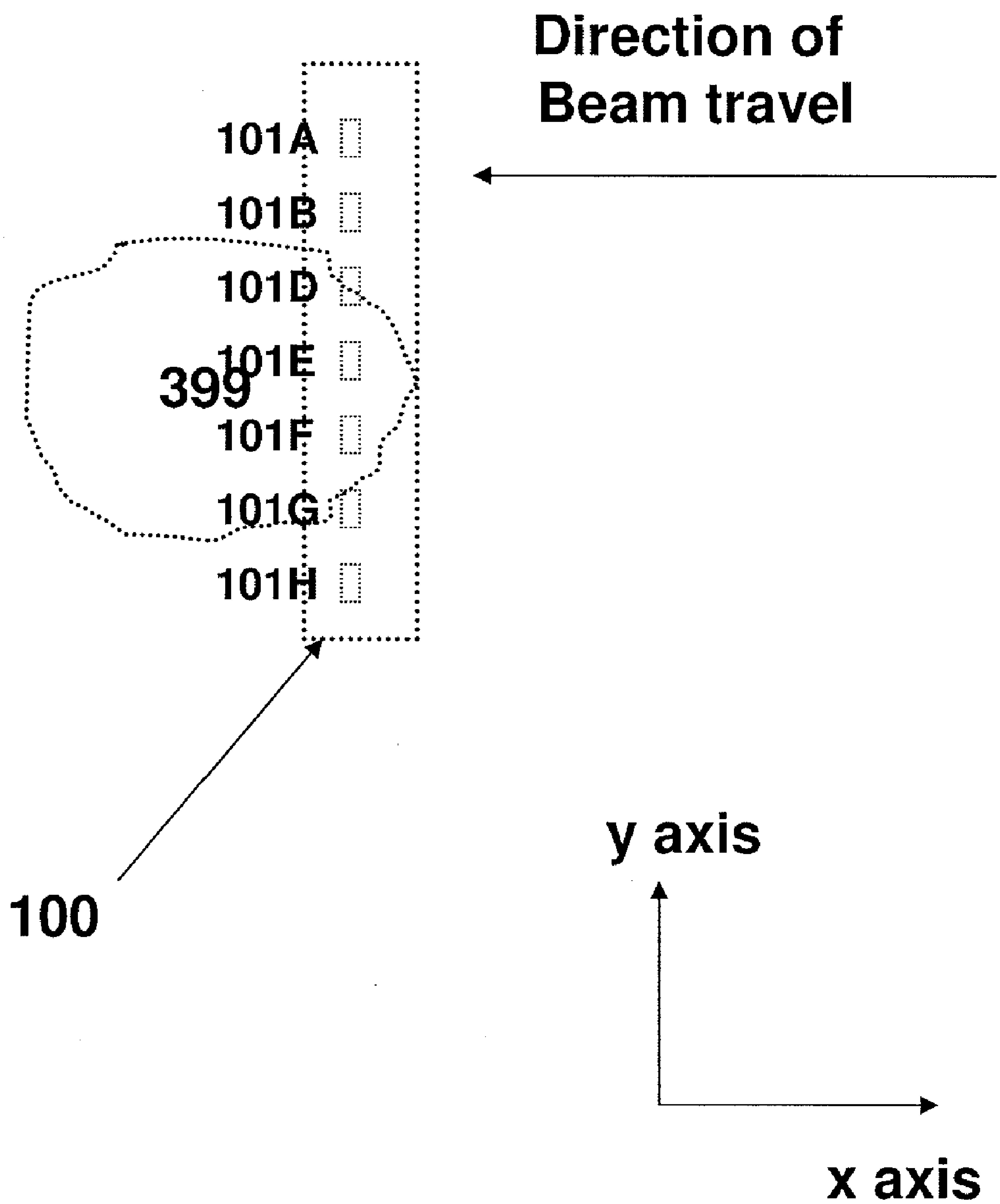
Time = t2

FIG. 4C



Time = t3

FIG. 4D



Time = t4

FIG. 4E

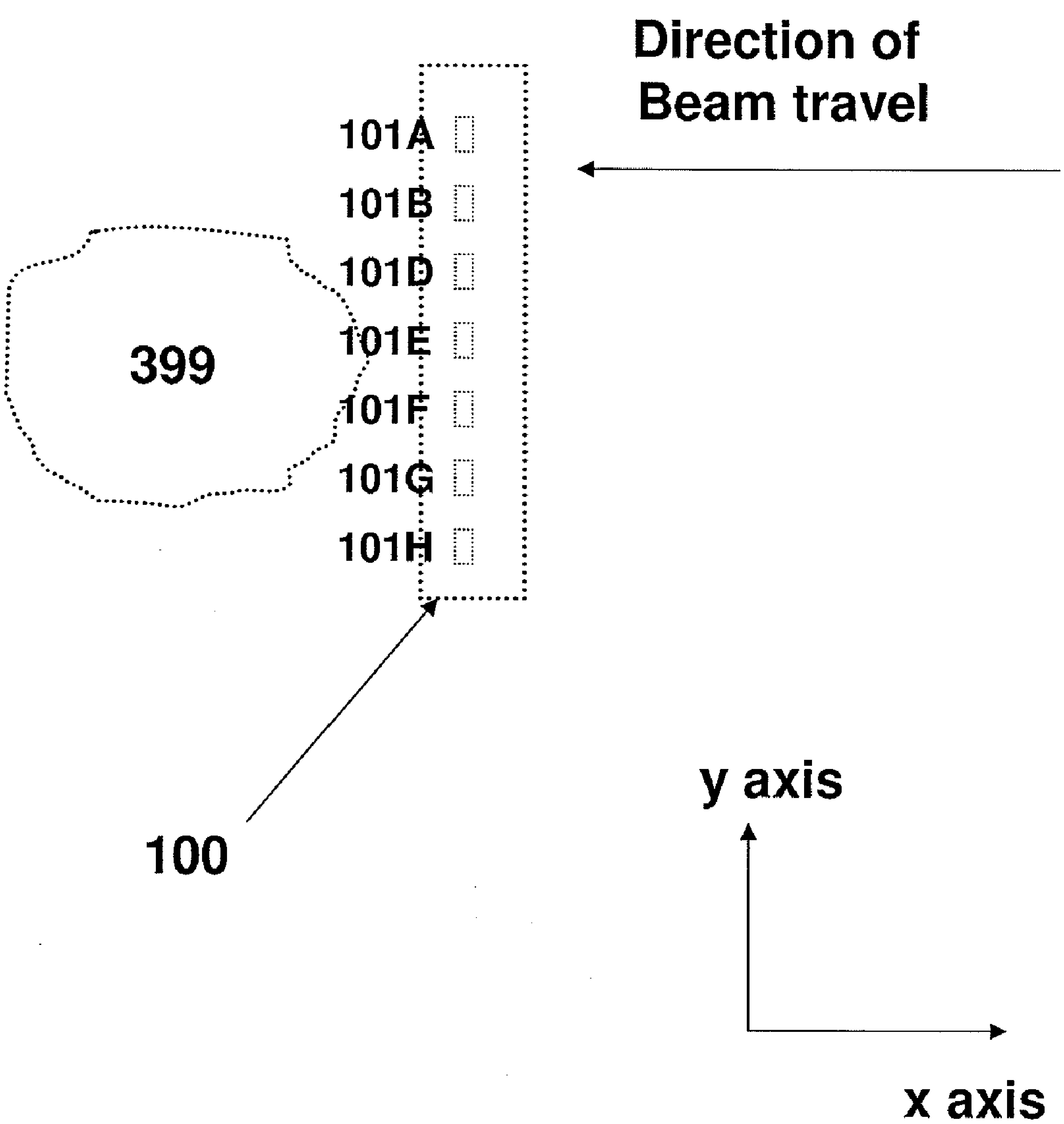


FIG. 5A

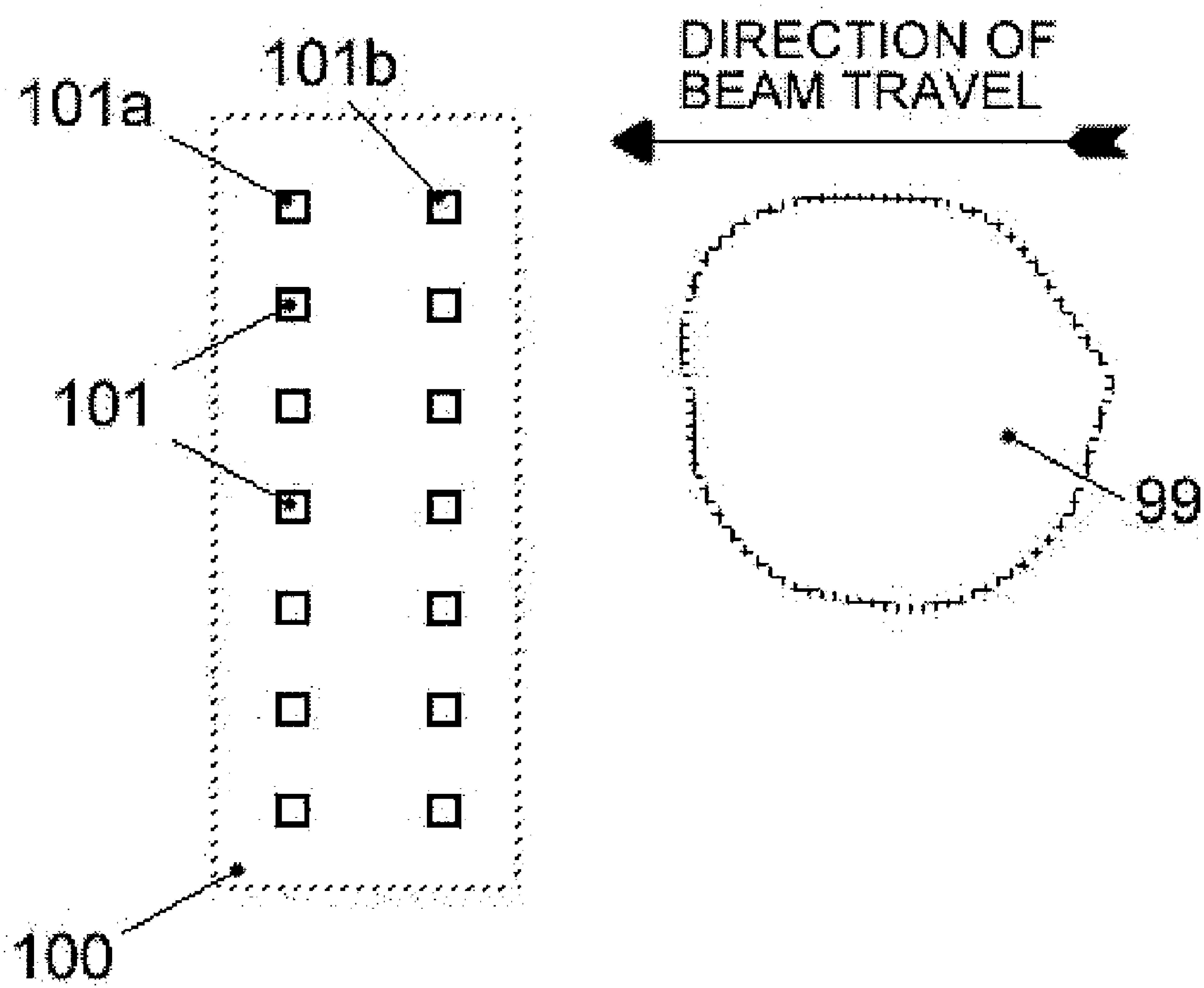


FIG. 5B

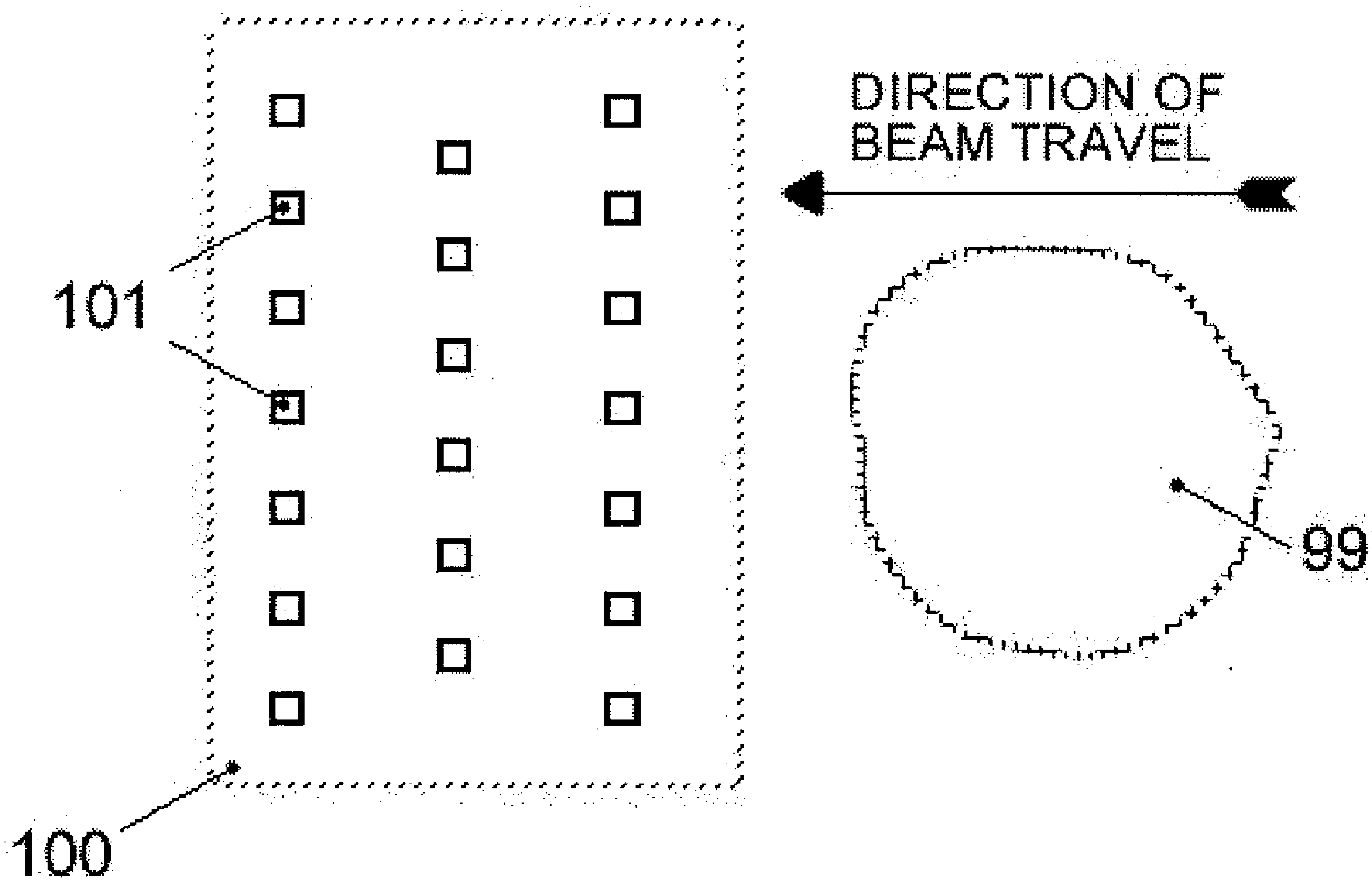


FIG. 6A

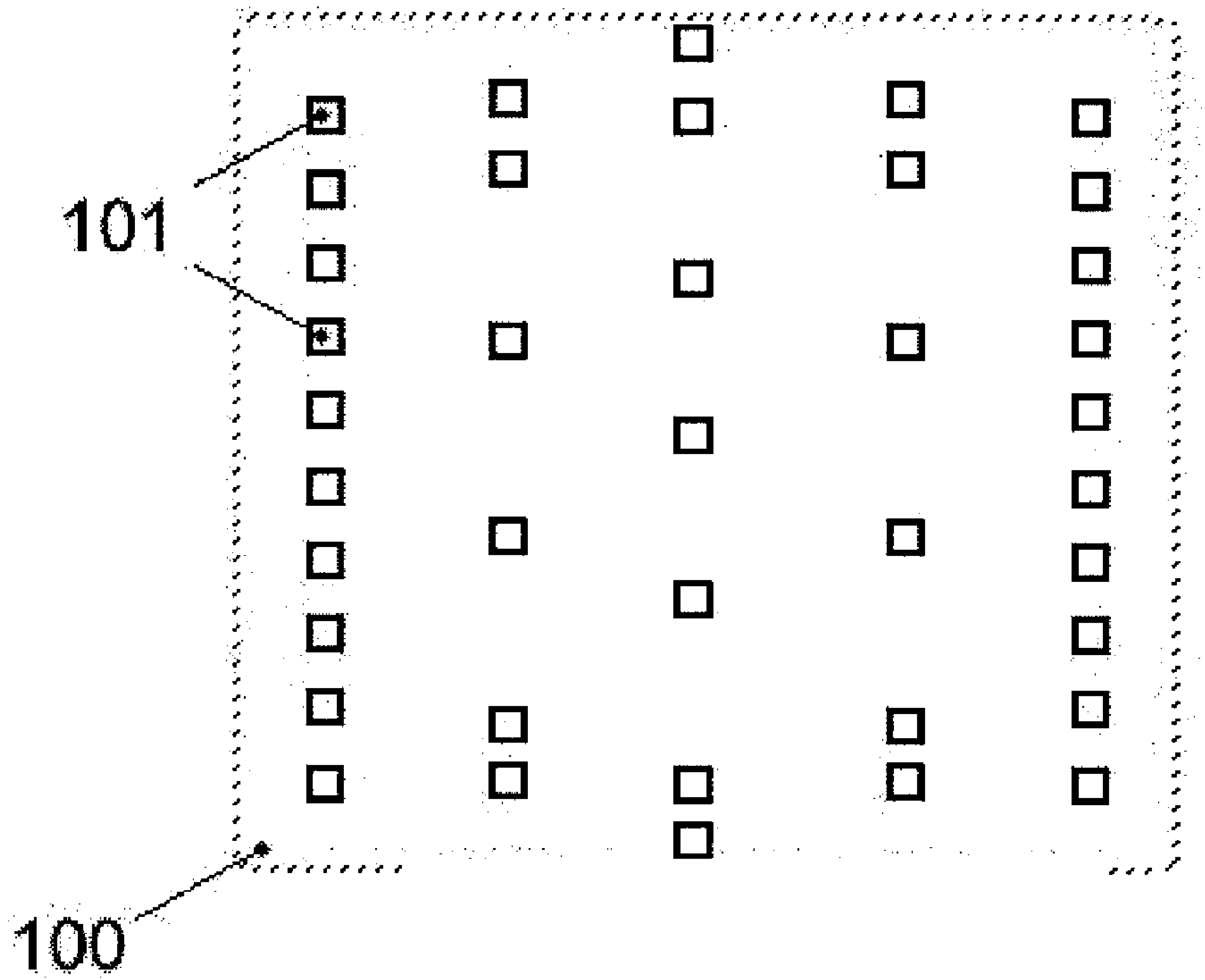
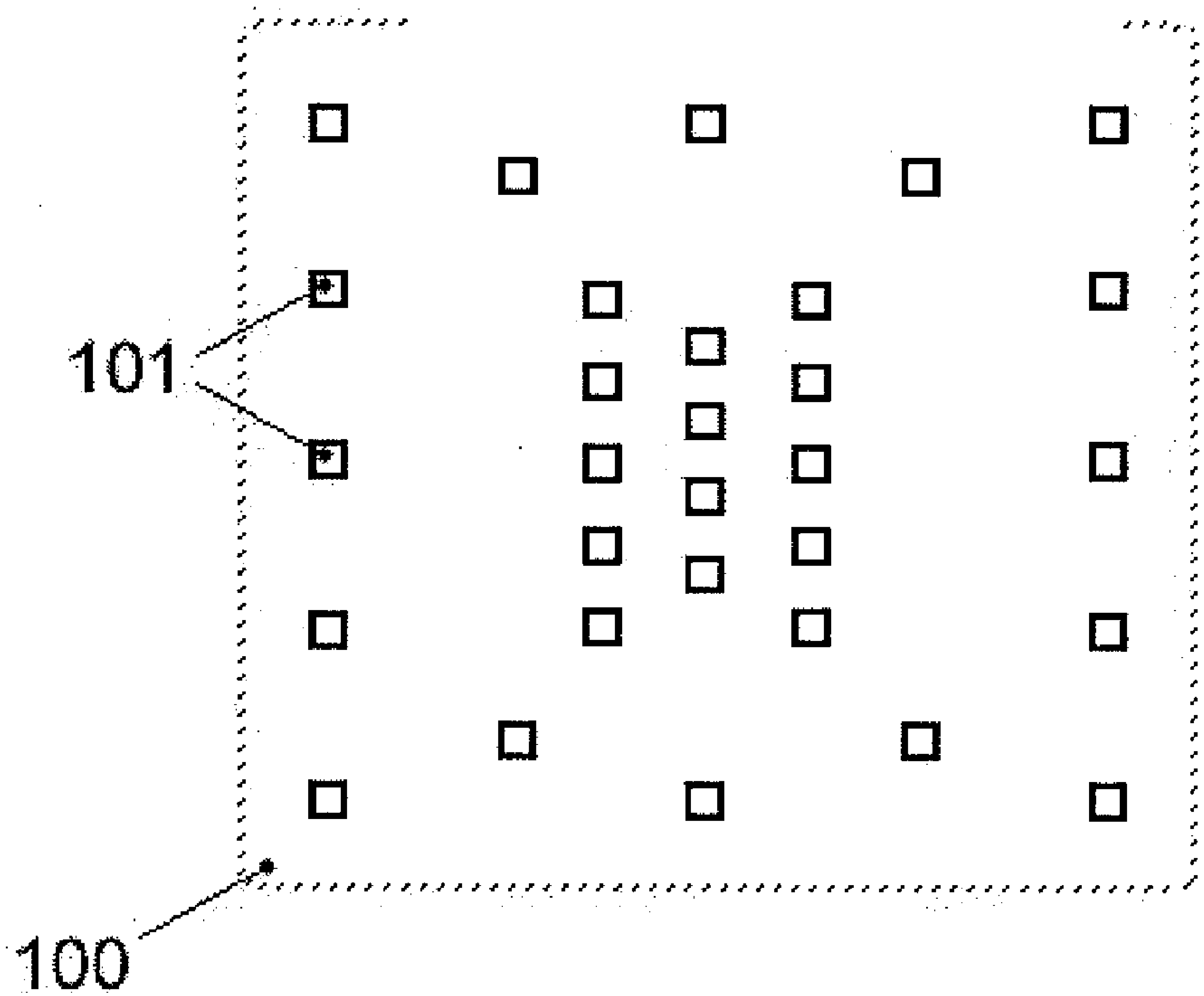


