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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G01S 5/12, H04B 7/185 — A2

(11) International Publication Number: WO 00/14564

(43) International Publication Date: 16 March 2000 (16.03.00)

(21) International Application Number: PCT/US99/20255

(22) International Filing Date: 2 September 1999 (02.09.99)

(30) Priority Data:
09/149,061 8 September 1998 (08.09.98) US

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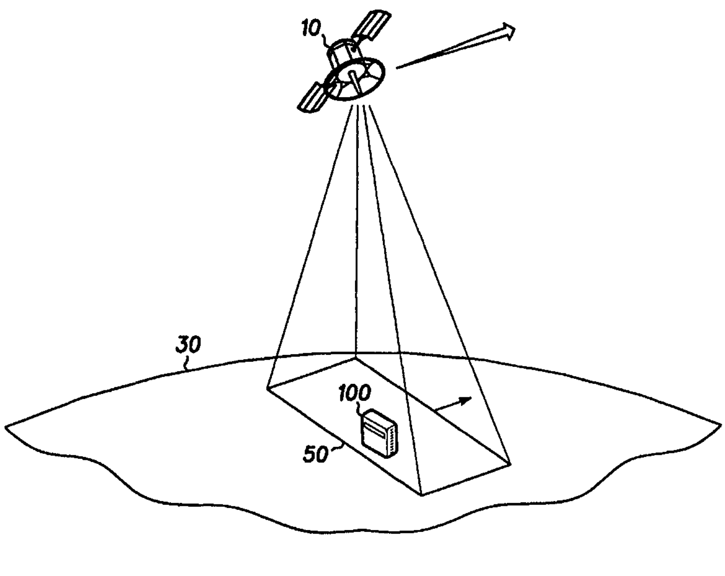
(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: MOVABLE SUBSCRIBER DEVICE LOCATION USING DUAL SATELLITES



(57) Abstract

In a communication system where two orbiting satellites (10, 20) travel in nonparallel paths, a movable subscriber device (100) is accurately located. Each satellite transmits geolocation information which is received by the movable subscriber device (100). The movable subscriber device (100) then uses Doppler frequency shift information as well as time of arrival to locate itself along a first strip on the surface of the earth (30) which extends perpendicular to the direction of motion of the first satellite (10). When geolocation information from the second satellite (20) is received by the movable subscriber device (100), the device locates itself along a second strip on the surface of the earth (30) which extends perpendicular to the direction of motion of the second satellite (20). The movable subscriber device (100) can then be accurately located at the intersection of the first and second strips.

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MOVABLE SUBSCRIBER DEVICE LOCATION USING DUAL SATELLITES

Field of the Invention

The invention relates to satellite communications and, more particularly, to techniques for locating a movable subscriber device at or near the surface of the earth.

Background of the Invention

In a satellite communication system, where orbiting satellites provide communication services to earth-based subscribers, it is particularly important to be able to determine the location of the subscriber. Consequently, in order to provide relatively efficient and low-cost communication services, an orbiting satellite must accurately locate earth-based subscribers. This allows the satellite to radiate signals to only those areas occupied by earth-based subscribers. Accurate location of subscribers also allows the satellite to generate receive beams from the particular direction occupied by a subscriber and avoid in-band interfering signals from those areas where subscribers do not exist.

As satellite communication systems transmit and receive increasing amounts of information to and from earth-based subscribers, transmit and receive antenna beams must become correspondingly more narrow. The need for narrow transmit and receive antenna beams stems from the increased gain requirements which transmit and receive antenna beams must possess in order to convey larger amounts of data per unit time to and from earth-based subscribers. Additionally, transmissions to earth-based subscribers must penetrate difficult environments such as forested areas or other locations where significant propagation loss can occur. Thus, the locations of earth-based subscribers must be known with greater accuracy as these transmit antenna beams become progressively more narrow.

Conventional methods for geolocation of movable subscriber devices such as pagers, cellular telephones, and other devices which receive messages from orbiting satellites, do not provide sufficient accuracy for advanced spacecraft in determining the area in which a particular movable subscriber device is located. Additionally, as more sophisticated geolocation methods are employed, more sophisticated movable subscriber devices are required. This results in increased cost to earth-based subscribers due to the additional complexity of the movable subscriber device. Additionally, the movable subscriber device must be capable of receiving information from an orbiting satellite at all times. Thus, the movable subscriber device must be powered ON for a substantial period of time in order to receive geolocation, paging, and other information beams from the orbiting satellite. This places a strain on the power requirements of the movable subscriber device. The resulting battery or other charge storage element within the movable subscriber device must then be larger or more often recharged. Both of these are undesirable to the user of the movable subscriber device.

Therefore what is needed are a method and apparatus for accurately locating movable subscriber devices. What is also needed is a movable subscriber device with minimum ON time to receive geolocation and paging information from an orbiting satellite.

Brief Description of the Drawings

The invention is pointed out with particularity in the appended claims. However, a more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the figures, wherein like reference numbers refer to similar items throughout the figures, and:

FIG. 1 illustrates an orbiting satellite moving in relation to the earth's surface in accordance with a preferred embodiment of the invention;

FIG. 2 illustrates an angle φ which represents a beam scan angle measured from the nadir of the satellite in the fore and aft directions in accordance with a preferred embodiment of the invention;

FIG. 3 illustrates a Doppler frequency shift as a function of the angle φ shown FIG. 2 in accordance with a preferred embodiment of the invention;

FIG. 4 illustrates a second derivative of a Doppler frequency with respect to angle φ of FIG. 3 in accordance with a preferred embodiment of the invention;

FIG. 5 illustrates an angle θ which represents a beam scan angle measured in a side-to-side dimension perpendicular to the direction of motion of an orbiting satellite in accordance with a preferred embodiment of the invention;

FIG. 6 illustrates a change in time of arrival of information conveyed from an orbiting satellite with respect to angle θ of FIG. 5 in accordance with a preferred embodiment of the invention;

FIG. 7 illustrates a second orbiting satellite moving in relation to the earth's surface in accordance with a preferred embodiment of the invention;

FIG. 8 illustrates a satellite transmit antenna beam sweep from a maximum scan angle, θ_m, to a minimum scan angle in accordance with a preferred embodiment of the invention;

FIG. 9 illustrates a method for geolocation of a movable subscriber device using dual satellites in accordance with a preferred embodiment of the invention; and

FIG. 10 illustrates a movable subscriber device in accordance with a preferred embodiment of the invention.

Description of the Preferred Embodiments

A method and apparatus for geolocation using dual satellites facilitates the accurate location of an earth-based movable subscriber device. This allows a satellite communication system to deliver messages to a particular area wherein a movable subscriber device is located using a narrow transmit antenna beam. Additionally this geolocation can be achieved with only a minimal increase in the complexity of the movable subscriber device.

FIG. 1 illustrates an orbiting satellite moving in relation to the earth's surface in accordance with a preferred embodiment of the invention. In FIG. 1, satellite 10 transmits timing information to movable subscriber device 100, which is located at or near the surface of the earth. Satellite 10 can be an orbiting communication satellite moving in a non-geostationary orbit. In an alternative embodiment, satellite 10 can be another type of moving communications node which moves relative to earth-based movable subscriber device 100. Thus, although FIG. 1 illustrates a satellite, the present invention is not limited to the use of orbiting communication satellites but can include other moving communications nodes such as suitably equipped aircraft.

As satellite 10 passes over the area of the surface of the earth 30 wherein movable subscriber device 100 is located, a transmit beam is radiated from the satellite's antenna. In a preferred embodiment, this beam comprises geolocation information in the form of timing and frequency data and is transmitted to areas substantially directly beneath the satellite and to the sides of satellite 10. Thus, the transmit beam is directed toward areas substantially perpendicular to the direction of motion of satellite 10, while the amount of energy radiated in front of or behind the satellite is minimal.

As this information is transmitted from satellite 10, movable subscriber device 100 can obtain both Doppler frequency shift information as well as time of arrival information from the transmission from satellite 10. As will be discussed in reference to FIG. 4, this allows movable subscriber device 100 to locate itself on or near the surface of the earth with accuracy sufficient for many applications. Additionally, as is discussed in reference to FIG. 7, when a second satellite 20 is moving in an orbit which is nonparallel to the path of satellite 10, movable subscriber device 100 can locate itself on the surface of the earth with exceptional accuracy.