FIG. 6B



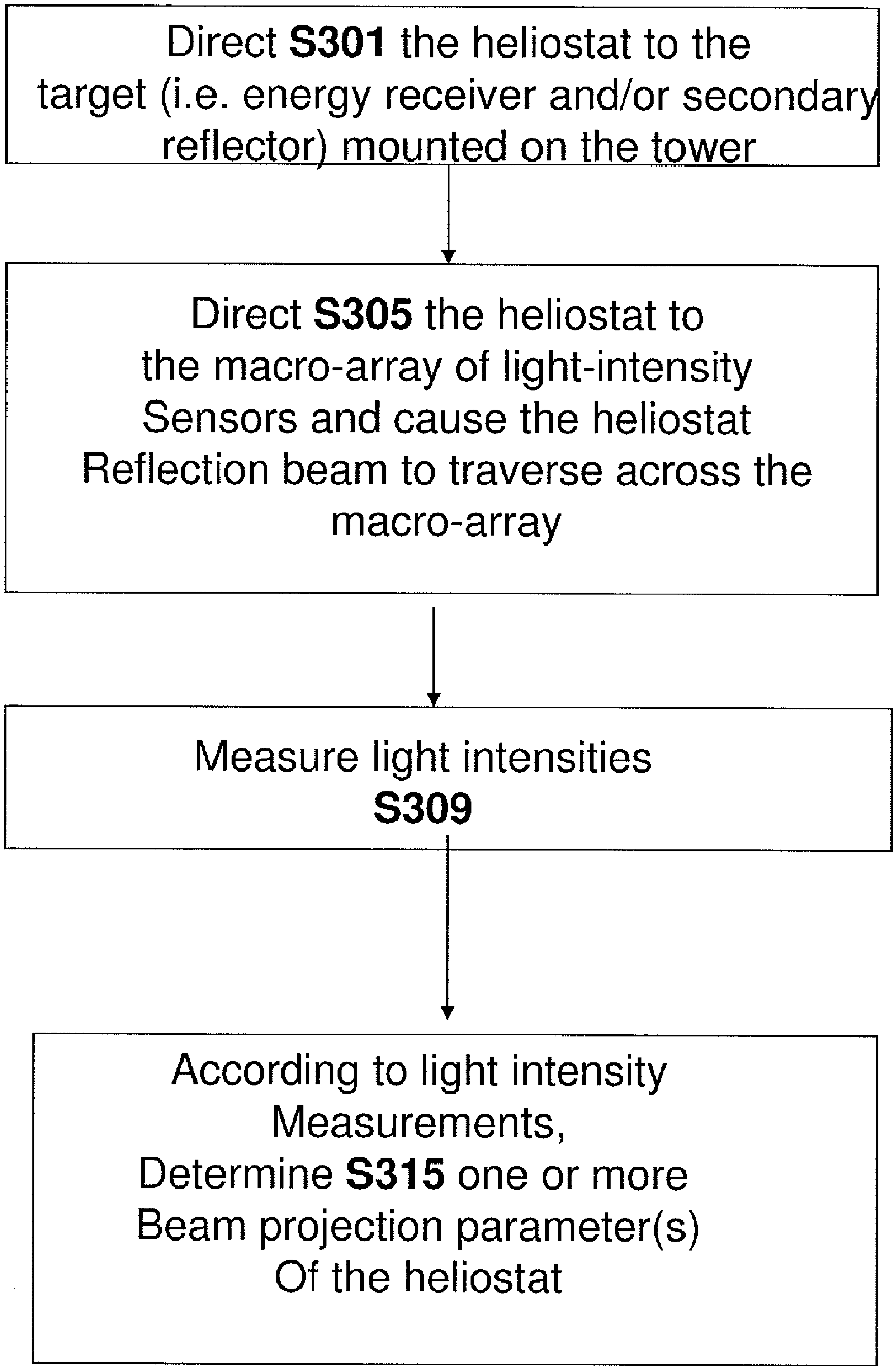

Direct **S301** the heliostat to the target (i.e. energy receiver and/or secondary reflector) mounted on the tower
Direct **S305** the heliostat to the macro-array of light-intensity Sensors and cause the heliostat Reflection beam to traverse across the macro-array
Measure light intensities **S309**
According to light intensity Measurements, Determine **S315** one or more Beam projection parameter(s) Of the heliostat

FIG. 7A

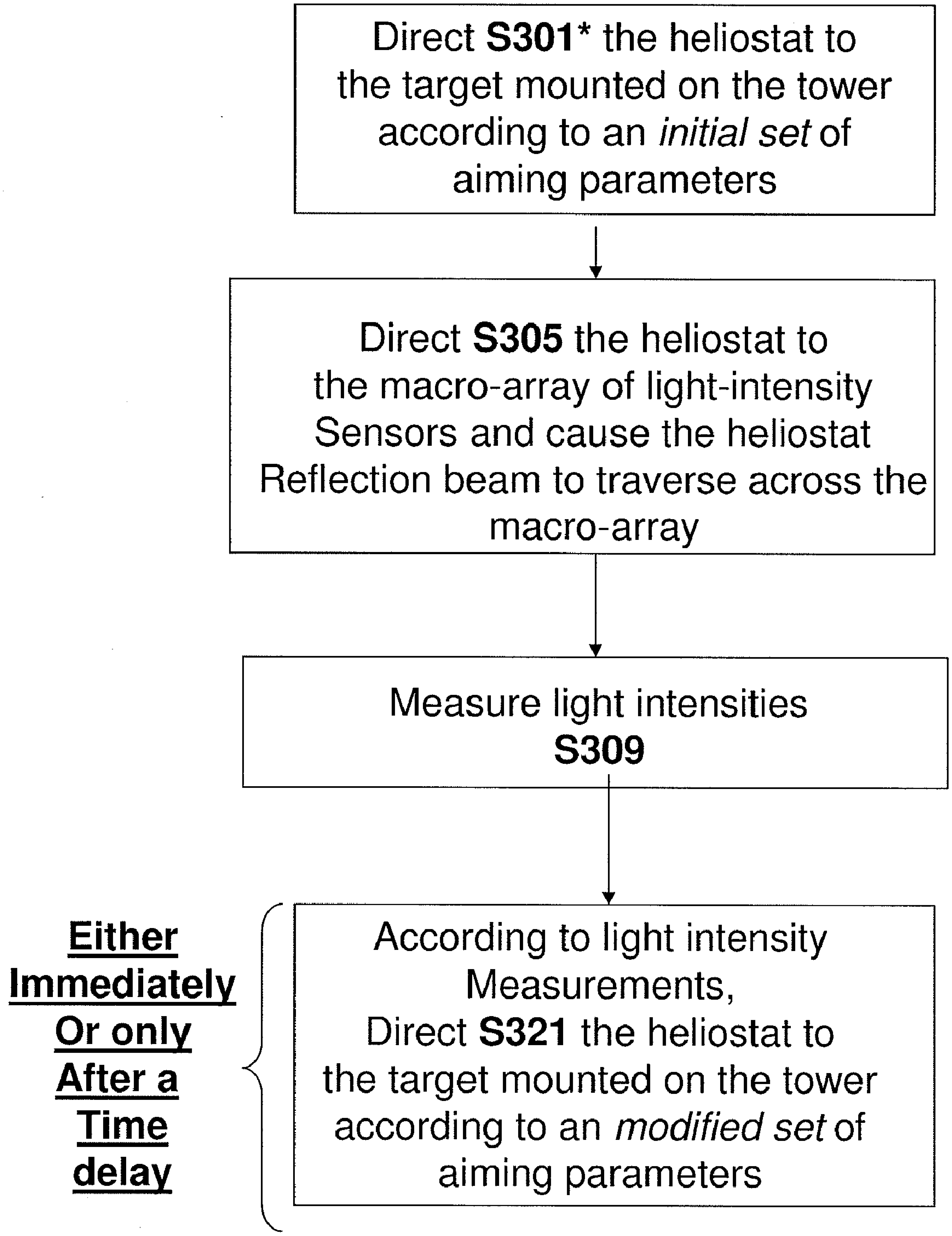

Direct **S301*** the heliostat to the target mounted on the tower according to an *initial set* of aiming parameters
Direct **S305** the heliostat to the macro-array of light-intensity Sensors and cause the heliostat Reflection beam to traverse across the macro-array
Measure light intensities **S309**
According to light intensity Measurements, Direct **S321** the heliostat to the target mounted on the tower according to an *modified set* of aiming parameters
Either Immediately Or only After a Time delay

FIG. 7B

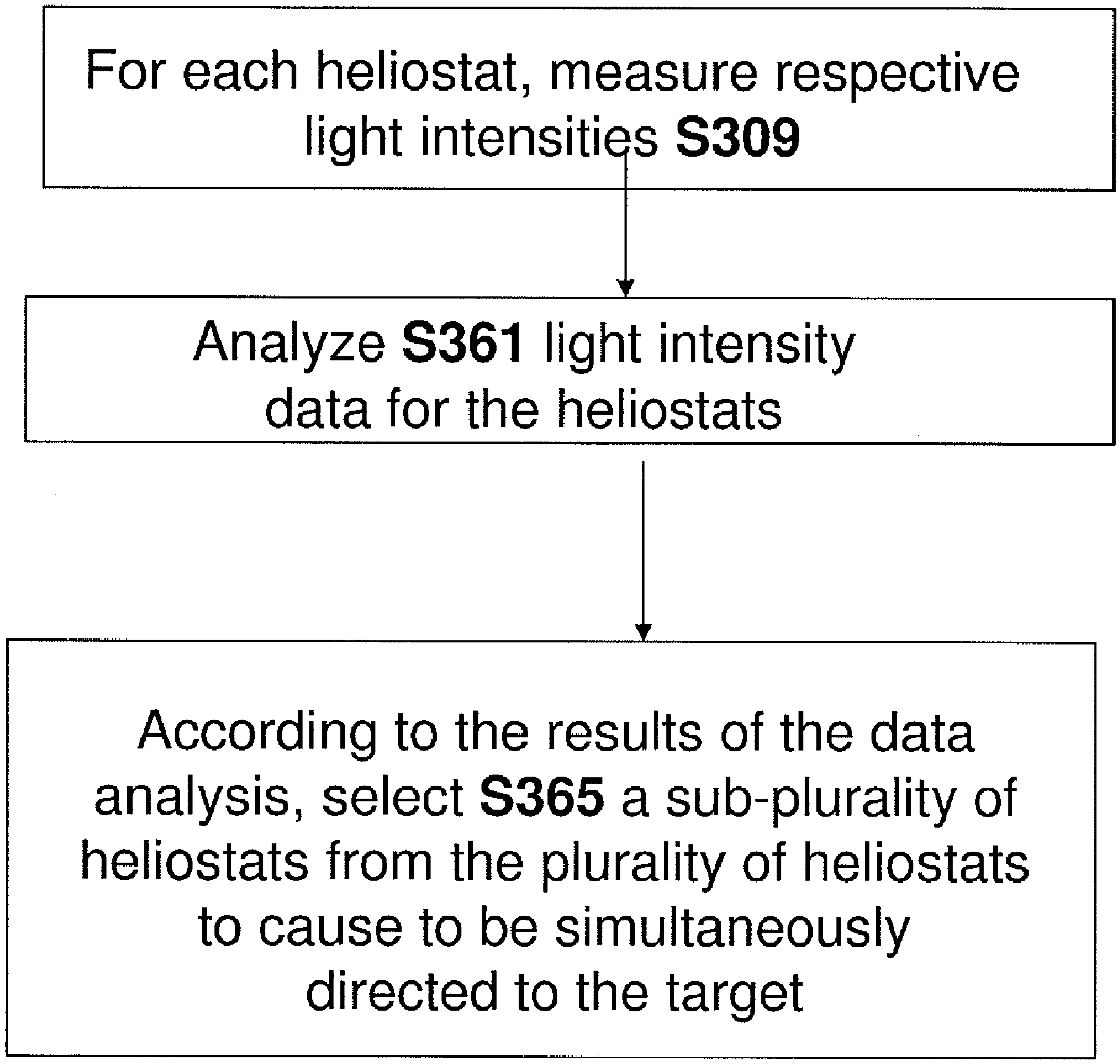

For each heliostat, measure respective light intensities S309
Analyze S361 light intensity data for the heliostats
According to the results of the data analysis, select S365 a sub-plurality of heliostats from the plurality of heliostats to cause to be simultaneously directed to the target

FIG. 7C

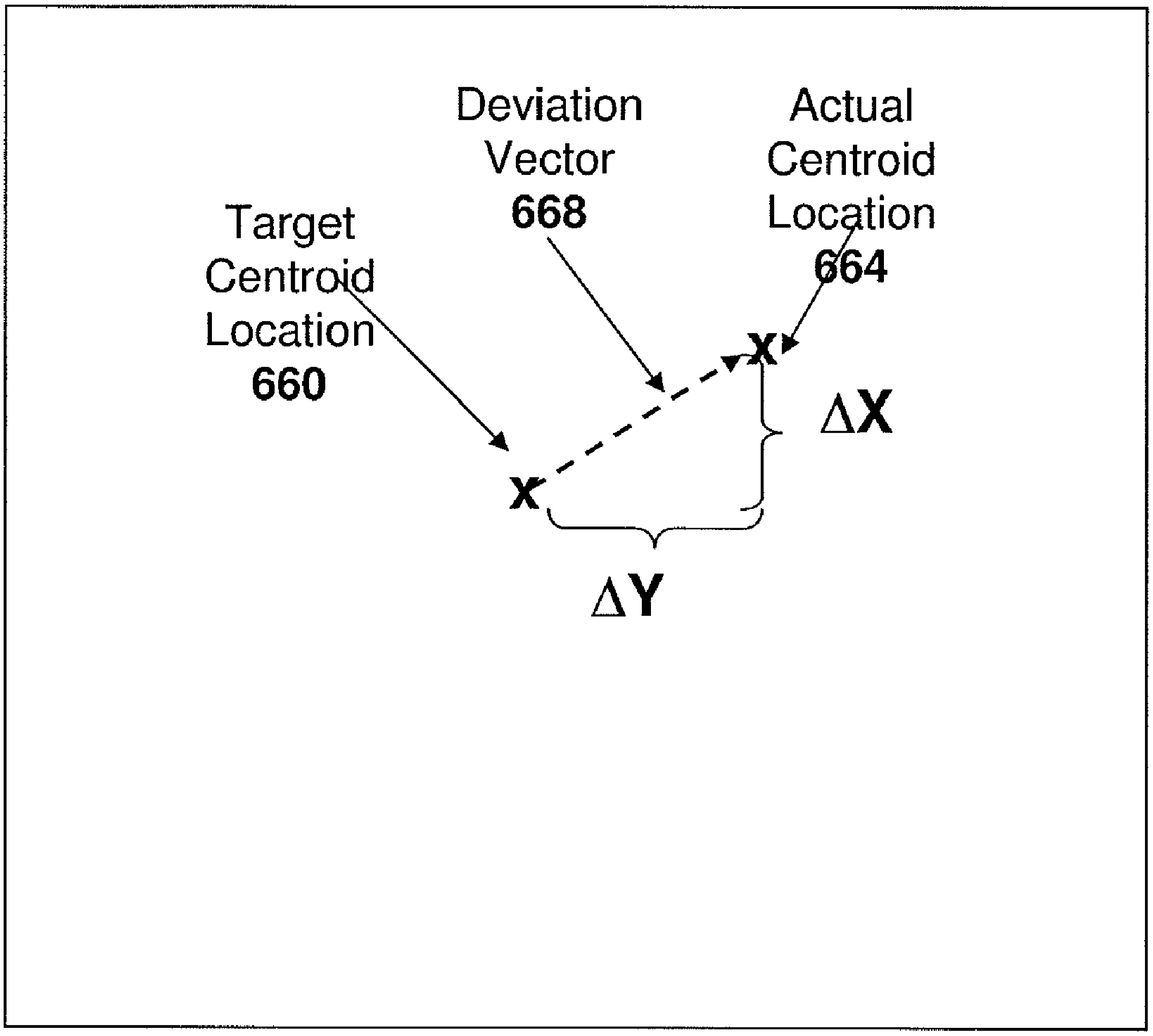

Deviation
Vector
668
Actual
Centroid
Location
664
Target
Centroid
Location
660
X
X
ΔX
ΔY