FIG. 2 illustrates an angle φ which represents a beam scan angle measured from the nadir of the satellite in the fore and aft directions in accordance with a preferred embodiment of the invention. Areas behind satellite 10 assume negative values of angle φ, while areas in front of satellite 10 assume positive values of angle φ. Satellite 10 is assumed to be in motion relative to movable subscriber device 100.

FIG. 3 illustrates a Doppler frequency shift as a function of the angle φ shown FIG. 2 in accordance with a preferred embodiment of the invention. As illustrated in FIG. 3, the larger positive and negative values of angle φ correspond to those areas significantly in front of and behind satellite 10 of FIG. 1, respectively. For those values of φ which are significantly close to zero, which corresponds to areas considerably beneath and to the sides of satellite 10, changes in Doppler frequency shift occur rapidly. Therefore, any offset errors in the rate of Doppler frequency which occur in a region near φ=0 have only a small impact on the angle φ.

Thus, it is desirable to make use of Doppler frequency rate of change during those intervals when satellite 10 passes overhead or to the side of movable subscriber device 100. By extracting Doppler frequency rate of change information, such as a first or second derivative, from a transmit beam radiated by satellite 10 as the satellite passes overhead or to the side of movable subscriber device 100, errors in frequency measurement have the least impact on the determination of angle φ.

Thus, movable subscriber device 100 is not required to possess extreme frequency accuracy in order to determine that satellite 10 has passed overhead or to the side of movable subscriber device 100. In FIG. 1, this corresponds to a location on strip of constant Doppler frequency shift 50. As the frequency measurement capability of movable subscriber device 100 increases, strip of constant Doppler frequency shift 50 reduces in width. For many paging applications, this provides sufficient geolocation for the efficient delivery of paging messages.

FIG. 4 illustrates a second derivative of a Doppler frequency with respect to angle φ of FIG. 3 in accordance with a preferred embodiment of the invention. In FIG. 4, it can be seen that the second derivative of a Doppler frequency shift, when taken with respect to angle φ, assumes a value of zero when angle φ assumes a value of zero. This technique is insensitive to frequency measurement errors inherent in any frequency generation or frequency measurement system. The significance of FIG. 4 will be appreciated by those skilled in the art as providing an indication of Doppler frequency crossover without requiring precise frequency measurement by movable subscriber device 100. Movable subscriber device 100 can obtain a precise indication that satellite 10 has crossed strip of Doppler frequency shift 50 without requiring accurate Doppler signal frequency measurement by the movable subscriber device.

FIG. 5 illustrates an angle θ which represents a beam scan angle measured in a side-to-side dimension perpendicular to the direction of motion of an orbiting satellite in accordance with a preferred embodiment of the invention. Satellite 10 of FIG. 5 moves in a direction coming out of the page. In FIG. 5, negative values of angle θ denote directions to the left of satellite 10, while positive values of angle θ denote directions to the right of satellite 10. The nadir direction of satellite 10 corresponds to the direction of θ=0.

FIG. 6 illustrates a change in time of arrival of information conveyed from an orbiting satellite with respect to angle θ of FIG. 5 in accordance with a preferred embodiment of the invention. In FIG. 6 it is evident that the shortest time required for a signal to travel from satellite 10 to movable subscriber device 100 occurs for values of θ=0. For angles which correspond to locations to the sides of the ground track of satellite 10, larger times of arrival result due to the additional distance from satellite 10.

From FIG. 6, it can be seen that delayed time of arrival (DTOA) information can provide an indication regarding θ that is necessary for geolocation from a single satellite, such as satellite 10. To remove the ambiguity of $\theta < 0$ or $\theta > 0$, a different signal should be broadcast by satellite 10. Through the transmission of an additional geolocation signal from satellite 10, the relative change in the delayed time of arrival can be assessed in order to determine whether the DTOA is increasing or decreasing. The ambiguity as to the polarity of angle θ can thus be removed.

FIG. 7 illustrates a second orbiting satellite moving in relation to the earth's surface in accordance with a preferred embodiment of the invention. In FIG. 7, satellite 20 moves substantially perpendicular to the satellite of FIG. 1. Although shown and discussed as moving substantially perpendicular to satellite 10, this is only intended to facilitate an understanding of the present invention and is not intended to be limiting. The only requirement on the orbital path of satellite 20 is that the orbital path be nonparallel to that of satellite 10.

As satellite 20 moves in an orbit substantially perpendicular to that of satellite 10 of FIG. 1, geolocation information similar to that transmitted by satellite 10 of FIG. 1 is radiated from satellite 20. This second transmission of geolocation information allows movable subscriber device 100 to locate itself in an area along strip of constant Doppler frequency shift 51. Additionally, as is the case for the moving satellite 10 of FIG. 1, movable subscriber device 100 can make use of the time of arrival information to further identify the location of movable subscriber device 100. When a second satellite, such as satellite 20 of FIG. 7 is used, DTOA information is not required in order to locate movable subscriber device 100.

In an alternate embodiment, satellite 20 moves in an orbit that is not substantially perpendicular to that of satellite 10. In this embodiment, strips of constant Doppler frequency shift 50 and 51 intersect at other than right angles. As the orbit of satellite 20 diverges from perpendicularity with the orbit of satellite 10, the area of intersection between strips of constant Doppler frequency shift encompass more area on the surface of the earth 30. In the limiting case, where satellites 10 and 20 move in parallel orbits, the second transmission of geolocation information from satellite 20 provides no significant capability for movable subscriber device 100 to refine its location since the strips of constant Doppler frequency shift 50 and 51 will not intersect.

FIG. 8 illustrates a satellite transmit antenna beam sweep from a maximum scan angle, θ_m, to a minimum scan angle in accordance with a preferred embodiment of the invention. In FIG. 8, satellite 10 positions an antenna and transmits the geolocation information beam beginning at an outer scan angle θ_m. The satellite initiates a transmission of timing information and scans the antenna beam to a minimum angle, such as $\theta=0$. In a preferred embodiment, geolocation beam 70 is scanned in a manner such that geolocation information is received at movable subscriber devices 101 and 102 which are at or near the earth's surface at substantially the same time. As geolocation beam 70 is scanned, timing information contained with geolocation beam 70 is updated at discrete angles between θ_m and $\theta=0$.

As can be seen from FIG. 8, movable subscriber device 102 is located at a substantially greater distance from satellite 10 than movable subscriber device 101. Therefore, as geolocation beam 70 is scanned from angle θ_m to $\theta=0$, geolocation information can be received by both movable subscriber devices 101 and 102 simultaneously in time. This allows timing information to be received simultaneously at all points on or near the earth's surface which lie between movable subscriber devices 101 and 102 which are within the scan range of satellite 10. Because the timing information is independent of path delay, movable subscriber devices 101 and 102 can use this signal to remove any timing offset error. With the removal of any offset errors, accurate time of arrival measurements can be made. Thus, a subsequent measurement of timing information from satellite 10 enables movable subscriber devices 101 and 102 to use DTOA from the satellite as discussed in relation to FIG. 6 as an indication of position. In a preferred embodiment, timing information from satellite 10 is used to update the internal clocks of movable subscriber devices 101 and 102. Therefore, when satellite 10 transmits a second timing signal, movable subscriber devices 101 and 102 can use DTOA to determine distance from satellite 10.

For a satellite at 850 km orbit, the relationship between scan angle θ and time T (in microseconds) can be approximated as:

$$T=(-3\times10^{-06})\theta^4 + 0.0003\theta^3 - 0.0099\theta^2 + 0.1223\theta + 4.9529$$

This equation specifies the amount of precorrection which satellite 10 desirably applies to the timing information transmitted from the satellite to a plurality of movable subscriber devices, such as 101 and 102. Thus, for larger values of angle θ, a correspondingly larger amount of precorrection is applied. For the case of angle θ being close to zero, such as for transmission to an area directly beneath satellite 10, the amount of precorrection is approximately equal to 4.95 microseconds.