FIG. 8

FIG. 9A

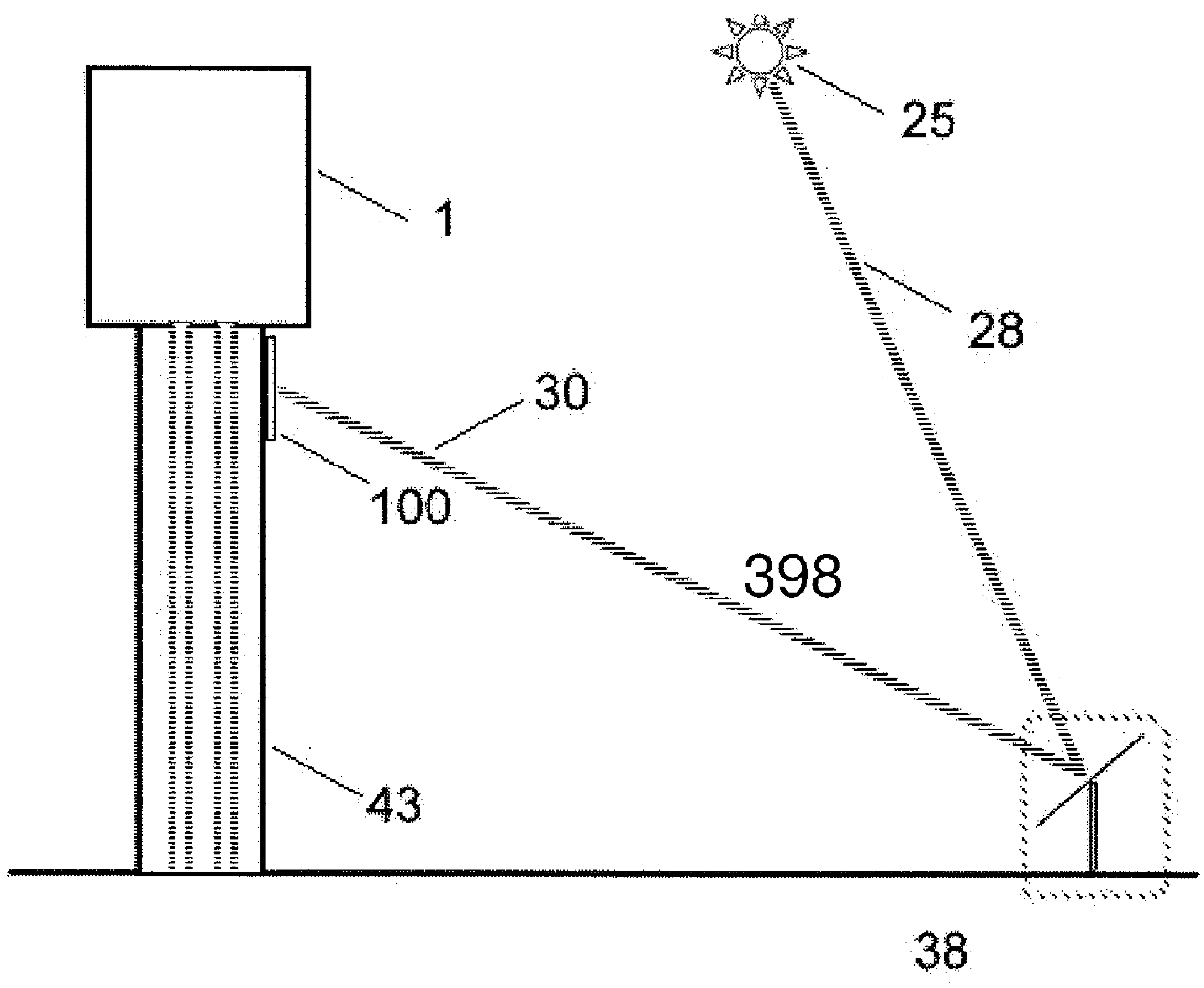


FIG. 9B

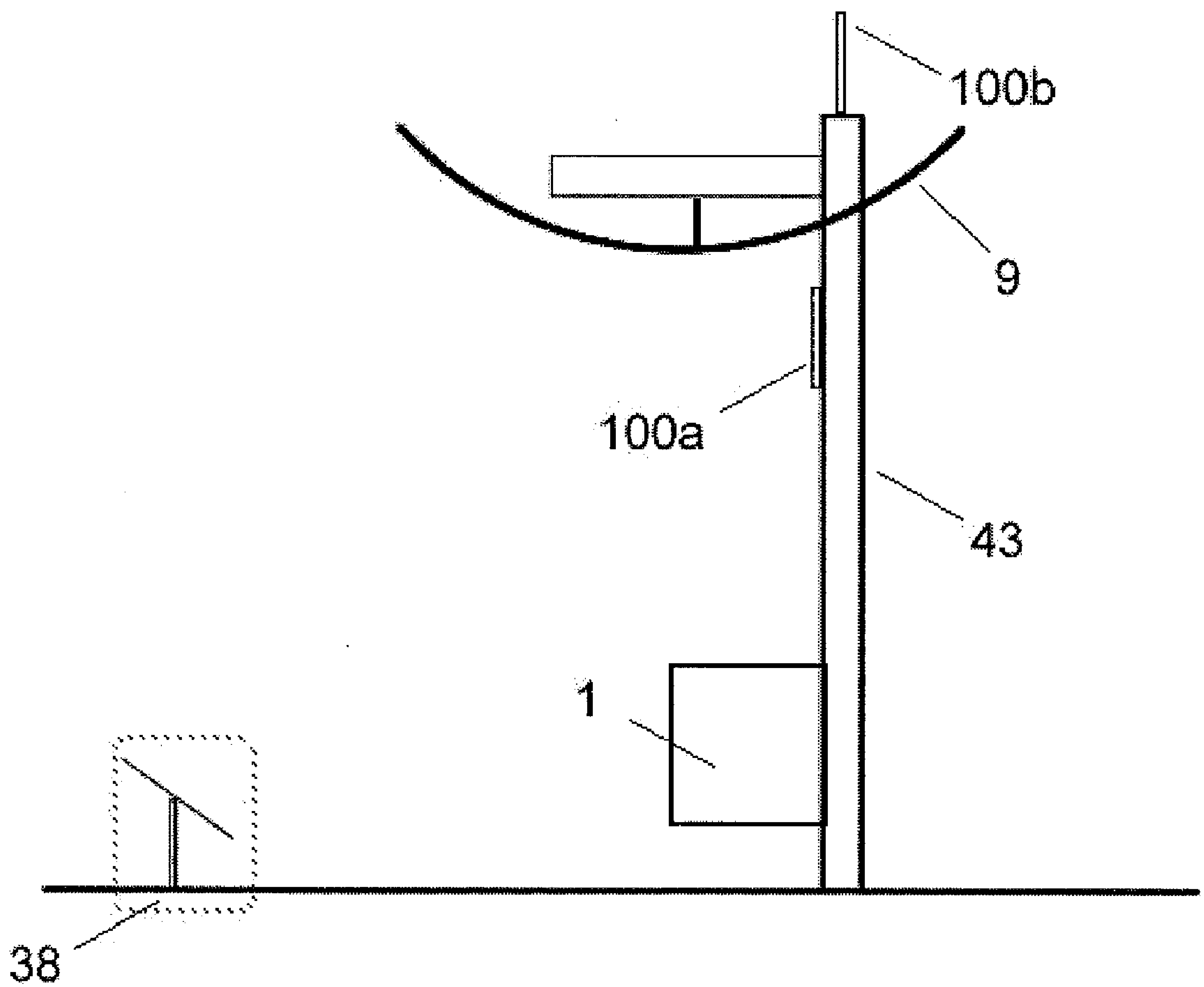


FIG. 10

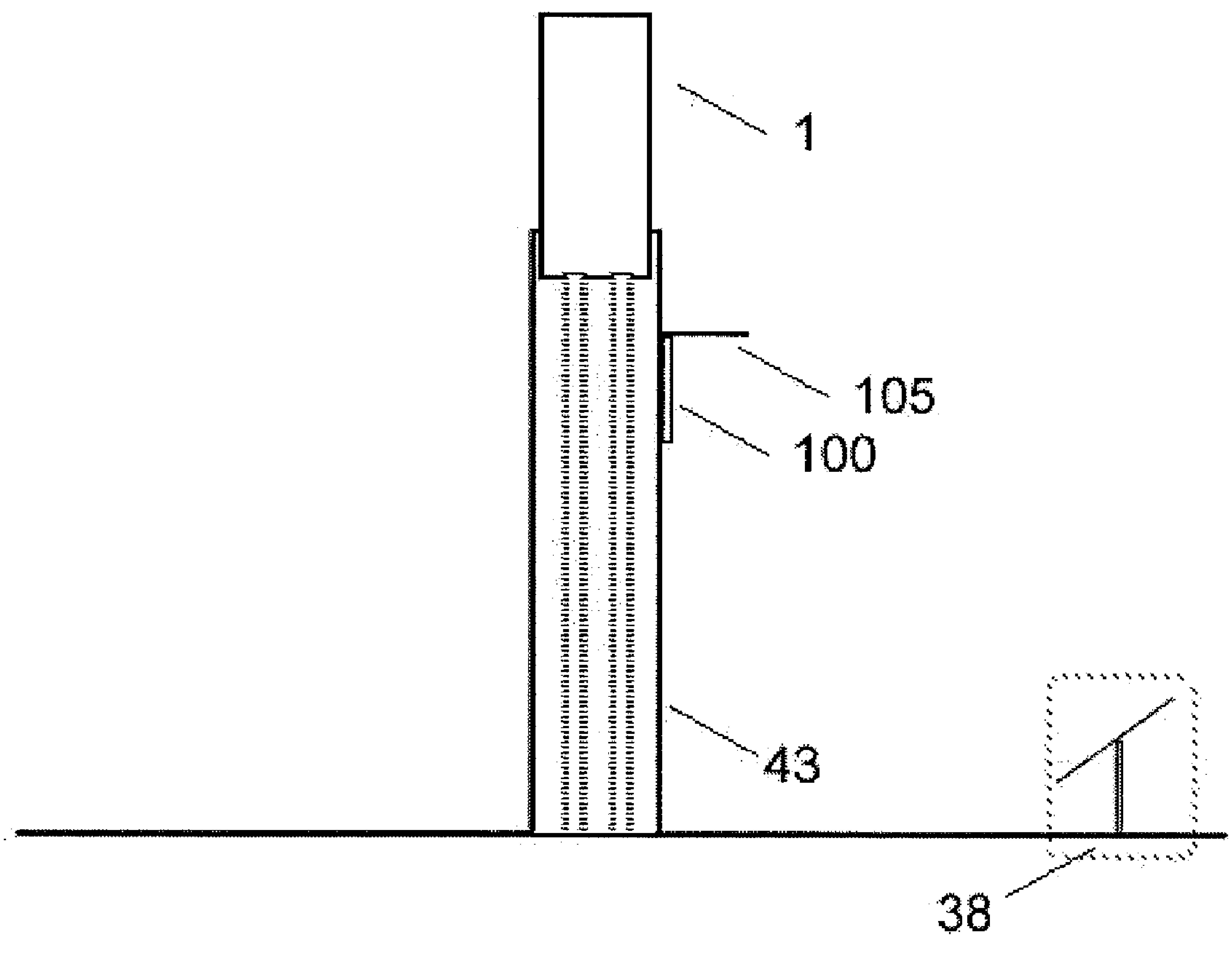


FIG. 11

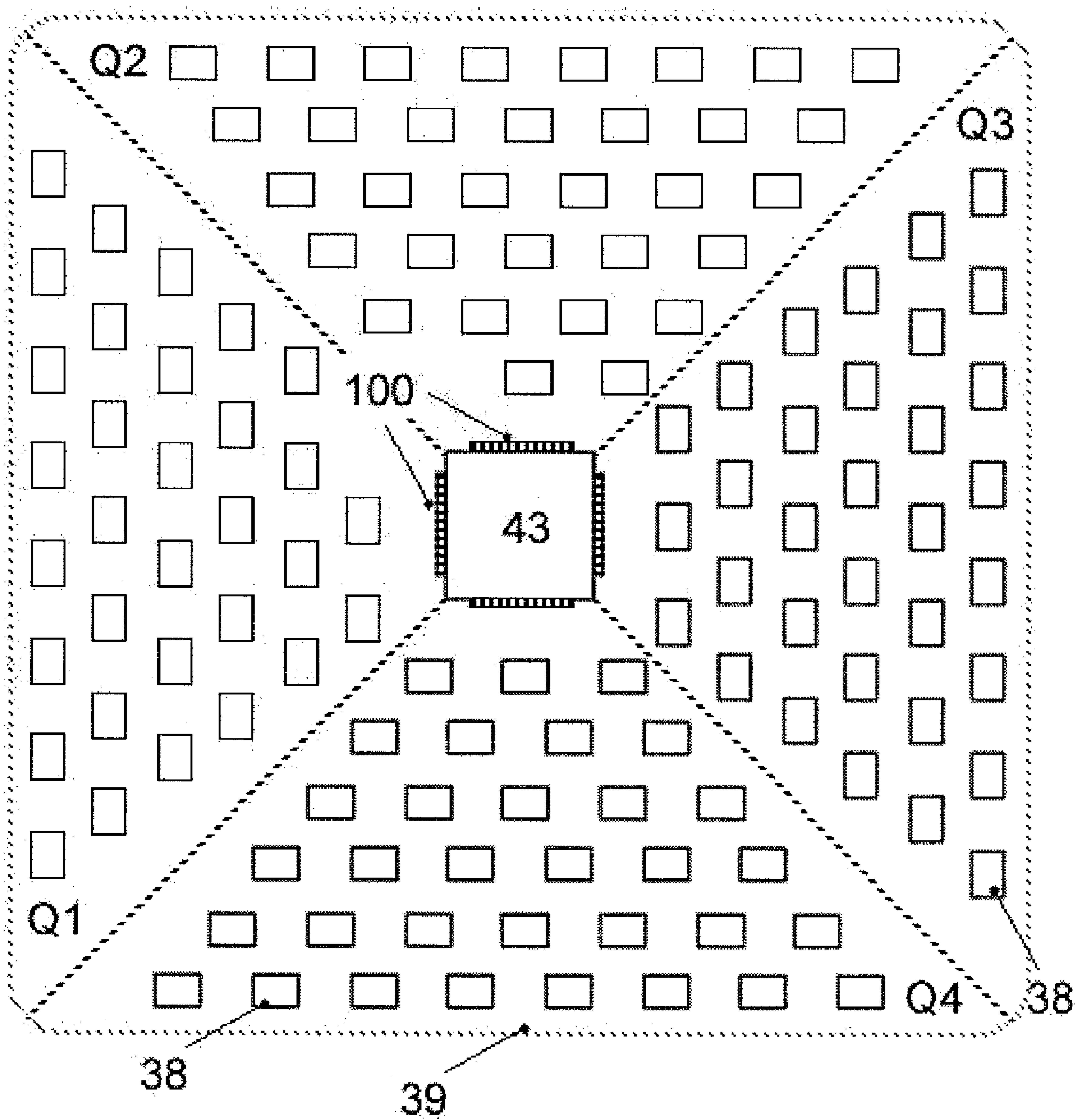


FIG. 12

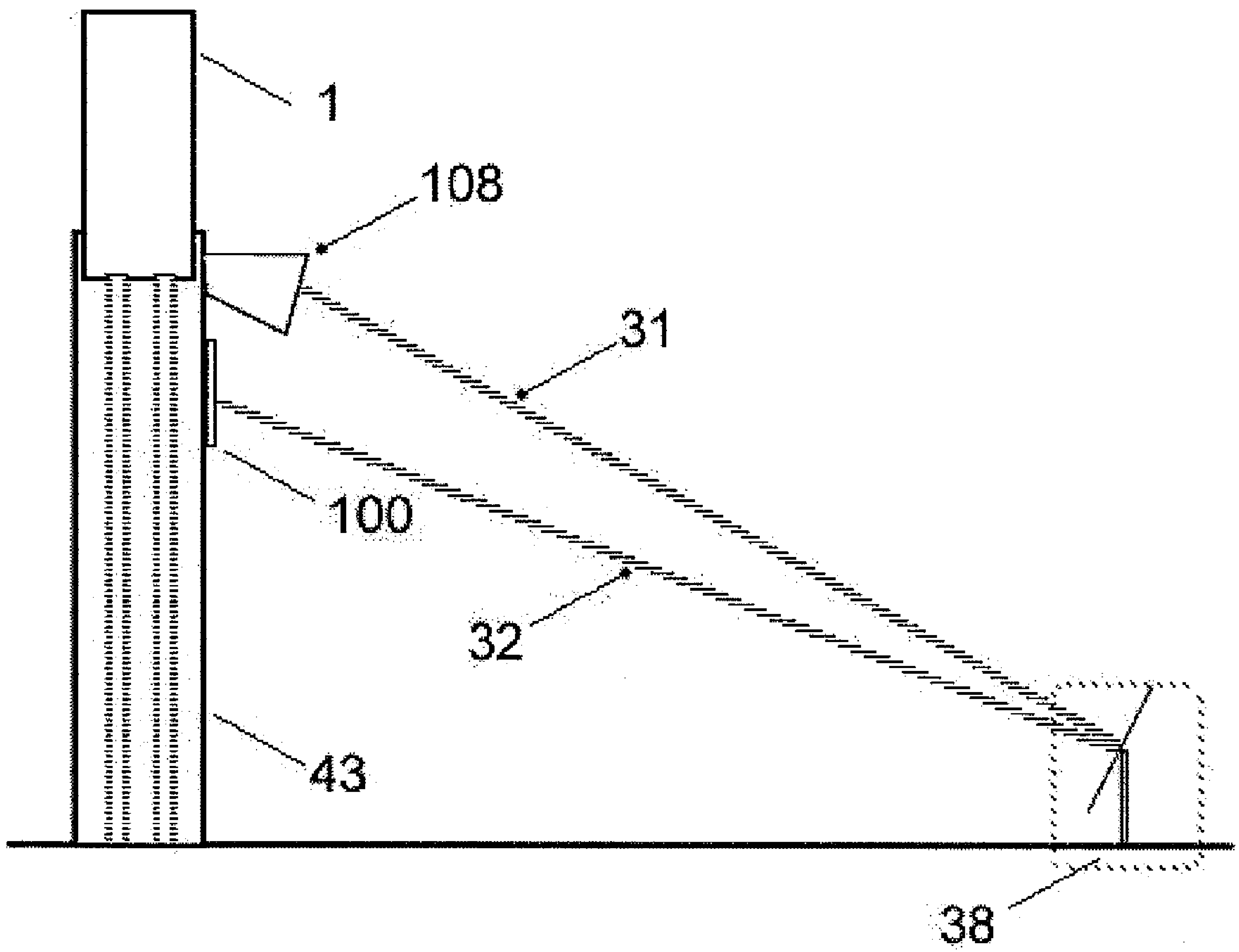
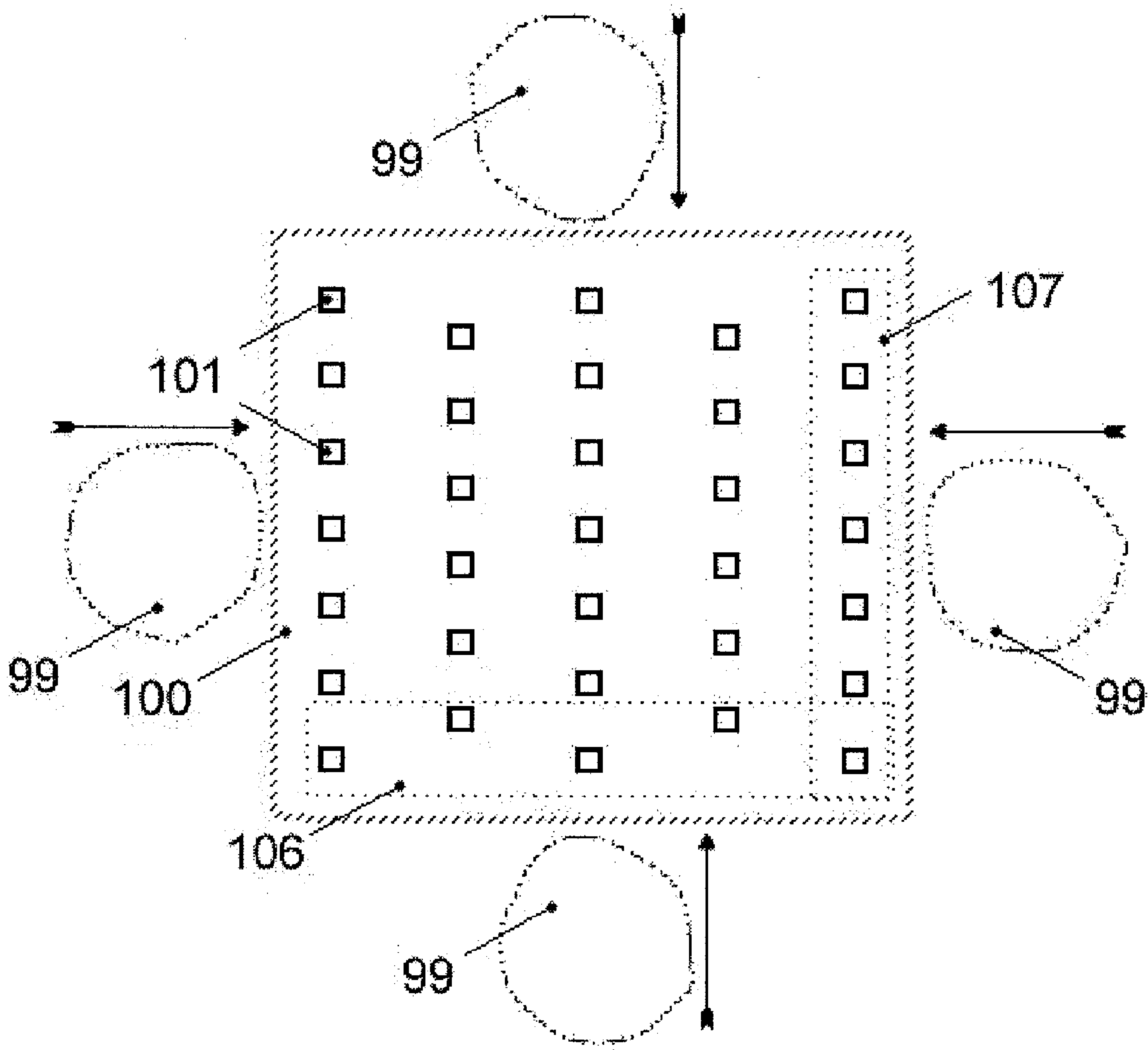