FIG. 9 illustrates a method for geolocation of a movable subscriber device using dual satellites in accordance with a preferred embodiment of the invention. In step 200, a movable subscriber device is activated and placed in a receive state. This activation can be the result of a timer or other control element determining that a satellite is expected to pass within range of the movable subscriber device. Desirably, a satellite passes within communications range of the movable subscriber device approximately every 10 minutes according to the ephemeris of the satellite; however, more or less frequent satellite passes may occur according to the orbits chosen for a particular application. Although the method of FIG. 9 is optimized for Low Earth Orbit satellites, the method is applicable to larger intervals such as those intervals which are characteristic of Medium Earth Orbit satellites.

In step 210, a satellite communications node transmits a geolocation information signal to a movable subscriber device. In the event that the movable subscriber device does not receive the geolocation information signal from the satellite within the expected window, which can occur when the movable subscriber device has been moved to a new location, step 220 is executed. In step 220, the movable subscriber device remains in an activated state until a geolocation information signal is received.

When a geolocation information signal has been received, as in step 230, the movable subscriber device can develop an estimate of its current location, as in step 240. In step 240, the movable subscriber device makes an estimate of its location through the use of Doppler frequency shift and a derivative, or using time of arrival information. Thus, the movable subscriber device estimates its location relative to the path of a first satellite communications node. When this estimate has been made, the movable subscriber device registers a new position through a transmission to the orbiting satellite, as in step 250. Note that the movable subscriber device may optionally wait for the second transmission before reregistering to provide increased accuracy. For this case, step 250 is not executed.

After completing the calculation of a new position, as in step 240, and optional registration, as in step 250, the movable subscriber device then executes step 260 which includes waiting for a second geolocation information signal. When this signal has been received from a second satellite communications node, as in step 270, the movable subscriber device executes step 280, where it refines the previous estimate of its current location. In step 290, a registration is performed by transmitting the current location to the satellite communications node. The device then returns to a sleep mode, as in step 300, and the process returns to step 200.

In the event that the movable subscriber device receives the transmission from the satellite within the expected window of step 210, then no registration transmission to the satellite is made, since the movable subscriber device can be assured that it has not been moved to a new location. Step 300 is then executed, where the device returns to a sleep mode. The process then returns to step 200.

FIG. 10 illustrates a movable subscriber device in accordance with a preferred embodiment of the invention. In FIG. 10, signals are received through antenna 110 and conveyed to receiver 120. Receiver 120 functions to convert signals received from first and second moving communications nodes through antenna 110 to baseband. These baseband signals are then interpreted through processor 130. Subscriber data, such as text or other information, is presented to the user through display 170. Signaling data, such as geolocation and timing information, is used by processor 130 to develop an estimate of its location. This signaling data can comprise Doppler frequency and timing information signals. Processor 130 is coupled to memory 140, which stores a past estimate of the location of the movable subscriber unit. In a preferred embodiment, these estimates are in the form of indications that either a first or second moving communications node has passed overhead.

Movable subscriber device 100 also comprises timer 160, which functions to alert processor 130 and receiver 120 that a predetermined interval of time has elapsed. In a preferred embodiment, this predetermined interval is determined in accordance with the ephemeris for the satellite constellation. When processor 130 determines that movable subscriber device 100 has changed locations, acknowledge messages are generated and transmitted through transmitter 150 and antenna 110.

In conclusion, a method and apparatus for geolocation using dual satellites facilitates the accurate location of an earth-based movable subscriber device. This function is performed by the movable subscriber device without requiring the movable subscriber device to maintain accurate timing or frequency references. Additionally, the receive function of the movable subscriber device does not need to be activated at all times. The resulting system provides guaranteed delivery of messages from the orbiting communication satellite while minimizing costs to subscribers.

Accordingly, it is intended by the appended claims to cover all modifications of the invention that fall within the true spirit and scope of the invention.

CLAIMS

What is claimed is:

1. In a communication system comprising a first and second satellite and a movable subscriber device, said first and second satellites moving in nonparallel paths, a method of geolocating said movable subscriber device comprising the steps of:

said movable subscriber device receiving a signal from said first satellite;

said movable subscriber device developing an estimate of an area wherein said movable subscriber device is located;

said movable subscriber device receiving a signal from said second satellite; and

said movable subscriber device refining said estimate of the area wherein said movable subscriber device is located.

2. The method of claim 1 wherein said developing step additionally comprises the step of using a derivative of a Doppler frequency shift to develop said estimate.

3. The method claim 1 wherein said developing step additionally comprises the step of using a delayed time of arrival to develop said estimate.

4. A movable subscriber device, comprising:

a timer which activates said movable subscriber device at a predetermined interval;

a receiver responsive to said timer which receives timing information from a first and second moving communications nodes; and

a processor which determines an estimate of a location of said movable subscriber device based on said timing information from said first and second moving communications node.

5. The movable subscriber device of claim 4 further comprising a transmitter which conveys said estimate of said location of said movable subscriber device to one of said first and second moving communications nodes.

6. The movable subscriber device of claim 4 further comprising a memory unit which stores a past estimate of a location of said movable subscriber device.

7. The movable subscriber device of claim 4 wherein said processor additionally determines a derivative of a Doppler signal received from said first moving communications node.

8. The movable subscriber device of claim 4, wherein said predetermined interval corresponds to time periods during which said movable subscriber device receives signals from said first and second moving communications nodes according to an ephemeris for said first and second moving communications nodes.

9. The movable subscriber device of claim 4, wherein said processor initiates a registration based on a distance which said movable subscriber device has moved.

10. A method of conveying timing information from an orbiting communications node to a plurality of receiving stations dispersed on or near the surface of the earth which allows said plurality of receiving stations to simultaneously receive said timing information, said method comprising:

positioning an antenna toward a maximum scan angle of said antenna;

initiating a transmission from said antenna; and

scanning said antenna toward a minimum scan angle in a manner which allows said timing information to be received substantially simultaneously at said plurality of receiving stations.