FIG. 13



ARROW INDICATES DIRECTION OF BEAM TRAVEL

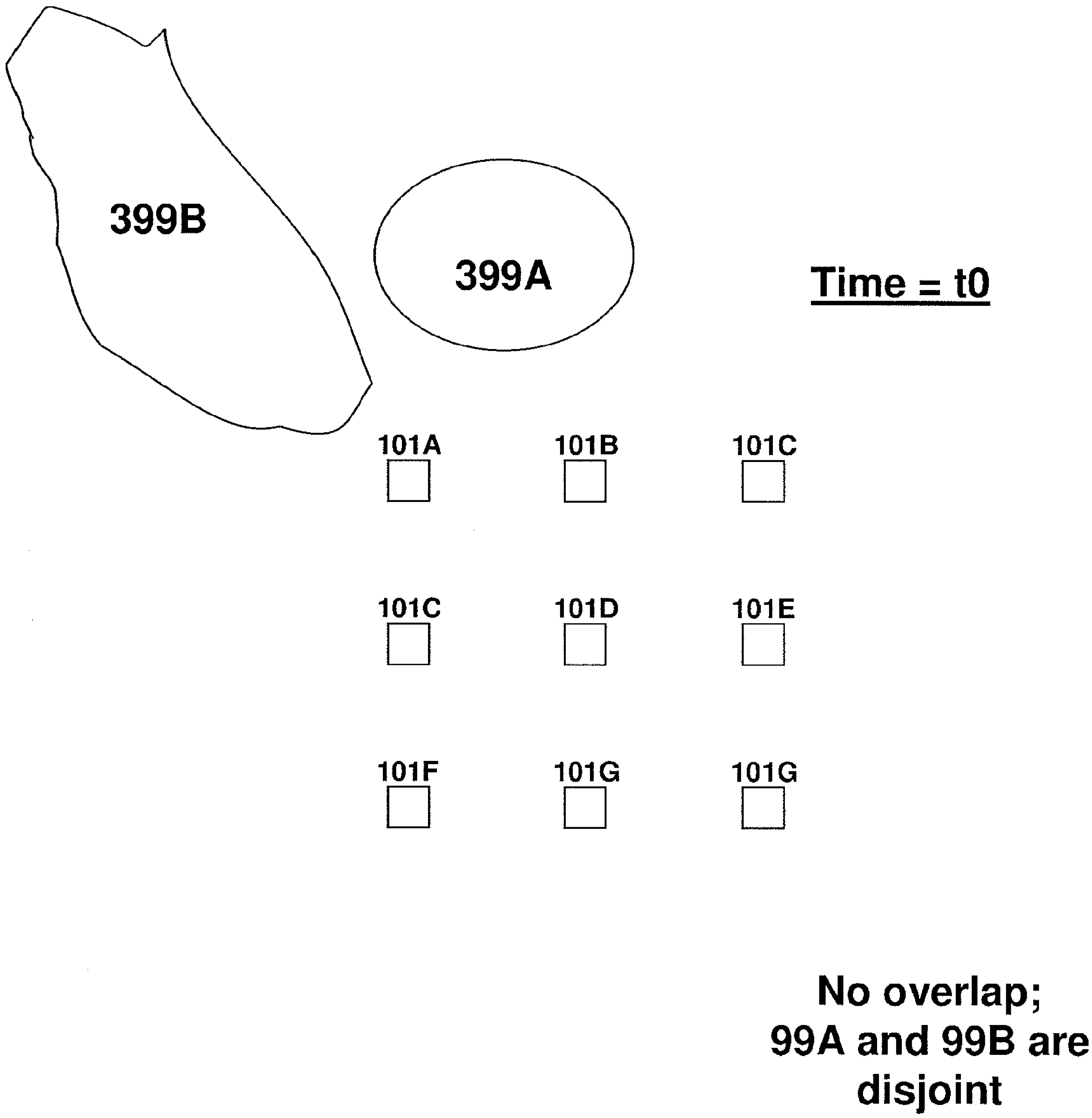

399B
399A
Time = t0
101A
101B
101C
101C
101D
101E
101F
101G
101G
No overlap;
99A and 99B are
disjoint

FIG. 14A

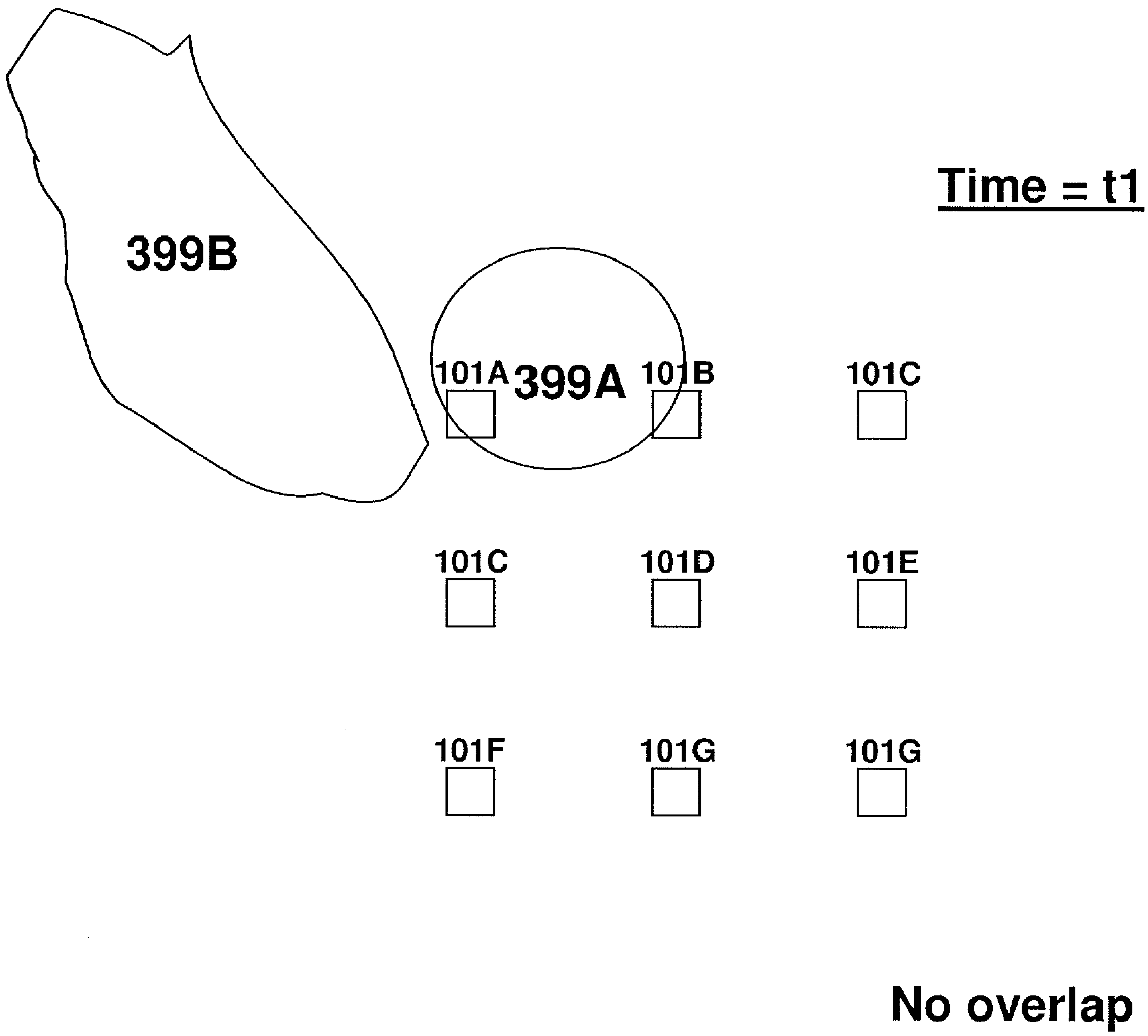

Time = t1
399B
101A
399A
101B
101C
101C
101D
101E
101F
101G
101G
No overlap

FIG. 14B

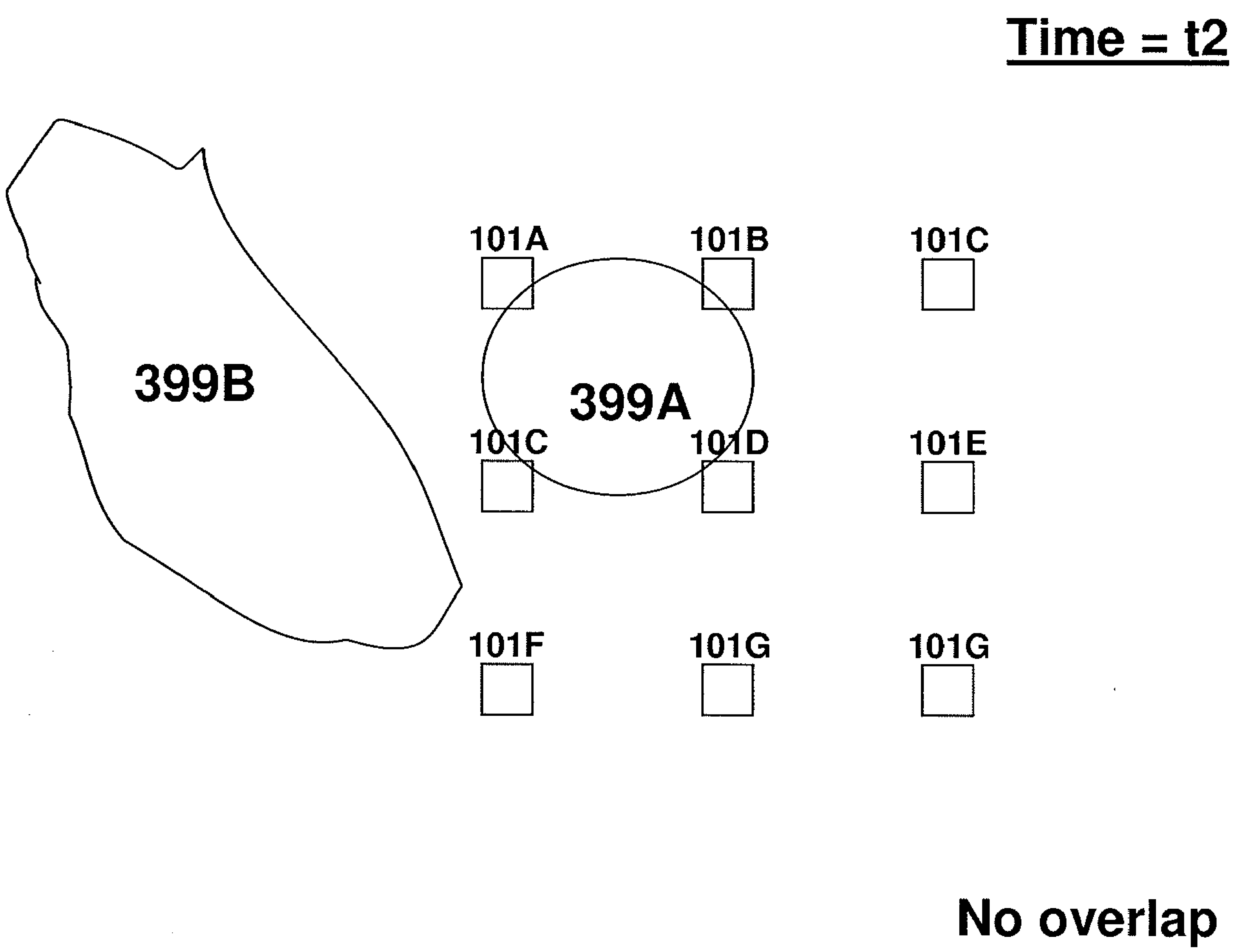

Time = t2
399B
101A
101B
101C
399A
101C
101D
101E
101F
101G
101G
No overlap

FIG. 14C

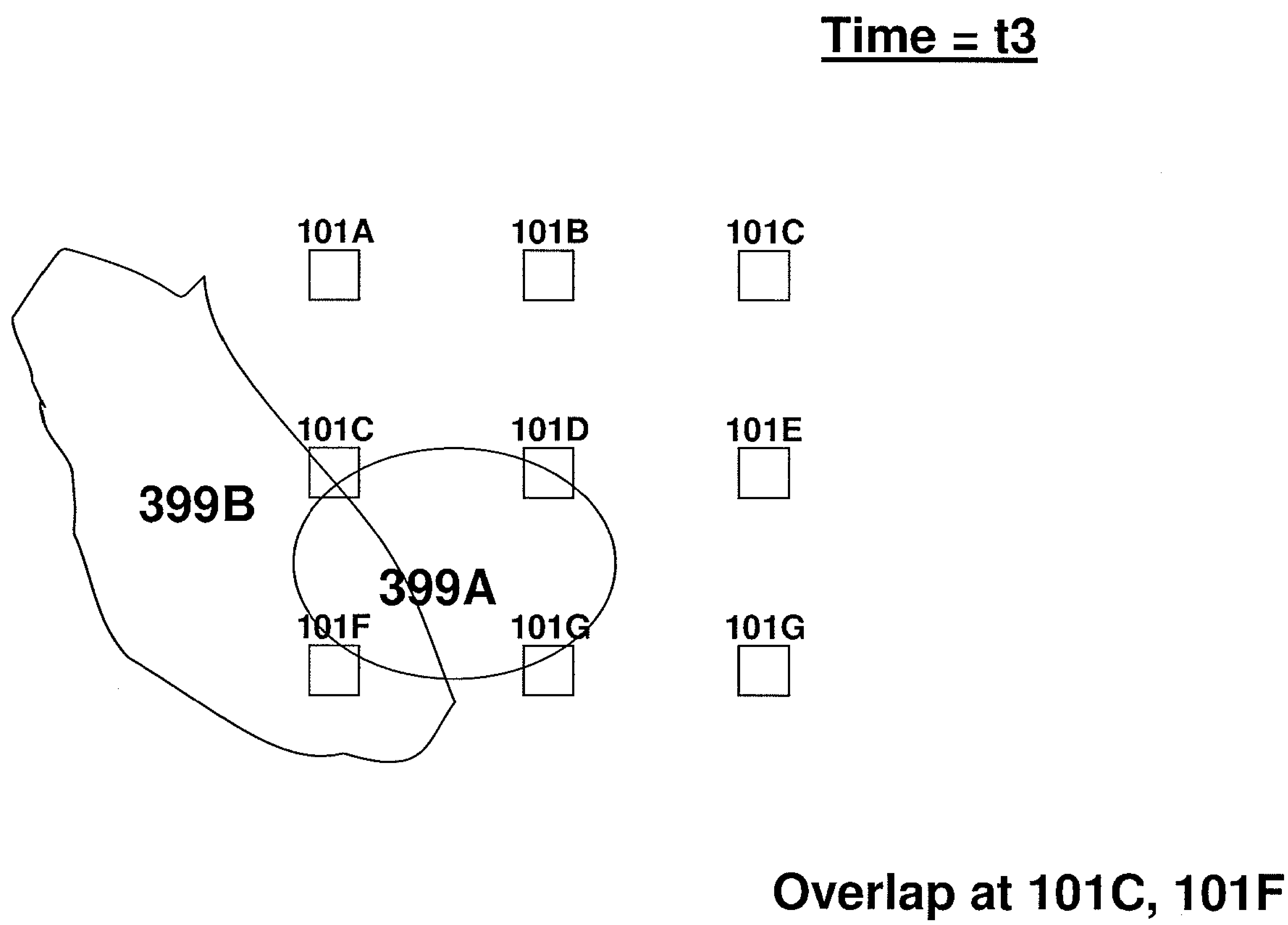

Time = t3
101A
101B
101C
101C
101D
101E
399B
399A
101F
101G
101G
Overlap at 101C, 101F

FIG. 14D

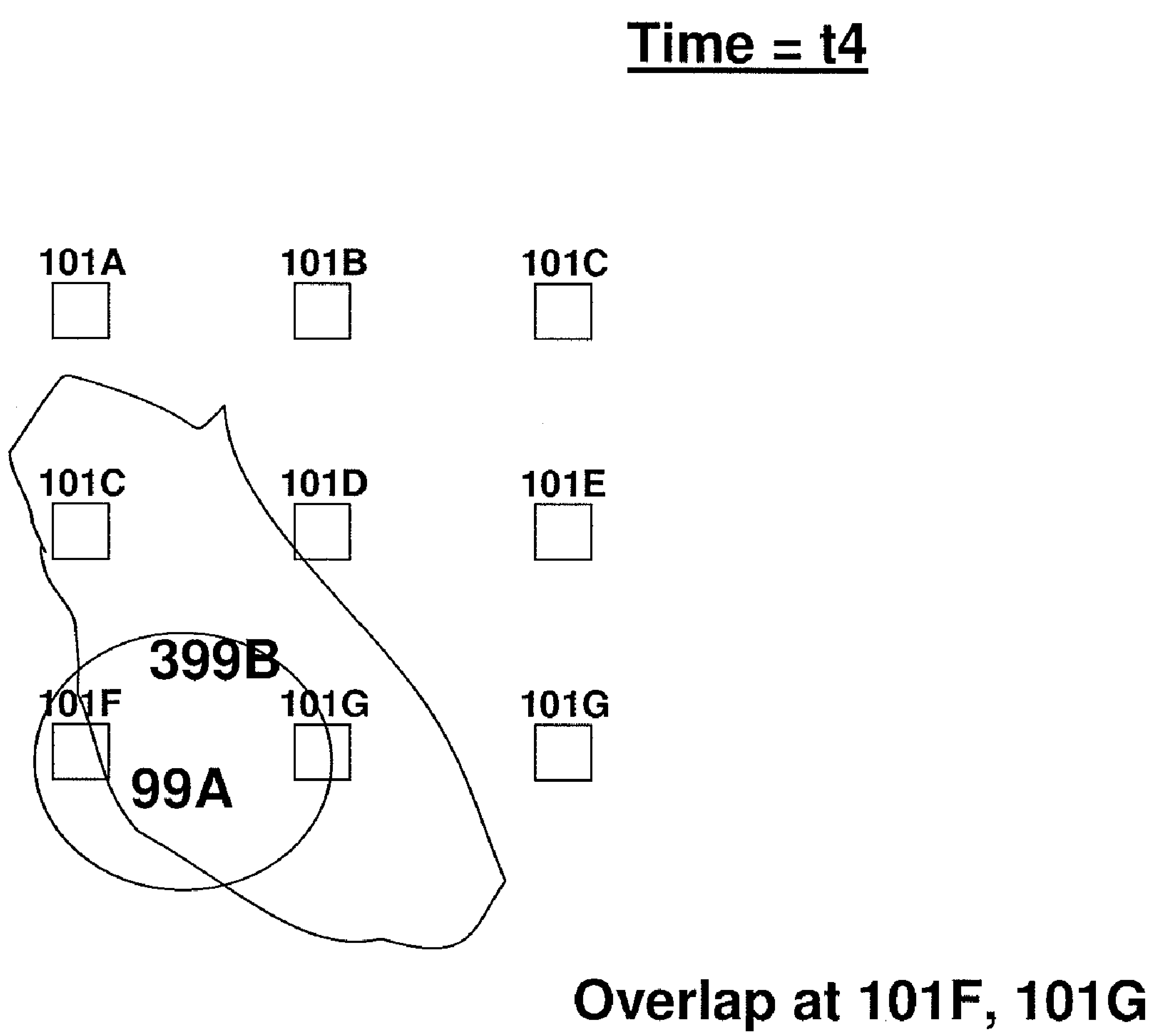

Time = t4
101A
101B
101C
101C
101D
101E
399B
101F
101G
101G
99A
Overlap at 101F, 101G

FIG. 14E

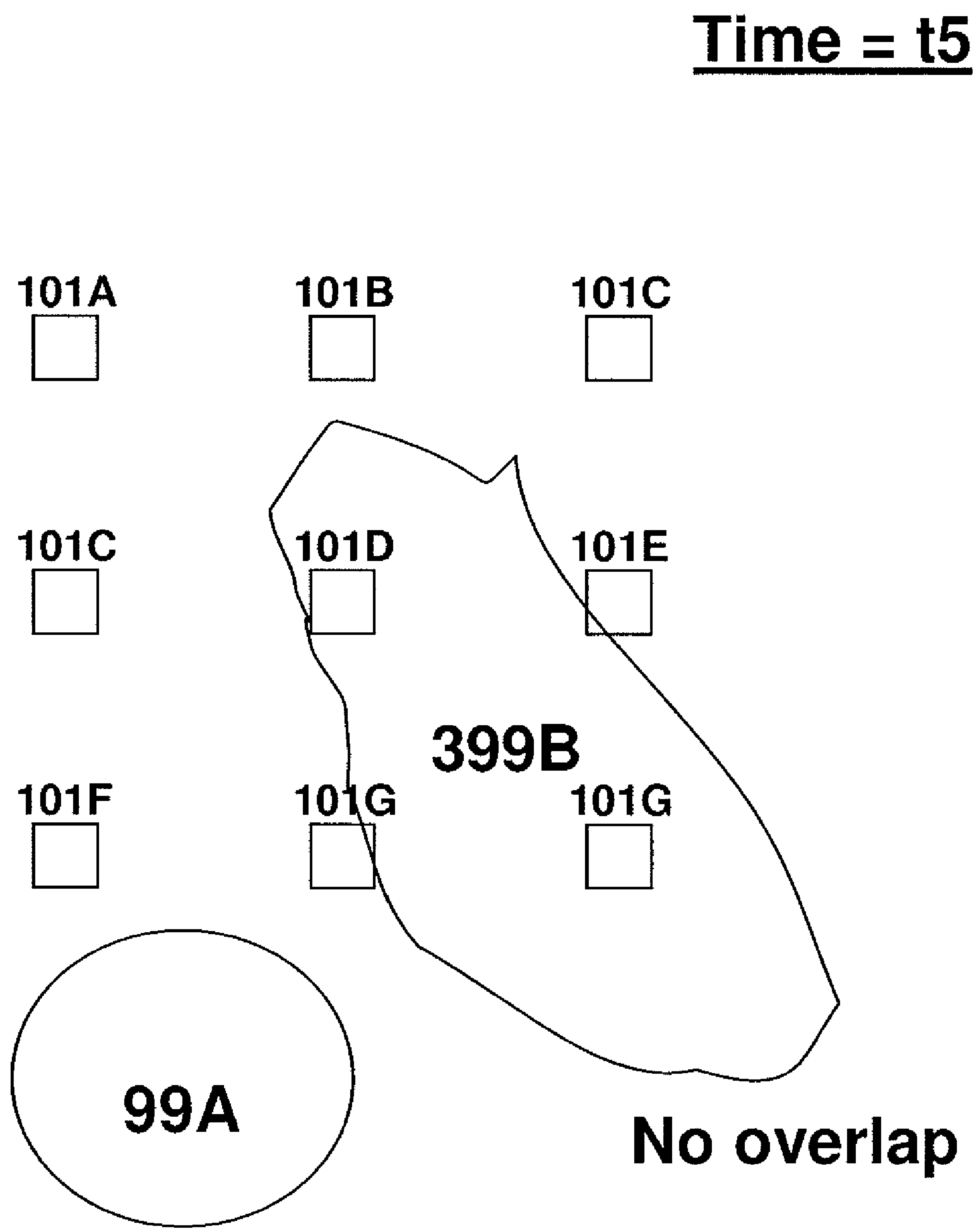

Time = t5
101A
101B
101C
101C
101D
101E
399B
101F
101G
101G
99A
No overlap

FIG. 14F

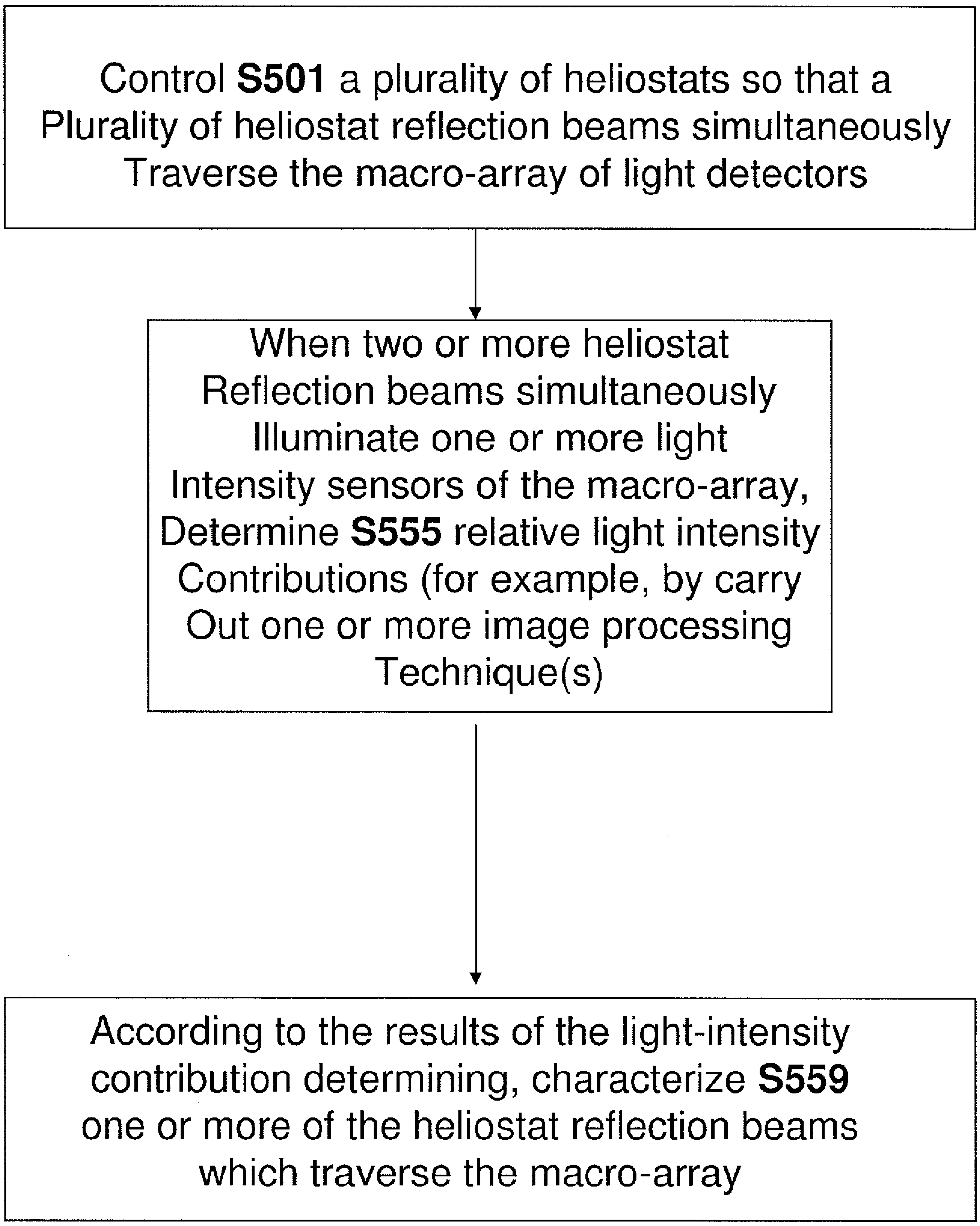
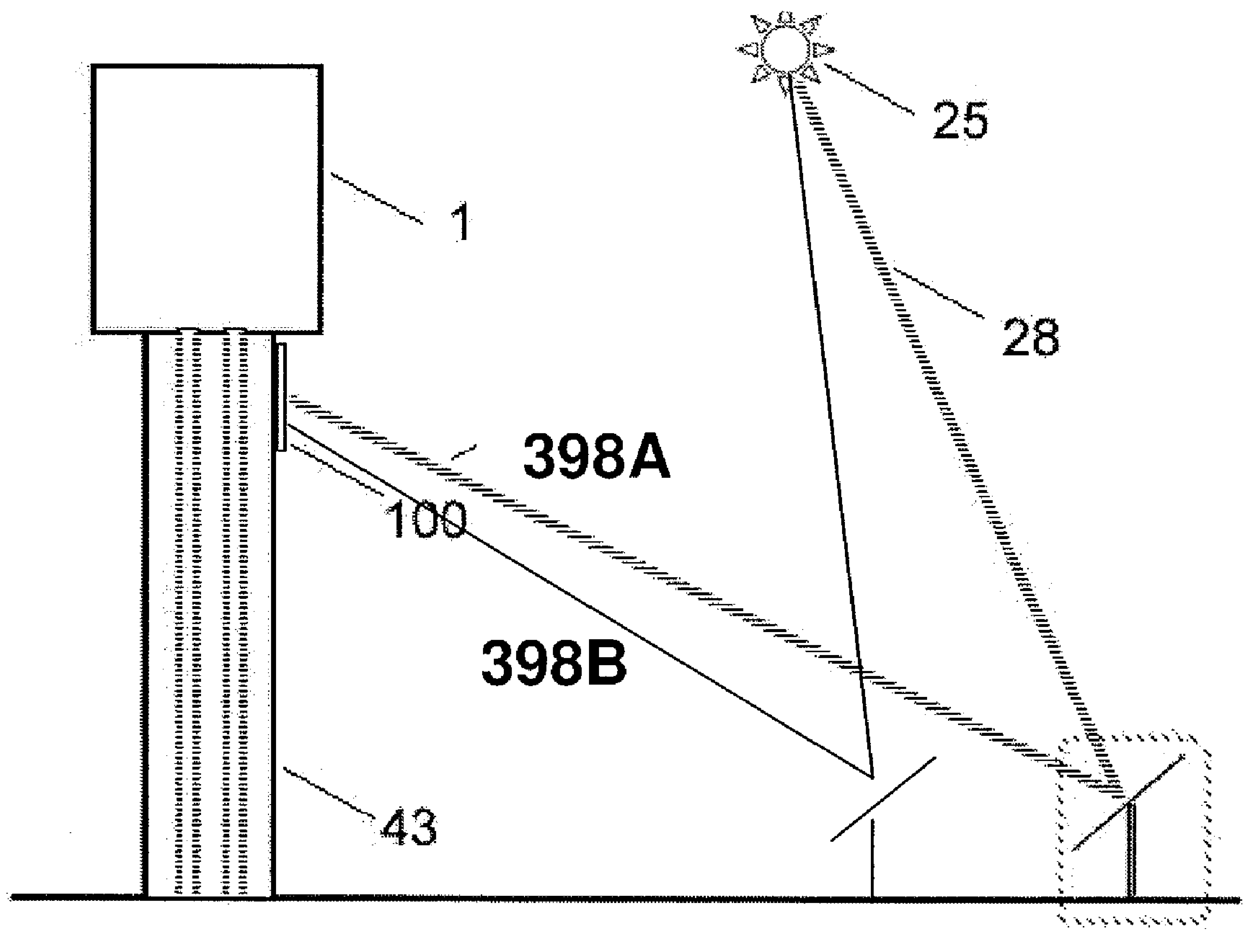

Control **S501** a plurality of heliostats so that a Plurality of heliostat reflection beams simultaneously Traverse the macro-array of light detectors
When two or more heliostat Reflection beams simultaneously Illuminate one or more light Intensity sensors of the macro-array, Determine **S555** relative light intensity Contributions (for example, by carry Out one or more image processing Technique(s)
According to the results of the light-intensity contribution determining, characterize **S559** one or more of the heliostat reflection beams which traverse the macro-array

FIG. 15A

FIG. 15B



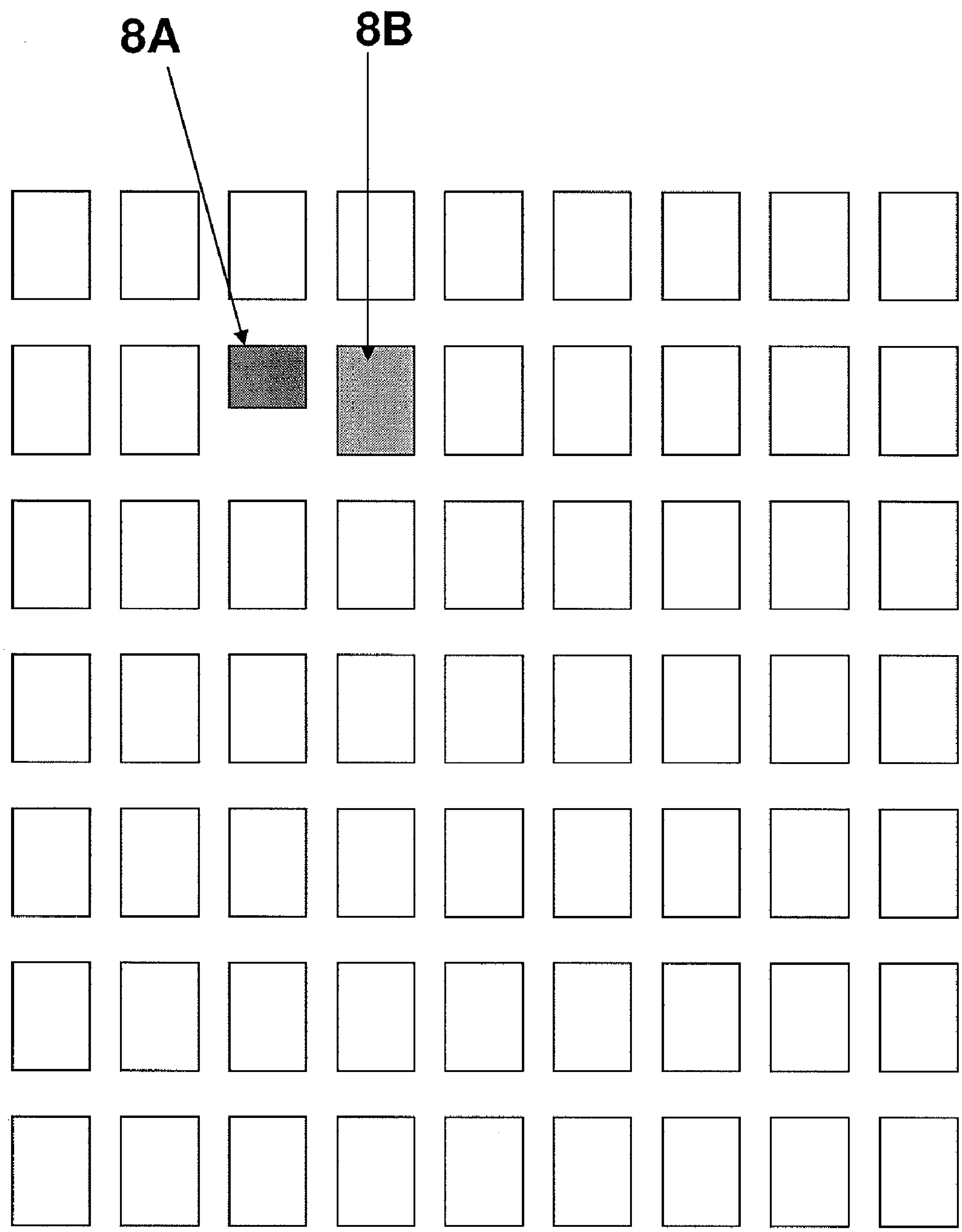


FIG. 15C

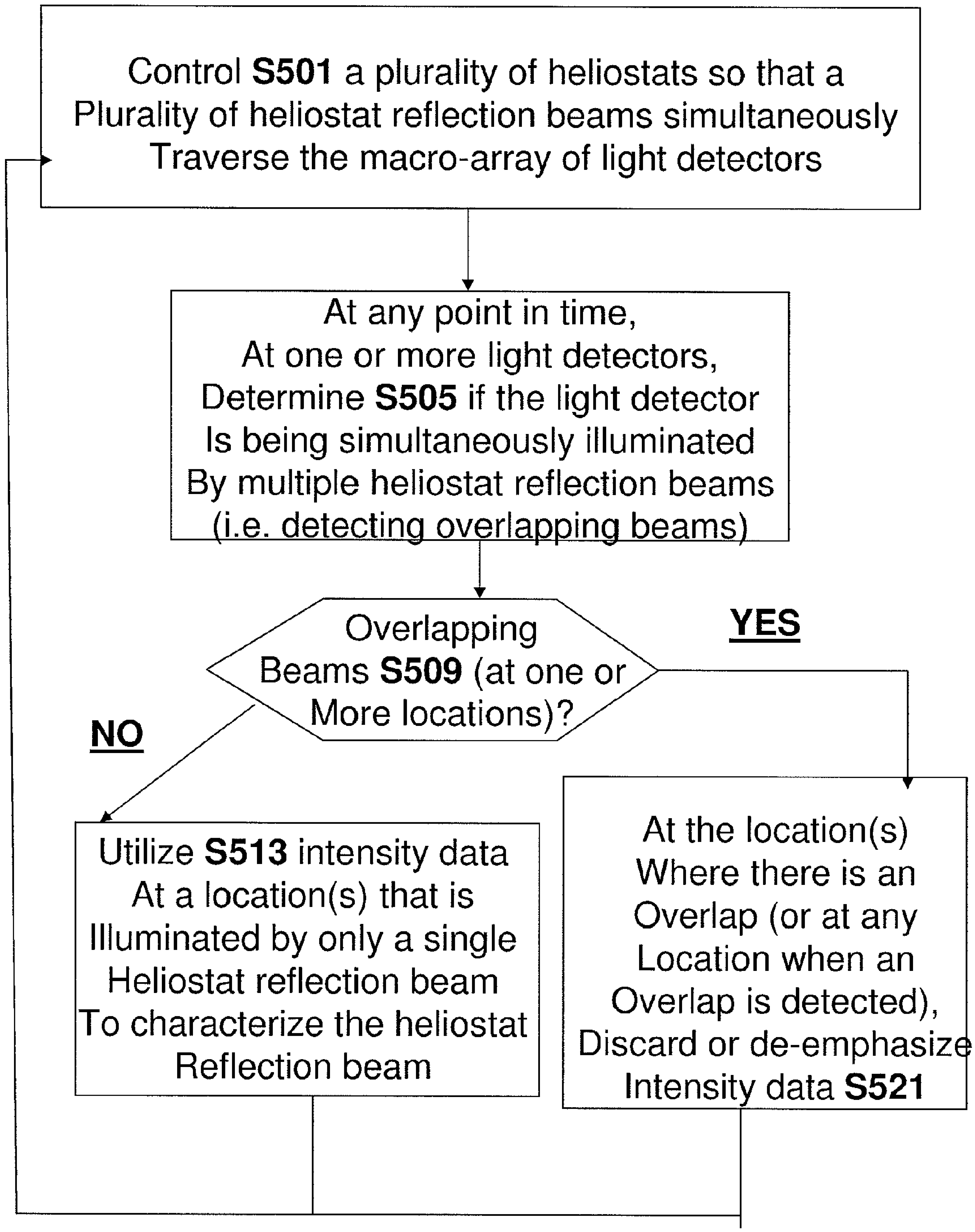

Control **S501** a plurality of heliostats so that a Plurality of heliostat reflection beams simultaneously Traverse the macro-array of light detectors
At any point in time, At one or more light detectors, Determine **S505** if the light detector Is being simultaneously illuminated By multiple heliostat reflection beams (i.e. detecting overlapping beams)
Overlapping Beams **S509** (at one or More locations)?
YES
NO
Utilize **S513** intensity data At a location(s) that is Illuminated by only a single Heliostat reflection beam To characterize the heliostat Reflection beam
At the location(s) Where there is an Overlap (or at any Location when an Overlap is detected), Discard or de-emphasize Intensity data **S521**

FIG. 16

HELIOSTAT CALIBRATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application claims the benefit of U.S. Provisional Patent Application No. 61/109,205 filed on Oct. 29, 2008.

FIELD OF THE INVENTION

[0002] Embodiments relate to the conversion of solar radiation to usable forms of energy such as heat or electricity.

SUMMARY OF EMBODIMENTS

[0003] Some embodiments of the present invention relate to systems, methods and articles of manufacturing for facilitating the conversion of solar radiation to thermal and electric energy.

[0004] Embodiments of the present invention relate to a solar energy system comprising: (a) a plurality of heliostats configured to reflect sunlight to a target mounted on a tower, each heliostat including a respective heliostat controller, the target, the target being selecting from the group consisting of an energy conversion target and/or a secondary reflector; and (b) a macro-array of light-intensity sensors characterized by a maximum sensor-sensor distance and mounted on the tower such that when any heliostat of the plurality of heliostats reflects a beam of light onto the macro-array of light-intensity sensors, the maximum dimension of the reflected beam's projection on the macro-array is at most twice the maximum sensor-sensor distance, wherein each heliostat controller is operative to control its respective heliostat so that the light beam reflected by the heliostat traverses the macro-array of light-intensity sensors.

[0005] In some embodiments, the macro-array is substantially co-planar.

[0006] In some embodiments, the macro-array of light-intensity sensors is a two dimensional macro-array.

[0007] In some embodiments, the light-intensity sensors are configured to acquire time-series light intensity data while the projected light beam traverses across the macro-array of light sensors.

[0008] In some embodiments, the heliostat controller is operative to: i) before the beam traversing, direct the heliostat to the target mounted on the tower according to an initial set of aiming parameters; and ii) after the beam traversing, redirect the heliostat to the target mounted on the tower according to a modified set of aiming parameters that is modified in accordance with light intensity data generated by light intensity sensors of the macro-array.

[0009] In some embodiments, the heliostat controller is operative to effect the re-directing according to the modified set of aiming parameters after the beam traversing.

[0010] In some embodiments, the heliostat controller is operative to effect the re-directing according to the modified set of aiming parameters immediately only after a time delay.

[0011] In some embodiments, during the period of the time delay, the controller is operative to re-direct the heliostat to the target according to the initial set of aiming parameters.

[0012] In some embodiments, the modified set of aiming parameters is modified in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; ii) a beam traversal speed of the traversing reflected heliostat beam.

[0013] In some embodiments, the system further comprises: c. a heliostat-field controller operative to: i) select, from the plurality of heliostats, a sub-plurality of heliostats that is to be simultaneously directed to the target (i.e., operated so that at least one point in time they are all directed to the target—there is no requirement to simultaneously re-orient the heliostats of the sub-plurality); and ii) direct the selected sub-plurality of heliostats the target (i.e., cause a situation where the selected sub-plurality is simultaneously directed to the target), wherein the heliostat field controller is operative to carry out the heliostat selection in accordance with respective light intensity measurements of macro-array taken when each heliostat's reflected beam respectively traverses the macro-array.

[0014] In some embodiments, only the selected sub-plurality is directed to the target. Alternatively, at least the selected sub-plurality is directed to the target.

[0015] In some embodiments, the heliostat-field controller is operative to effect the selection in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0016] In some embodiments, the system further comprises: c) electronic circuitry configured to measure at least one beam projection parameter of the heliostat beam according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

[0017] In some embodiments, the electronic circuitry is configured to effect the measuring in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0018] In some embodiments, the system further comprises: c) electronic circuitry configured to measure at least one of: i) a shape of the heliostat beam; ii) a flux intensity map of the heliostat beam; and iii) an offset of the heliostat beam, according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

[0019] In some embodiments, the electronic circuitry is configured to effect the measuring in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0020] In some embodiments, the heliostat controllers collectively are configured so that multiple overlapping heliostat reflection beams including first and second heliostat reflection beams simultaneously traverse the macro-array to simultaneously illuminate one or more of the light-intensity sensors.

[0021] In some embodiments, i) the light-intensity sensors of the macro-array are image sensors; and ii) the system further comprises: c) electronic circuitry operative to: A) determine, from the images generated by the image sensors, relative light intensity contributions of the overlapping first and second heliostat beams when the first and second beams overlap and traverse the macro-array; and B) in accordance with the relative light intensity contributions, determine at least one of: I) a shape of the first and/or second heliostat beam; II) a flux intensity map of the first and/or second heliostat beam; and III) an offset of the first and/or second heliostat beam.

[0022] In some embodiments, the heliostat controllers collectively are configured so that the first and second heliostat beams overlap at some times and are disjoint at other times while the first and second beams traverse the macro-array.

[0023] In some embodiments, i) the light-intensity sensors of the macro-array are image sensors; and ii) the system further comprises: c) electronic circuitry operative to determine when the first and second beams are disjoint, and in accordance with the disjoint time period(s), determine at least one of: I) a shape of the first and/or second heliostat beam; II) a flux intensity map of the first and/or second heliostat beam; III) an offset of the first and/or second heliostat beam; and IV) an indication of beam area (for example, beam diameter or any other indication).

[0024] In some embodiments, each of the light sensors of the macro-array are image sensors.

[0025] In some embodiments, the image sensors are selected from the group consisting of a CCD microarray and a CMOS microarray.

[0026] In some embodiments, each of the light sensors of the macro-array are photo-detectors incapable of detecting an image.

[0027] In some embodiments, each of the light sensors are photo-voltaic cells.

[0028] In some embodiments, each of the light-intensity sensors is mounted to the tower.

[0029] In some embodiments, the energy conversion target is selected from the group consisting of solar boiler target and a molten salt solar receiver.

[0030] In some embodiments, the solar boiler target is selected from the group consisting of a solar evaporator, a solar re-heater and a solar superheater.

[0031] In some embodiments, the energy conversion target includes one or more photovoltaic and/or photo-electrovoltaic cells.

[0032] In some embodiments, the tower height is at least 25 meters.

[0033] In some embodiments, the tower height is at least 100 meters.

[0034] In some embodiments, the system further comprises: c. a projector configured to project artificial light onto the heliostat such that the traversing reflected beam that traverses the macro-array includes the artificial light generated by the projector.

[0035] In one example, the projector is configured so that the apparent width (i.e., either as detectable at the heliostat mirror or at the macro-array of light sensors) of the light source of the projector is equivalent to the apparent width from the sun.

[0036] In some embodiments, the projector is mounted on the tower.

[0037] Some embodiments of the present invention provide a method of operating a solar energy system, the method comprising:

[0038] a. reflecting sunlight from each of a plurality of heliostats to a target mounted on a tower, the target being selecting from the group consisting of an energy conversion target and/or a secondary reflector; and

[0039] b. respectively controlling each heliostat of the plurality so that the light beam reflected by the heliostat traverses the macro-array of light-intensity sensors characterized by a maximum sensor-sensor distance and mounted on the tower such that when any heliostat of the plurality of heliostats reflects a beam of light onto the macro-array of light-intensity sensors, the maximum dimension of the reflected beam's projection on the macro-array is at most twice the maximum sensor-sensor distance.

[0040] In some embodiments, time-series light intensity data is acquired by the light-intensity sensors while the projected light beam traverses across the macro-array of light sensors.

[0041] In some embodiments, the method further comprises: before the beam traversing, directing the heliostat to the target mounted on the tower according to an initial set of aiming parameters; and after the beam traversing, re-directing the heliostat to the target mounted on the tower according to a modified set of aiming parameters that is modified in accordance with light intensity data generated by light intensity sensors of the macro-array.

[0042] In some embodiments, the re-directing is carried out according to the modified set of aiming parameters after the beam traversing.

[0043] In some embodiments, the re-directing is carried out according to the modified set of aiming parameters immediately only after a time delay.

[0044] In some embodiments, the re-directing the heliostat to the target is carried out according to the initial set of aiming parameters.

[0045] In some embodiments, the modified set of aiming parameters is modified in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; ii) a beam traversal speed of the traversing reflected heliostat beam.

[0046] In some embodiments, the method further comprises: i) selecting, from the plurality of heliostats, a sub-plurality of heliostats that is to be simultaneously directed to the target (i.e., operated so that at least one point in time they are all directed to the target—there is no requirement to simultaneously re-orient the heliostats of the sub-plurality); and ii) directing the selected sub-plurality of heliostats the target (i.e., cause a situation where the selected sub-plurality is simultaneously directed to the target), wherein the heliostat selection is carried out in accordance with respective light intensity measurements of macro-array taken when each heliostat's reflected beam respectively traverses the macro-array.

[0047] In some embodiments, only the selected sub-plurality is directed to the target. Alternatively, at least the selected sub-plurality is directed to the target.

[0048] In some embodiments, the selection is carried out in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0049] In some embodiments, at least one beam projection parameter of the heliostat beam is measured according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

[0050] In some embodiments, the measuring is carried out in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0051] In some embodiments, at least one of the following is measured: i) a shape of the heliostat beam; ii) a flux intensity map of the heliostat beam; and iii) an offset of the heliostat beam, according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

[0052] In some embodiments, the measuring is carried out in accordance with at least one of: i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and ii) a beam traversal speed of the traversing reflected heliostat beam.

[0053] In some embodiments, multiple overlapping heliostat reflection beams including first and second heliostat reflection beams simultaneously traverse the macro-array to simultaneously illuminate one or more of the light-intensity sensors.

[0054] In some embodiments, the method further comprises: A) determining, from the images generated by the image sensors, relative light intensity contributions of the overlapping first and second heliostat beams when the first and second beams overlap and traverse the macro-array; and B) in accordance with the relative light intensity contributions, determine at least one of: I) a shape of the first and/or second heliostat beam; II) a flux intensity map of the first and/or second heliostat beam; and III) an offset of the first and/or second heliostat beam.

[0055] In some embodiments, the first and second heliostat beams overlap at some times and are disjoint at other times while the first and second beams traverse the macro-array.

[0056] In some embodiments, i) the light-intensity sensors of the macro-array are image sensors; and ii) the method further comprises: determining at least one of: I) a shape of the first and/or second heliostat beam; II) a flux intensity map of the first and/or second heliostat beam; III) an offset of the first and/or second heliostat beam; and IV) an indication of beam area (for example, beam diameter or any other indication).

[0057] Other objects, advantages and novel features of the present invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0058] FIGS. **1** and **2** are diagrammatic elevation views of a plurality of heliostats and a central power tower in accordance with different embodiments of the invention.

[0059] FIG. **3** is a block diagram of a hierarchical control system for a solar power tower system.

[0060] FIGS. **4**A-**6**B are diagrammatic elevation views of various examples of arrays of light intensity detectors.

[0061] FIGS. **7**A-**7**C are flowcharts of routines of operating a solar energy system.

[0062] FIG. **8** illustrates heliostat offset.

[0063] FIGS. **9**A and **9**B are diagrammatic elevation views of a heliostat and a central power tower system equipped with an array of light intensity detectors.

[0064] FIG. **10** is a diagrammatic elevation view of a heliostat and a central power tower system equipped with an array of light intensity detectors and an additional mechanical element in accordance with a preferred embodiment.

[0065] FIG. **11** is a diagrammatic plan view of a solar power tower system showing an example of how a plurality arrays can be provided to cover a surround heliostat field.

[0066] FIG. **12** a diagrammatic elevation view of a heliostat and a central power tower system equipped with an array of light intensity detectors and a light projector in accordance with a preferred embodiment.

[0067] FIG. **13** is diagrammatic elevation view of an array of light intensity detectors illustrating a method for calibrating multiple heliostats at substantially the same time.

[0068] FIGS. **14**A-**14**F illustrate time series of multiple beams traversing an array of light intensity sensors in accordance with some embodiments.

[0069] FIGS. **15**A, **16** are flowcharts of routines for characterizing reflection beams of one or more heliostats.

[0070] FIG. **15**B illustrates multiple heliostats directed to a macro-array of light intensity sensors.

[0071] FIG. **16** illustrates an image of at least a portion of a field of heliostats.

DETAILED DESCRIPTION OF EMBODIMENTS

[0072] According to the some embodiments, a solar power tower system includes at least one tower and at least one set of heliostats. Each heliostat tracks to reflect light to a target on a tower. The heliostats can be arrayed in any suitable manner, but preferably their spacing and positioning are selected to provide optimal financial return over a life cycle according to predictive weather data and at least one optimization goal such as total solar energy utilization, energy storage, electricity production, or revenue generation from sales of electricity.

[0073] An 'energy conversion target' or solar receiver uses reflected and optionally concentrated solar radiation and converts it to some useful form of energy, such as heat or electricity. The solar receiver may be located at the top of a receiver tower or at some other location, for example if an intermediate reflector (also called a secondary reflector) is used to bounce light received at the top of a tower down to a receiver located at ground level or at an intermediate height. For the present disclosure, the terms 'energy conversion target' and 'solar receiver' are used interchangeably and refer to a device or apparatus for converting insolation into some other form of energy—for example, electricity or thermal energy.

[0074] Referring now to the figures and in particular to FIG. **1**, a solar power tower system **44** is provided in which heliostats **38** include mirrors **8** that reflect incident solar radiation **28** onto a target mounted on tower **44** (for example, solar receiver **1**). The heliostat-mounted mirrors **8** are capable of tracking the apparent movement of the sun **25** across the sky each day in order to maintain the reflective focus in the direction of the receiver **1** as the angle of the incident radiation **28** changes. This tracking capability may be provided at least in part by a heliostat controller (not shown in FIG. **1**—see, for example, element **65** of FIG. **3**) for controlling one or more orientation parameters of mirror **8** to aim reflection beam **398**.

[0075] The skilled artisan will realize that the heliostat controller may include any combination of mechanical parts (for example including motors, actuators, etc) and/or electrical circuitry (for example, integrated circuits). In one non-limiting example, the electrical circuitry includes one or more computer microprocessors configured to execute software or code module(s) residing in volatile memory. In another non-limiting example, the heliostat controller may include gate array electronics for example, field-programmable gate array (FPGA). As will be explained below, in some embodiments, heliostat controller of heliostat **38** may also be configured for aiming the mirrors **8** at locations other than the target located atop tower **43**.

[0076] In the example of FIG. **1**, solar receiver **1** (for the present disclosure, "receiver" and "solar receiver" are used interchangeably) is located atop a tower **43**. FIG. **2** illustrates an alternative embodiment where receiver **1** is located on the ground, and the target is a secondary reflector (in contrast to FIG. **1** where the target is a solar receiver). Thus, in the example of FIG. **2**, the heliostat-mounted mirrors **8** reflect solar radiation onto one or more secondary reflectors **9** which further reflect the radiation onto the receiver **1**.

[0077] As shown in the figures, the reflection of the incident radiation beam **28** produces a reflection beam **398** which is reflected to the target, which is either a solar receiver (i.e., for converting insolation to another form of energy such as thermal energy or electricity) or a secondary reflector configured to relay light to a solar receiver. In one example, the solar receiver (either mounted on the tower as in FIG. **1** or operative to receive insolation from a secondary mounted on the tower as in FIG. **2**) is a solar boiler for boiling water and/or heating steam—this solar boiler may be operatively linked to an apparatus **45** for converting solar steam to electricity. In another example, the solar receiver is a molten salt solar receiver. In yet another example, the solar receiver includes one or more 'efficient' photovoltaic and/or photoelectrochemical cells.

[0078] For the present disclosure, 'efficient' photovoltaic and/or photoelectrochemical cell are cells capable of effecting 'efficient' (i.e., at least 10% efficiency) photovoltaic conversion at concentrations of at least 20 suns. Photovoltaic and/or photoelectrochemical cell that are unable to reach this level of efficiency are referred to as 'inefficient' cells.

[0079] It is appreciated that FIG. **1** (and none of the figures) is not required to be to scale—for example, in some embodiment, tower is much taller (e.g. at least 5 times or 10 times or 20 times or more) than heliostats **38**. In one example, the tower height is at least 25 meters. In another example, the tower height is at least 100 meters.

[0080] Although the heliostat mirror is drawn in the figs as a straight line representing a planar mirror, it is appreciated that this is not a limitation, and that other shaped mirrors may be employed.

[0081] As noted above, each heliostat may include a heliostat controller (NOT SHOWN) including mechanical parts and electrical circuitry for tracking the sun. In some embodiments and as will be discussed below, heliostat controllers may be operative to move the reflection beam to another location other than the target (i.e., the receiver **1** or the reflector **9**). One example of such a target is the 'macro-array' of light-intensity detectors discussed below.

[0082] In some embodiments, each heliostat controller is autonomous and may aim mirror **8** to provide a certain functionality without requiring external input. Alternatively or additionally, each heliostat controller may respond to one or more electronic communications (for example, external commands) received from external electronic device or system (located at any location) describing how to aim mirror **8**. For both cases, it may be said that the heliostat controller is 'operative' to provide the functionality (for example, aiming functionality).

[0083] A solar power tower system **44** also generally includes a heliostat field control system (not shown in FIGS. **1**-**2**) for helping the system operator or owner attain or maintain pre-defined operating parameters and/or constraints, some of which may be based on achieving optimization goals and some of which may be based on maintaining the safety of the system and its operation. For example, a heliostat field control system can be used to ensure that light energy flux is distributed across the surface of a target in accordance with a predetermined set of desired values (see for example, WO/2009/103077 incorporated herein by reference in its entirety), or it can be used to maximize conversion of energy from solar radiation to latent and/or sensible heat in a working fluid within a receiver, and/or conversion of solar energy to electricity by photovoltaic (or photoelectrochemical) means, while ensuring that local temperatures on the surface of the receiver, or local concentrations of solar flux, do not exceed a predetermined local maximum.

[0084] Overall control of the multiple heliostats can be either centralized in a single computer or distributed among several or many processors. Thus, in some embodiments, decisions about where to aim the heliostats may be carried out locally by the various heliostat controllers. Alternatively or additionally, heliostat field controller may communicate aiming instructions to one or more heliostat controllers which are configured to then provide this aiming functionality.

[0085] In an exemplary embodiment, a central heliostat field control system communicates hierarchically through a data communications network with controllers of individual heliostats. FIG. **3** illustrates an example of such a hierarchical control system **91** that includes three levels of control hierarchy, although in other embodiments there can be more or fewer levels of hierarchy, and in still other embodiments the entire data communications network can be without hierarchy, for example in a distributed processing arrangement using a peer-to-peer communications protocol.

[0086] At a lowest level of control hierarchy (i.e., the level provided by heliostat controller) in the illustration there are provided programmable heliostat control systems (HCS) **65**, which control the two-axis (azimuth and elevation) movements of heliostats (not shown), for example as they track the movement of the sun. At a higher level of control hierarchy, heliostat array control systems (HACS) **92**,**93** are provided, each of which controls the operation of heliostats **38** in heliostat fields **96**,**97** respectively, by communicating with programmable heliostat control systems **65** associated with those heliostats **38** through a multipoint data network **94** employing a network operating system such as CAN, Devicenet, Ethernet, or the like. At a still higher level of control hierarchy a master control system (MCS) **95** is provided which indirectly controls the operation of heliostats in heliostat fields **96**,**97** by communicating with heliostat array control systems **92**,**93** through network **94**. Master control system **95** further controls the operation of a solar receiver (not shown) by communication through network **94** to a receiver control system (RCS) **99**. In the example illustrated in the figure, the portion of network **94** provided in heliostat field **96** is based on copper wire or fiber optics connections, and each of the programmable heliostat control systems **65** provided in heliostat field **96** is equipped with a wired communications adapter **76**, as are master control system **95**, heliostat array control system **92** and wired network control bus router **100**, which is optionally deployed in network **94** to handle communications traffic to and among the programmable heliostat control systems **65** in heliostat field **96** more efficiently. In addition, the programmable heliostat control systems **65** provided in heliostat field **97** communicate with heliostat array control system **93** through network **94** by means of wireless communications. To this end, each of the programmable heliostat control systems **65** in heliostat field **97** is equipped with a wireless communications adapter **77**, as are heliostat array control system **93** and wireless network router **101**, which is optionally deployed in network **94** to handle network traffic to and among the programmable heliostat control systems **65** in heliostat field **97** more efficiently. In addition, master control system **95** is optionally equipped with a wireless communications adapter (not shown).

[0087] One of the possible functions of a control system (including local heliostat controller(s) and/or one or more higher-level controllers—for example, a centralized heliostat field controller) is to direct heliostats to various aiming points on the surface of a target, or alternatively not on the surface of a target when operating conditions require it. This is done on the basis of periodically or continuously evaluating various inputs, which can include (but not exhaustively): predictive and/or measured meteorological data; and measured and/or calculated operating conditions and parameters of heliostats and receivers. Among the operating conditions and parameters which can be used in applying control functions are instant and historical temperature data for the external surface of the receiver, and instant and historical light energy flux density data for the external surface of the receiver. For example, the distribution of temperature across the surface of a receiver at a given moment can be compared with a predetermined set of desired values or with the data for an earlier moment in time in order for the controller to decide whether current heliostat aiming instructions are adequate to meet system optimization goals or safety-based operational constraints, and especially when taking into account measured and predictive weather data. Similarly, the distribution of light energy flux density across the surface of a target at a given moment can be compared with a predetermined set of desired values, or, alternatively, used to calibrate the calculation of predicted flux densities that are used by a control system which generates sets of aiming points and directs heliostats to those aiming points based on those predicted patterns of resultant light energy flux density. The skilled artisan is directed, for example, WO/2009/103077 incorporated herein by reference in its entirety.

[0088] Another function of a control system includes the calibration of heliostats, or more specifically, the calibration of the reflection of solar radiation on a target with respect to a desired or predicted reflection, for example in terms of the location of the reflection, or in terms of the shape of the reflection, or in terms of the intensity of light flux at a plurality of points in the reflection, or in terms of any combination of data that describes the beam projection (reflection) in a desired format. As noted above, this functionality may be provided by the heliostat controller of a single heliostat either autonomously or in response to electronic communications received, for example, from a heliostat field controller.

[0089] In some embodiments, a system for calibrating heliostats includes an array of light intensity detectors. FIGS. **4**A-**4**E, **6**A-**6**B, **7**A-**7**B, **13** illustrate various arrays **100** of light intensity detectors **101**. In one non-limiting example, (see, for example, FIGS. **8-10**, **12**) the array **100** of light detectors **101** is mounted on tower **43**, for example, below the heliostat target.

[0090] In some embodiments, at one or more times, instead of being directed at the target, the reflection beam **398** (i.e., a reflection of a beam of sunlight or artificial light incident to mirror **8**) produced by each heliostat may be directed at array **100** of light intensity detectors. Each light intensity detector is used for detecting the intensity of light reflected by heliostats. In the figures, element **399** represents the cross section of reflection beam **398** as it is projected onto the array **101** of light sensors—in various embodiments, a maximum dimension of the cross section **399** of reflection beam **398** as projected onto the target and/or the array **101** of light intensity may be at least 30 cm, or at least 70 cm or at least 1 meter or at least 1.5 meters.

[0091] As will be discussed in greater detail below, light intensity data acquired by each of the light intensity sensors may be used to characterize reflection beam **398** and/or a property of the cross-section **399** thereof to determine a 'projected beam property.' In one non-limiting example, a measurement of the shape or cross-sectional-area (or an indicative parameter thereof) may be derived from the light intensity data. In another example, a beam intensity map measuring the flux intensity at different locations of the reflected beam cross section **399** may be derived from the light intensity data. In yet another example, a so-called beam offset may be derived from the light intensity data (see the discussion below with reference to FIG. **8**).

[0092] The light intensity data and/or data may be useful calibrating the heliostat to determine and/or modify one or more operating parameters of one or more of heliostats **38**. The heliostat calibration may be carried out in a closed-loop system although alternatively it can be used in a open-loop system. A closed-loop system is one in which the data obtained or derived by the light intensity detector array is used to change heliostat aiming instructions, to change the characterization of a heliostat in a database, or to bring about heliostat maintenance by having a computer program analyze the data and issue electronic instructions on a periodic or real-time basis without significant operator intervention. An open-loop system is one in which the data is stored or analyzed, and used at a later time for changing heliostat aiming instructions or for bringing about heliostat maintenance, usually after intervention by a human operator.

[0093] Light intensity detectors can include image sensors using charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) technology, or devices incorporating such a sensor. For example, a consumer digital camera with a CCD 'chip' can serve as an image sensor. Light intensity detectors can also include photodetectors, so-called light meters, which generally include a photovoltaic or photoresistant sensor. Alternatively, as is known in the art, ordinary solar cells such as photovoltaic or photoelectrochemical cells (for example, inefficient photovoltaic or photoelectrochemical cells) can be used as light intensity detectors. According to some embodiments, any one of these devices can be used to register a digital representation of the light reflected by a heliostat mirror **8** from a light source, either via digital imaging or by direct or indirect registration of light intensity levels.

[0094] In some embodiments, the array **100** of light intensity detectors **101** is preferably positioned so as to be accessible to the reflected light beams of large numbers of heliostats and therefore are best located at, near or on a central tower on which a receiver or other target is located since large numbers of heliostats are generally capable of aiming reflected light in the direction of a central tower. The array **100** is most preferably close to a target (such as a receiver or secondary reflector) so as to minimize travel time of heliostats diverted from regular tracking (focusing reflected light onto the target) for the purposes of calibration (see for example, FIGS. **8-10**, **12**).

[0095] FIGS. **4**A-**4**E are illustrations of a one dimensional array **100** of light intensity detectors **101**. FIGS. **6**A-**7**B and **13-14**F are illustrations of a two dimensional array **100** of light intensity detectors **101**. In the example of the figures, the array of light intensity detectors are 'macro-arrays' of light intensity detectors where the maximum sensor-sensor distance between light-intensity sensors of the array is (i) at least 0.5 meter and/or (ii) at least 0.5 times or at least 1.0 time or at least 1.5 times or at least 2.0 times the maximum dimension of the reflected beam's projection **399** onto the macro-array of light-intensity sensors.

[0096] The "maximum sensor-sensor distance" is the maximum distance between any pair of sensors of the macro-array **100** of sensors **101**—in the example of FIGS. **4**A-**4**E the maximum sensor-sensor distance is the distance between **101**A and **101**H, in FIGS. **14**A-**14**F the maximum sensor-sensor distance is the distance between **101**A and **101**G. In FIG. **4**A, the maximum dimension of the reflected beam's **398** projection **399** is indicated by **397**.

[0097] FIGS. **4**A-**4**F indicate a plurality of snapshots in time as the reflected beam's **398** projection **99** beam projection traverses the macro-array of light-intensity sensors. In the example of FIGS. **4**A-**4**F, light intensity readings at each of the sensors **101**A-**101**H may be recorded for a plurality of points in time **t0**-**t4**. The shape of the beam (or any other beam projection parameter) may be determined according to: (i) the time series of the light intensity measurements; (ii) the speed at which the projection beam traverses the macro-array of light intensity sensors (this may be constant or may vary in team); and/or (iii) the distance between the various sensors **101** at which light intensity measurements are taken.

[0098] Thus, in one example related to FIGS. **4**A-**4**F, the computed area of the reflection beam **399** may be a function of the distance between **101**B and **101**G (where a large distance would indicate a larger area). Furthermore, in the example of FIGS. **4**A-**4**F, the computed area of the reflection beam **399** may be a function of the reflected beam's projection traversal speed. In this case, a faster speed may indicate a larger beam area for fixed points in time, a larger speed indicates that the projection of the reflection beam has traveled a greater distance.

[0099] Thus, in some embodiments, the system is capable of measuring or approximating the shape of a heliostat beam projection from time series data of light intensity detectors, including data obtained from moving heliostats. This is best accomplished by designing the size and shape of the array of light intensity detectors that can do this in conjunction with the movement of a heliostat. For example, as illustrated in FIGS. **4**A-**4**F, the array **100** comprises a single line (or alternatively arc, not shown) of light intensity detectors **101**, provided substantially transversely to the tracking path of the beam projection **399** of light reflected from a heliostat, may be used to generate a set of time series that can be used by the system, together with 'external' data on the tracking speed of a heliostat and optionally the distance of a heliostat from the array, to approximate the shape of a heliostat beam projection. In another example, illustrated in FIG. **5**A, an array **100** includes at least one additional and optionally parallel line or arc of light intensity detectors **101**, which can be added in order to facilitate measurement or approximation of the speed of the beam projection **399** (since the distance between any two detectors **101** in the path of the beam projection **399**, for example **101***b* and **101***a* in the figure, could be made known to the system). In yet another example, illustrated in FIG. **5**B, the array **100** includes a two-dimensional array, or matrix, of at least partly offset rows or columns of detectors **101** that serve to increase resolution, in one or two dimensions, of the detection or measurement of light intensity. The size of the matrix can be continually increased to improve the resolution of the data capture, but ultimately the decision on the size of the matrix will be based on an economic tradeoff between the cost of additional light intensity detectors versus the incremental added value of higher resolution in the raw data. The incremental added value may also depend on the size of a heliostat beam projection and the number of heliostats. For example, if the detectors are expensive, and the deployment of a very large number of heliostats (tens of thousands) allows the achievement of only a moderate level of precision in calibration, then a system designer may prefer to use a small number of detectors (say, fewer than ten), whereas if the detectors were to be inexpensive and a smaller number of larger heliostats were to be involved which would typically demand a higher level of calibration accuracy, then a system designer may choose to use a larger number of detectors. In yet a further example, illustrated in FIGS. **6***a* and **6***b*, an array **100** of light intensity detectors **101** may be arranged with different and non-uniform densities of detectors **101** in different areas of the array **100**, for example so as to provide higher resolution at the edges of the array **100** (FIG. **6***a*), or alternatively so as to provide higher resolution at the center of the array **100** (FIG. **6***b*). Such non-uniform placement of detectors **101** may be, for example, in order to obtain a projection perimeter with greater resolution (as in FIG. **6***a*) or for the purpose of determining with greater precision the statistical distribution or even the calculated centroid of a heliostat beam projection **399** (as in FIG. **6***b*).

[0100] In FIGS. **4**A-**4**E (and in other figures) the light intensity detectors are separated by a distance on the order of magnitude of the size of the cells—however, this is not a limitation, and larger or smaller separations are certainly possible. In some embodiments, larger or smaller separations are certainly possible. as long as the maximum separation is on the order of magnitude of the size of the team. In one non-limiting embodiment, all of the light detectors are part of a large PVC panel having inefficient PVC cells.

[0101] FIGS. **7**A-**7**C are flow charts of routines for operating a heliostat of a solar energy system according to some embodiments.

[0102] Reference is made to FIG. **7**A. In step S**301** a heliostat is directed at the target (e.g. a solar energy conversation target and/or a secondary reflector) mounted on the tower—for example, to generate energy from the reflected beam that is projected onto the target. In step S**305**, the same heliostat is directed to the macro-array **100** such that the projected heliostat reflection beam traverses across the macro-array of light sensors.

[0103] In a first example, the heliostat is redirected from a first orientation when it is aiming at the target to a second orientation when to aim at the macro-array of light sensors (and traverse across the macro-array). In a second example, the heliostat is directed at the target, and then may be redirected to aim away from both the tower and the macro-array altogether—according to this second example, only at after some time delay. (e.g. a time delay of minutes, hours or days between the time when step S**301** finishes and the time when step S**305** begins). In step S**309** the light intensities are measured by light intensity sensors **101** of macro-array **100**. In step S**315**, one or more beam projection parameters of the heliostat are determined.

[0104] Reference is now made to FIG. **7**C. In step S**309**, for each heliostat, respective light intensities are measured. In step S361, the light intensity data is analyzed. In one particular example, the respective shape or flux intensity map of each heliostat is determined—for example, to create a database of heliostat shapes or heliostat intensity maps. In step S365, according go the results of the data analysis, heliostat selection may be carried out—i.e., a sub-plurality of the plurality of heliostats may be selected for simultaneous aiming at the target. In one example, it may be desired to provide a certain flux distribution at the target, and heliostat reflection beams (whose beam parameters are known from the light intensity data) may be selected accordingly.

[0105] FIG. **8** illustrates the concept of heliostat offset. It is noted that in many cases, heliostat controller attempts to aim the heliostat at the target so that the centroid of the reflection beam is located at target centroid location **660**. In many real-world scenarios, over time certain factors may cause the heliostat to deviate from its preferred operating parameters—for example, wind or rain may move the mirror or one or more heliostat moving parts associated with the aiming the heliostat, changes in temperature may distort the mirror, seismic activity may influence heliostat aiming or any other factors may influence heliostat aiming.

[0106] For the present disclosure, the terms 'aiming' and 'directing' are used interchangeably.

[0107] Thus, as illustrated in FIG. **8**, the actual centroid location **664** of the reflected heliostat beam obtained when the heliostat controller attempts to aim at location **660** actually deviates from the target centroid location

[0108] Embodiments of the present invention provide techniques and apparatus for measuring the actual centroid location **664** according to the light intensity measurements detected by light intensity sensors **101** of the macro-array. If desired, this information may then be used to determine the offset vector **668**.

[0109] Reference is now made to FIG. **7**B. In step S**301***, the heliostat is directed to the target mounted on the tower (i.e., an solar energy conversion target and/or a secondary reflector) according to an initial set of aiming parameters. Steps S**305** and S**309** of FIG. **7**B is the same as step as steps S**305** and S**309** of FIG. **7**A.

[0110] In step S**321**, the heliostat is directed to the target according to a modified set of aiming parameters. Thus, in one non-limiting use case, it is possible to compute the actual centroid location **664** and/or offset vector **668** and then to configure the heliostat control to compensate for any offset. In one particular example, it is possible to immediately re-aim the heliostat at the target according to the modified set of aiming parameters. Alternatively, it is possible to only do so after a time delay.

[0111] In another example, it is possible (i) at an initial time t**1** to direct the heliostat in step S**301*** according initial parameters at the target according to an initial set of aiming parameters; (ii) at a later time t**2** (either immediately after S**301*** or after any time delay—it is appreciated that in the interim the heliostat may be directed in any direction including away from both the target and the macro-array in the interim) to direct the heliostat in step S**305** at the macro-array of light-intensity sensors where in step S**309** the light intensities measurements are taken and (iii) at yet a later time t**3** (either immediately after S**305** or after any time delay—it is appreciated that in the interim the heliostat may be directed in any direction including away from both the target and the macro-array in the interim) in step S**321** to direct the heliostat back at the target according to a modified set of aiming parameters.

[0112] In some embodiments, the system includes software for providing instructions to heliostats to track to the array, including at least one set of tracking coordinates and tracking speed. The instructions can be propagated through a data network or communicated directly in accordance with the architecture of the solar field control system. The instructions, if transmitted in advance, may include a time when the heliostat controller should initiate execution of the instructions, and the heliostat controller may be equipped with data storage means for storing such instructions. Alternatively the instructions can be pre-programmed in a heliostat controller. For example, a heliostat controller may include a stored set of instructions to track to the calibration array with a given periodicity such as, for example, weekly or monthly.

[0113] In preferred embodiments, the heliostat calibration system is capable of obtaining a time series of data points representing the light intensity reflected by a heliostat to each digital imaging device or other light intensity detector, including while the heliostat is in motion. For example, if it takes 30 seconds for the light reflected from a heliostat in motion to traverse a light intensity detector while the heliostat is tracking across the detector, then the time series would include a plurality of data points (digital images and/or digital light intensity measurements) captured during those 30 seconds and preferably at a resolution sufficiently high as to indicate with a desired level of precision the beginning and end of the incidence of light on the detector as well as the intensity level at each time point. In another example, all of the detectors in an array may capture a time series of data points beginning when a first detector in the array detects light reflected from a heliostat and ending only when no detectors in the array detect reflected light from the heliostat. In yet another example, all of the detectors in the array obtain, record or process light intensity data (or digital images) all of the time when it is known that heliostats are to be calibrated, leaving the task of determining beginning and ending time points for each individual heliostat to image- or data-processing software elsewhere in the system. The time series data from each light intensity detector can be recorded for later processing, and/or transmitted, whether directly or through a data network, to a computer or data storage device elsewhere in the system for processing and analysis of the data.

[0114] In particularly preferred embodiments, the system also includes computer hardware and software for analyzing the data obtained or recorded from the digital imaging devices or other light intensity detectors. The analysis is performed for the purpose of calibrating the heliostat, where calibrating may include at least one of: determining the deviation of the calculated centroid of the heliostat's beam projection from the predicted; determining or approximating the beam projection shape and its deviation from the predicted; determining the intensity of light at a plurality of points within the beam projection and any deviation from the projected distribution of light intensity; determining the speed of the traversal of the beam projection and any deviation from the predicted; correcting a structural or assembly error, or shape aberration, or any other malfunction or deviation from design in a heliostat; storing or using any of these data elements for the purpose of updating or changing a database of heliostat-related data or of updating or changing the aiming and/or tracking instructions of a heliostat; or analysis of the data by a system designer or operator.

[0115] Most preferably, the analysis software is capable of calculating a beam projection shape and/or calculating the statistical distribution and/or centroid of the beam projection distribution, using data obtained and/or recorded by the light intensity detectors, including time series data, and optionally using statistical techniques applying a Gaussian or other probabilistic distribution to the light intensity of a heliostat beam projection. Additionally, the software can be capable of producing a digital map of the light intensity at a plurality of points in the beam projection. Any of these calculated parameters can be used in the calibration of heliostats as described above. Heliostats (or a control system for heliostats and/or heliostat controllers) are configured to modify aiming instructions such as target coordinates in response to data obtained during the calibration process or in response to the result of the analysis of the data.

[0116] The analysis software can also include software to eliminate or cancel out the effects of diffuse or ambient light measured by a light intensity detector, for example by measuring such light before and/or after the traversal of a heliostat beam. The analysis software can also include software for transformation of a curvilinear projection in order to 'translate' a beam projection shape and/or map of light intensity values to the surface geometry of a receiver, taking into account: the different angle of incidence of reflected light on the receiver compared with that on the array; the different attitude of the receiver with respect to the heliostat field; and/or the external surface characteristics of the receiver (for example which may comprise individual round boiler tubes rather than a smooth external surface panel.

[0117] In another embodiment, a solar power tower system includes a solar field and an array of light intensity detectors on a tower. A target such as a thermal or photovoltaic receiver, or alternatively a secondary reflector, is situated at or near the top of the tower. The array of light intensity detectors can be provided in accordance with any of the embodiments described above.

[0118] In the case of a thermal receiver or photovoltaic target, for example, the array of detectors would optimally be provided just below the receiver on the side of the tower as shown in FIG. **9**A. Referring now to FIG. **9**A, a receiver **1** sits atop a tower **43**, similar to the arrangement of FIG. **1**. At least one heliostat **38** is configured with tracking and pivoting means as described above to reflect sunlight **28** onto the receiver **1**. An array **100** of light intensity detectors (not shown individually) is positioned on the tower **43** below the receiver **1** so that a heliostat **38** can also track to the array **100** and reflect sunlight **28** onto the array **100**. Reflected light **30** falls upon the array in accordance with tracking instructions executed by a heliostat **38** from time to time. The array **100** can optionally be angled toward the solar field in order to cause light reflected from heliostats to impinge upon the array at a more desirable angle, if the benefits of such an angling would outweigh additional material, installation and/or maintenance costs.

[0119] In the case of a secondary reflector used as a 'beam-down' mirror, the array of detectors could be either above the secondary reflector or on one of the tower supports of the secondary reflector as shown in FIG. **9**B. In FIG. **9**B, receiver **1** sits on—but not at the top of—a tower **43** (or alternatively near or at its base) on which is provided a secondary reflector **9**, similar to the arrangement of FIG. **2**. At least one heliostat **38** is configured with tracking and pivoting means as described above to reflect sunlight onto the secondary reflector **9**. An array **100*a*** of light intensity detectors (not shown individually) is positioned on the tower **43** below the secondary reflector **9** so that a heliostat **38** can also track to the array **100*b***. Alternatively, (or, optionally, additionally,) an array **100*b*** of light intensity detectors (not shown individually) is positioned on the tower **43** higher than the secondary reflector **9**, in a location allowing a heliostat to track to the array **100*b*** without the beam being blocked by the receiver at least part of the time.

[0120] In a preferred embodiment, the array of light intensity detectors includes optical or mechanical elements to improve the ability of the detectors to detect or measure the light reflected by heliostats. An example of a mechanical element is one that substantially blocks direct sunlight, or sunlight reflected by objects other than heliostat mirrors, from reaching the detectors during most of the hours of the day, such as a shade or awning. Such an element can also serve to keep precipitation and some windborne particles off the light intensity detectors. FIG. **10** shows an example of a mechanical element **105** positioned on a tower **43** so as to reduce direct sunlight and/or precipitation impinging on an array **100** of light intensity detectors (not shown individually).

[0121] An example of an optical element is a filter that can be placed over individual light intensity detectors, or alternatively over the entire array or a portion thereof, in order to reduce total or maximum light intensity to a level more appropriate to the sensitivity or operating characteristics of the light intensity detectors. Other examples of optical elements may include lenses with anti-reflective coatings or dust-repellent coatings, focusing lenses or spectrally selective filters. Alternatively, light intensity may be moderated by software.

[0122] In a particularly preferred embodiment, the solar power tower system includes multiple arrays of light intensity detectors in order to make such arrays accessible to all the heliostats in a solar field. In an example, a solar power tower system includes a surround receiver on a four-sided tower, and additionally includes a surround field of heliostats, i.e., 360° around the tower. In this case the system would include four arrays, one on each side of the tower. As the light intensity detectors should be selected to allow for an acceptance angle wide enough to accommodate the respective portion of the solar field, in this example the acceptance angle (for each of four arrays) would have to be 90°, as illustrated in FIG. **11**. Referring now to FIG. **11**, a tower **43**—on which a receiver (not shown) is sited—is surrounded by a solar field **39** comprising, inter alia, a plurality of heliostats **38** in each of four quadrants Q**1**, Q**2**, Q**3** and Q**4**. Light intensity detector arrays **100**, each with an acceptance angle of 90°, are positioned on the tower such that each array **100** can accommodate calibration of the heliostats in one of the four quadrants Q**1**, Q**2**, Q**3** and Q**4**.

[0123] In another preferred embodiment, the solar power tower system includes a light projector that can be used for performing heliostat calibration at night. The projector must be of sufficient power as to allow the light intensity detectors to register the intensity of its light when reflected thereupon by a heliostat, with a desired level of data resolution. An example of a suitable light projector is a Strong Britelight® 10000 available from Ballantyne of Omaha, Inc., of Omaha, Nebr., although it is possible to use a light projector of lower power rating as well. Operation of such an embodiment is illustrated in FIG. **12**, where a light projector **108** mounted on a tower **43** between a receiver **1** and a light intensity detector array **100** shines light **31** onto a heliostat **38**, and reflected light **32** strikes the light intensity detector array **100** in accordance with tracking instructions executed by the heliostat **38**

from time to time. In an alternative preferred embodiment, the projector will be designed so as to create a source of light (as seen from the solar field) of a size comparable to the apparent size of the disk of the sun (for example 9 mrad as 'seen' by a heliostat), in order to allow for registration and calibration of not only aiming and tracking accuracy but also of beam projection shape deviation from a desired or predicted shape.

[0124] In other embodiments, a method for operating a solar power tower system includes using an array of digital imaging devices or other light intensity detectors to capture and/or record the light reflected from a heliostat for the purposes of calibration, where calibration can include at least one of: determining or approximating a statistical distribution and/or centroid of a heliostat's beam project and/or its deviation from a desired or predicted set of values; determining the beam projection shape and/or its deviation from a desired or predicted set of values; determining the intensity of light at a plurality of points within the beam projection and/or any deviation from a desired or predicted set of values; determining the speed of the traversal of the beam projection and/or any deviation from a desired or predicted set of values; correcting a structural or assembly error, or shape aberration, or any other malfunction or deviation from design in a heliostat; storing or using any of these data elements for the purpose of updating or changing a database of heliostat-related data or of updating or changing the aiming and/or tracking instructions of a heliostat; or analysis of the data by a system designer or operator. According to the method, the array is used for calibration of heliostats in a solar power tower system by causing each heliostat, or alternatively groups of heliostats, to traverse the array periodically in accordance with a manufacturer's specification, for example once every two weeks, once every month, or once every two months. Therefore, the method preferably includes sending instructions, directly or through a data communications network, to a heliostat to cause it to track to the array. Alternatively it would be possible to make use of a preprogrammed heliostat controller which causes a heliostat to track to the array with a desired periodicity or under certain preset conditions. In any of the embodiments, light reflected by the heliostat onto an array of light intensity detectors can come from the sun, the moon, or from a light projector.

[0125] The method also preferably includes selecting heliostats for tracking to the light intensity detector array in accordance with their relative availability or, conversely, with in accordance with how much each heliostat is needed by the solar power tower system. For example, it is known that during hours of peak insolation many heliostats are turned away from their usual receiver or other target in order not to overload a receiver or some other system component (such as a turbine in the case of a concentrated solar thermal plant, or power inverters in the case of a concentrated photovoltaic plant), or so as not to exceed a contractual or regulatory limit (for example the conditions of a power purchasing agreement). It is therefore desirable to select those heliostats not instantly required during such peak insolation hours, and instead to cause them to track to the calibration array at that time. In another example, there may be excess heliostats on one side of a tower; for example, it is known that the heliostats east of a tower in the afternoon (in the northern hemisphere) can reflect up to three times as much light onto the eastern side of a receiver than they can in the morning (because reflected light is reduced in accordance with the cosine of half the angle between incidence and reflection). In accordance with the method it would be desirable to cause such excess heliostats to track to the calibration array during such times as they are not needed for energy conversion so as not to make them unavailable at other times when they are more acutely needed (e.g., the morning hours in the eastern field example).

[0126] The method also preferably includes obtaining and optionally recording a time series of the light intensity reflected by the heliostat to each digital imaging device or light intensity detector, including while the heliostat is moving. If the tracking speed of the heliostat and the distance from the heliostat to the array are known, then it is possible to calculate at least one dimension of the beam projection from the time series; alternatively, by using a known distance between members of the array, it is possible to calculate at least one dimension of the beam projection from the time series without the need for external data.

[0127] The method most preferably includes analyzing data obtained and/or recorded from the array of light intensity detectors (or digital imaging devices) to yield a characterization of the beam projection of a heliostat, where the characterization includes at least one of: a map of the light intensity at a plurality of points in the beam projection; the shape of the beam projection either as a set of points describing a perimeter or a mathematical expression for the shape; a mathematical expression for distribution of light in the beam such as a statistical distribution; a beam centroid; or the deviation of any of these measured or characterized parameters from a design target or from a predicted set of values. According to the method, the characterization, optionally including any measurable or calculable deviation from a design goal or predicted set of values, is optimally used by a control system and/or system operator to calibrate the aiming of the heliostat or for any other aspect of heliostat calibration as described above.

[0128] In a preferred embodiment, the method includes causing a plurality of heliostats to track simultaneously or nearly simultaneously to an array, and obtaining (or recording) light intensity indications for the purposes of heliostat calibration. In an example illustrated in FIG. **13**, four heliostats track simultaneously to a two-dimensional array (i.e., an array having at least two columns and two rows, where the columns and/or rows can be in the shape of lines, staggered lines or arcs) from different directions at the same time in such a way that each heliostat beam projection can be independently analyzed. This arrangement is optimally arranged so that at least part and preferably at least half of each beam projection **399** traverses at least one row **106** or column **107** of light intensity detectors **101** within the array **100** before intersecting or overlapping with another beam projection **399**. Similarly, after intersecting with other beam projections **399**, at least part and preferably at least half of each beam projection **399** traverses at least one row **106** or column **107** of light intensity detectors **101** within the array **100** after ceasing to intersect or overlap with other beam projections **399**. In the example, software captures most or all of the desired beam shape times series data for each beam projection during the time that the beam projection doesn't intersect with other beam projections. In another example, the light intensity detectors are digital imaging devices and different pixels or groups of pixels in the imaging sensor can be used for recording the light intensity of different heliostats.

[0129] FIGS. **14**A-**14**F illustrate time series of multiple beams **99**A, **99**B traversing an array **100** of light intensity sensors **101** in accordance with some embodiments. At times t**0**, t**1**, t**2** and t**5** beams **99**A and **99**B do not overlap (they are disjoint)—at times t**3** and t**4** beams **99***a* and **99**B overlap.

[0130] FIG. **15**A is a flow chart of an exemplary routine for determining one or more beam projection parameters of a heliostat in situations where multiple heliostat reflection beams are simultaneously incident on the macro-array **100** of light intensity detectors **101** so that multiple reflection beams overlap at one or more light intensity detectors **101**.

[0131] In step S**501**, a plurality of heilostats are controlled so that multiple reflection beams simultaneously traverse the macro-array of light detectors.

[0132] In step S**555**, when the projections of two or more heliostat reflection beams **398** simultaneously traverse the macro-array **100** of detectors **101**, one or more sensors are simultaneously illuminated by multiple reflection beams (for example, in FIG. **14**D sensors **101**C and **101**F are simultaneously illuminated by beams whose projection is **99**A and **99**B; in FIG. **14**E sensors **101**G and **101**F are simultaneously illuminated by beams whose projection is **99**A and **99**B).

[0133] According to some embodiments, when multiple beams reflected from a heliostat simultaneously illuminate a given light intensity sensor **101**, it is possible to determine the light intensity contribution of each reflection beam of multiple beams.

[0134] In one non-limiting example, the light intensity detectors are image detectors, and a respective image is acquired by each light intensity detector. It is possible to analyze the contents of each image and in accordance with the results of the image analysis, to determine the relative contributions.

[0135] FIG. **15**B illustrates a plurality of heliostats **38**A, **38**B configured to simultaneously reflect respective incident beams **28**A, **28**B onto a macro-array **100** of image detectors which provide light-intensity detector functionality.

[0136] When simultaneous reflection beams **98**A, **98**B are incident upon an image detector (i.e., overlapping beam projections as in FIGS. **14**D-**14**E), the image generated may, in one example, look like the image illustrated in FIG. **15**C. In FIG. **15**C, the image is at least a portion of the field of heliostats from the point of view of the one of the image sensors for the particular case of a light intensity sensor looking down upon the field of heliostats. The field of heliostats includes two heliostats **38**A, **38**B (having mirrors **8**A and **8**B) simultaneously directed to a given image detector to simultaneously illuminate the given image detector. In the example of FIG. **15**C, for illustrative purposes only, many of the heliostats are drawn identically—it is appreciated that in many applications, this typically is not the case, and heliostat mirrors may have different shapes and/or sizes and/or orientations.

[0137] It is now disclosed that it is possible to analyze the image acquired the image by the image detector, and according to the contents to determine (within some tolerance) the relative contributions of multiple heliostat reflection beams reflected onto the image detector. Thus, in the example of FIG. **15**C, the contribution of heliostat **38**A (**38**B) having mirror **8**A (**8**B) is a function of the size in the image of heliostat **38**A (**38**B) (where a larger size would indicate a larger light contribution) and the color and/or grey shade of heliostat **38**A (**38**B). Because the grey shade (or color) of the heliostat may be indicative of the intensity of the incident light beam **28** (and hence the reflected light beam **398**) on a heliostat, this may be useful for determining a relative contribution of light intensity of a particular heliostat. In addition, the size of the heliostat in the image may also be useful for determining a relative contribution of light intensity of a particular heliostat.

[0138] In some embodiments, towards this end, it may be useful to maintain a database of heliostats shapes and sizes in order to identify the particular heliostats in the image.

[0139] Thus, in the embodiment of FIG. **15**A, it is possible to determine relative contributions to the light intensity of reflection beams of different heliostats. Alternatively or additionally, as in FIG. **16**, it is possible to give a greater weight (when computing a heliostat projected beam parameter such as beam shape or centroid location or intensity or when determining modified operating parameters for one or more heliostats) to images acquired when the beams are not overlapping, For example, in some embodiments, it may be assumed that the measurements from a single heliostat beam are more reliable than measurements taken from a light detector simultaneously illuminated by multiple heliostat reflection beams.

[0140] Thus, in step S**501** of FIG. **501**, the plurality of reflection beams traverse the macro-array of light detectors.

[0141] In steps S**505**-S**509**, it is determined if multiple reflection beams are simultaneously illuminating a light intensity detector—for the example of FIGS. **14**A-**14**F, for detector **101**F this is true at time=t**3** and time=t**4**, for detector **101**A this is never true, for detector **101** C this is true only for time=t**3**.

[0142] In the event of an overlap (step S**521**) then the data acquired at a light intensity sensor simultaneously illuminated by multiple beams is discarded or is given a lower weight. In the event of no overlap (step S**513**), then a decision to utilize this data when characterizing the beam may be made and/or the data may be given a greater weight—for example, when computing or more beam projection parameters or when effecting a decision based upon the measurements of one or more light intensity detectors.

[0143] In addition to the techniques discussed above, multiple beams simultaneously incident on the macroarray may be numerically separated from multiple time samples of the overlapping beam images. This may be done using known image processing techniques. Further, images can be captured at higher resolution that a sparse detector array by disambiguating multiple sparse images from a time series.

[0144] Certain features of this invention may sometimes be used to advantage without a corresponding use of the other features. While a specific embodiment of the invention has been shown and described in detail to illustrate the application of the principles of the invention, it will be understood that the invention may be embodied otherwise without departing from such principles.

What is claimed is:

1. A solar energy system comprising:

a. a plurality of heliostats configured to reflect sunlight to a target mounted on a tower, each heliostat including a respective heliostat controller, the target, the target being selecting from the group consisting of an energy conversion target and/or a secondary reflector; and

b. a macro-array of light-intensity sensors characterized by a maximum sensor-sensor distance and mounted on the tower such that when any heliostat of the plurality of heliostats reflects a beam of light onto the macro-array of light-intensity sensors, the maximum dimension of the reflected beam's projection on the macro-array is at most twice the maximum sensor-sensor distance, wherein each heliostat controller is operative to control its respective heliostat so that the light beam reflected by the heliostat traverses the macro-array of light-intensity sensors.

2. The system of claim **1** wherein the macro-array of light-intensity sensors is substantially co-planar.

3. The system of claim **1**, where the macro-array of light-intensity sensors is a two dimensional macro-array.

4. The system of claim **1**, where the light-intensity sensors are configured to acquire time-series light intensity data while the reflected beam's projection traverses across the macro-array of light sensors.

5. The system of claim **1** wherein the heliostat controller is operative to:

i) before the traversing of the projection of the reflection beam, direct the heliostat to the target mounted on the tower according to an initial set of aiming parameters; and

ii) after the traversing of the projection of the reflection beam, re-direct the heliostat to the target mounted on the tower according to a modified set of aiming parameters that is modified in accordance with light intensity data generated by light intensity sensors of the macro-array.

6. The system of claim **5** wherein the heliostat controller is operative to effect the re-directing according to the modified set of aiming parameters after the beam traversing.

7. The system of claim **5** wherein the heliostat controller is operative to effect the re-directing according to the modified set of aiming parameters immediately after the beam traversing.

8. The system of claim **4** wherein the heliostat controller is operative to effect the re-directing according to the modified set of aiming parameters immediately only after a time delay.

9. The system of claim **8** wherein during the period of the time delay, the controller is operative to re-direct the heliostat to the target according to the initial set of aiming parameters.

10. The system of claim **6** wherein the modified set of aiming parameters is modified in accordance with at least one of:

i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and

ii) a beam traversal speed of the traversing reflected heliostat beam.

11. The system of claim **1** further comprising:

c. a heliostat-field controller operative to:

i) select, from the plurality of heliostats, a sub-plurality of heliostats that is to be simultaneously directed to the target; and

ii) direct the selected sub-plurality of heliostats the target,

wherein the heliostat field controller is operative to carry out the heliostat selection in accordance with respective light intensity measurements of macro-array taken when each heliostat's reflected beam respectively traverses the macro-array.

12. The system of claim **11** wherein the heliostat-field controller is operative to effect the selection in accordance with at least one of:

i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and

ii) a beam traversal speed of the traversing reflected heliostat beam.

13. The system of claim **1** wherein the system further comprises:

c) electronic circuitry configured to measure at least one beam projection parameter of the heliostat beam according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

14. The system of claim **13** wherein the electronic circuitry is configured to effect the measuring in accordance with at least one of:

i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and

ii) a beam traversal speed of the traversing reflected heliostat beam.

15. The system of claim **1** wherein the system further comprises:

c) electronic circuitry configured to measure at least one of:

i) a shape of the heliostat beam;

ii) a flux intensity map of the heliostat beam;

iii) an offset of the heliostat beam; and

iv) an indication of beam area.

according to the light intensity measurements acquired by light-intensity sensors while the heliostat beam traverses the macro-array of light-intensity sensors.

16. The system of claim **15** wherein the electronic circuitry is configured to effect the measuring in accordance with at least one of:

i) distances between light-intensity sensors of the macro-array of light-intensity sensors; and

ii) a beam traversal speed of the traversing reflected heliostat beam.

17. The system of claim **1** wherein: the heliostat controllers collectively are configured so that multiple overlapping heliostat reflection beams including first and second heliostat reflection beams simultaneously traverse the macro-array to simultaneously illuminate one or more of the light-intensity sensors.

18. The system of claim **17** wherein:

i) the light-intensity sensors of the macro-array are image sensors; and

ii) the system further comprises:

c) electronic circuitry operative to:

A) determine, from the images generated by the image sensors, relative light intensity contributions of the overlapping first and second heliostat beams when the first and second beams overlap and traverse the macro-array; and

B) in accordance with the relative light intensity contributions, determine at least one of:

I) a shape of the first and/or second heliostat beam;

II) a flux intensity map of the first and/or second heliostat beam;

III) an offset of the first and/or second heliostat beam; and

IV) an indication of beam area.

19. The system of claim **17** wherein the heliostat controllers collectively are configured so that the first and second heliostat beams overlap at some times and are disjoint at other times while the first and second beams traverse the macro-array.

20. The system of claim **19** wherein:

i) the light-intensity sensors of the macro-array are image sensors; and

ii) the system further comprises:

c) electronic circuitry operative to determine when the first and second beams are disjoint, and in accordance with the disjoint time period(s), determine at least one of:

I) a shape of the first and/or second heliostat beam;

II) a flux intensity map of the first and/or second heliostat beam;

Ill) an offset of the first and/or second heliostat beam; and

IV) an indication of beam area.

21. The system of claim **1** wherein each of the light sensors of the macro-array are image sensors.

22. The system of claim **21** wherein the image sensors are selected from the group consisting of a CCD microarray and a CMOS microarray.

23. The system of claim **1** wherein each of the light sensors of the macro-array are photo-detectors incapable of detecting an image.

24. The system of claim **23** wherein each of the light sensors are photo-voltaic cells.

25. The system of claim **1** wherein each of the light-intensity sensors is mounted to the tower.

26. The system of claim **1** wherein the energy conversion target is selected from the group consisting of solar boiler target and a molten salt solar receiver.

27. The system of claim **26** wherein the solar boiler target is selected from the group consisting of a solar evaporator, a solar re-heater and a solar superheater.

28. The system of claim **1** wherein the energy conversion target includes one or more photovoltaic and/or photo-electrovoltaic cells.

29. The system of claim **1** wherein a height of the tower is at least 25 meters.

30. The system of claim **1** wherein a height of the tower is at least 100 meters.

31. The system of claim **1** further comprising:

c. a projector configured to project artificial light onto the heliostat such that the traversing reflected beam that traverses the macro-array includes the artificial light generated by the projector.

32. The system of claim **31** wherein the projector is mounted on the tower.

33. A method of operating a solar energy system, the method comprising:

a. respectively reflecting sunlight from each of a plurality of heliostats to a target mounted on a tower, the target being selecting from the group consisting of an energy conversion target and/or a secondary reflector; and

b. respectively controlling each heliostat of the plurality so that the light beam reflected by the heliostat traverses the macro-array of light-intensity sensors characterized by a maximum sensor-sensor distance and mounted on the tower such that when any heliostat of the plurality of heliostats reflects a beam of light onto the macro-array of light-intensity sensors, the maximum dimension of the reflected beam's projection on the macro-array is at most twice the maximum sensor-sensor distance.

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