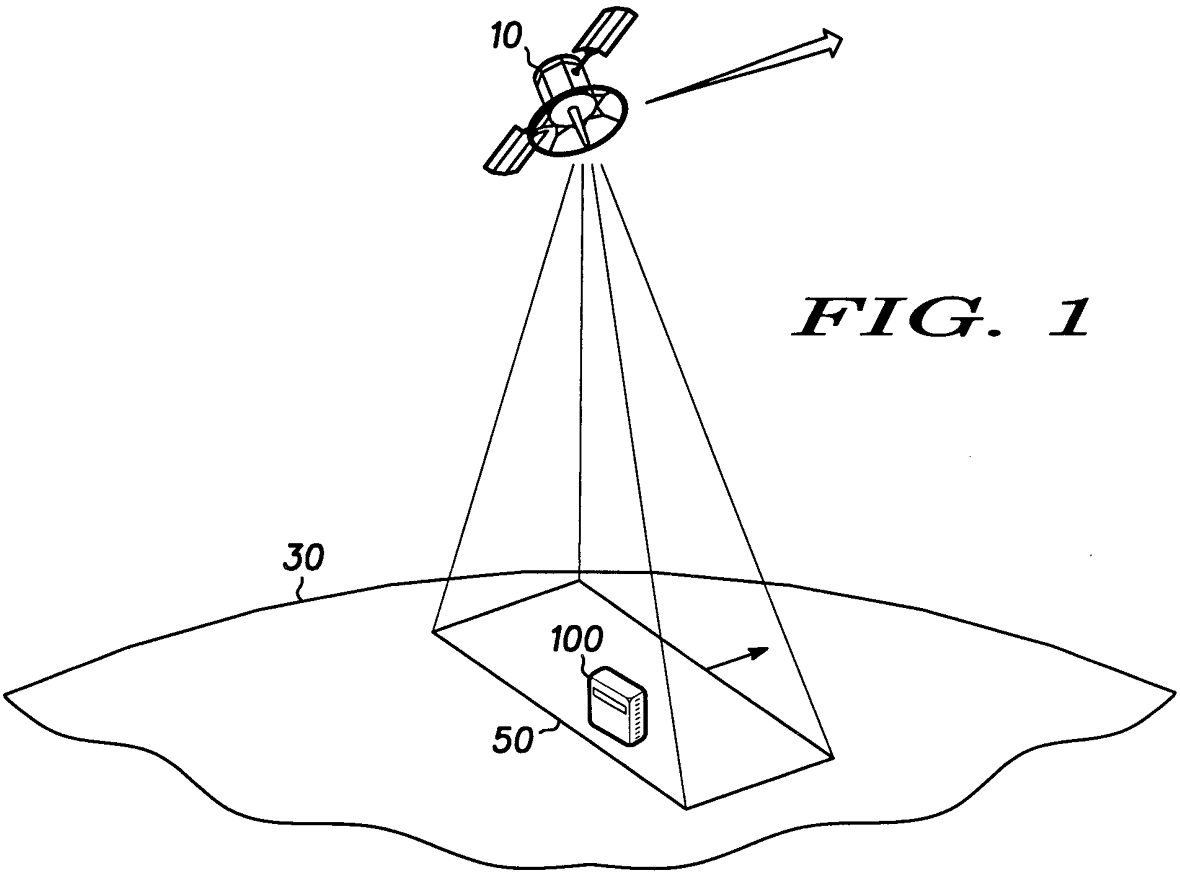

FIG. 1

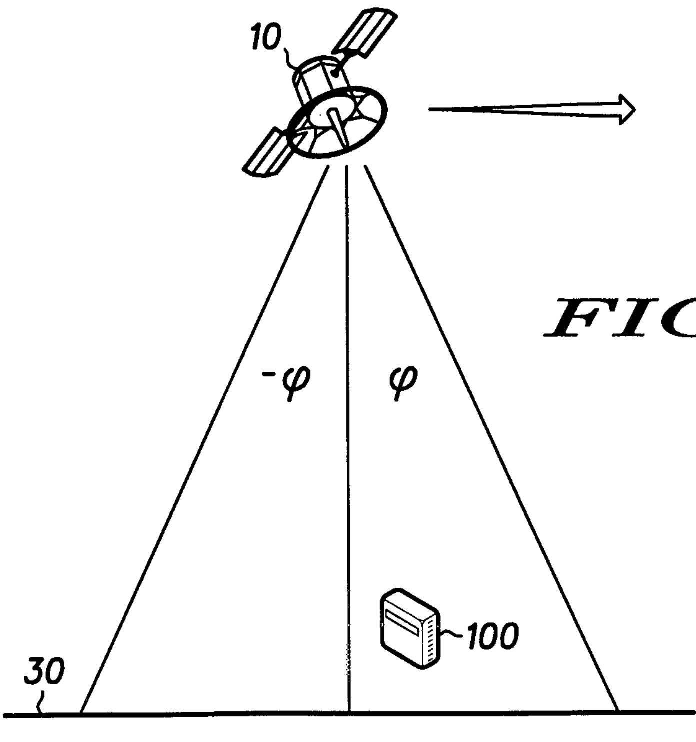

FIG. 2

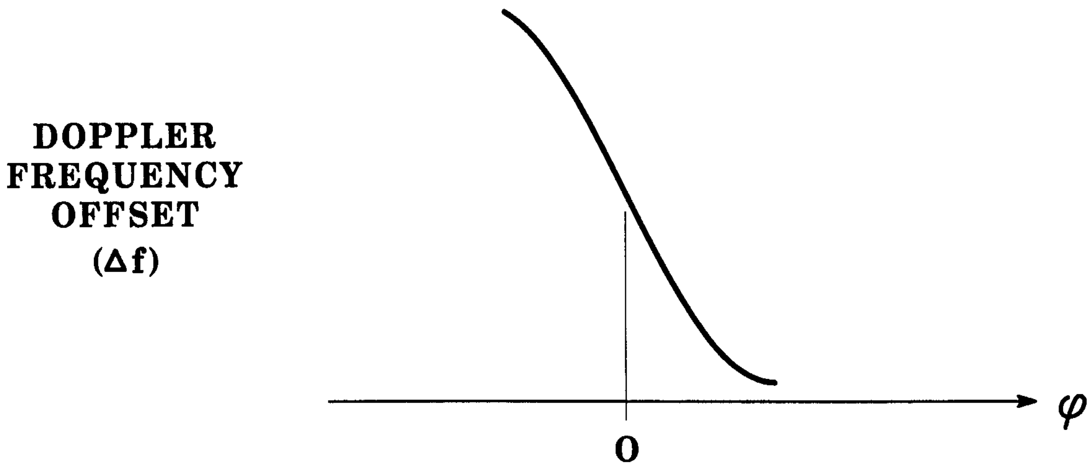

FIG. 3

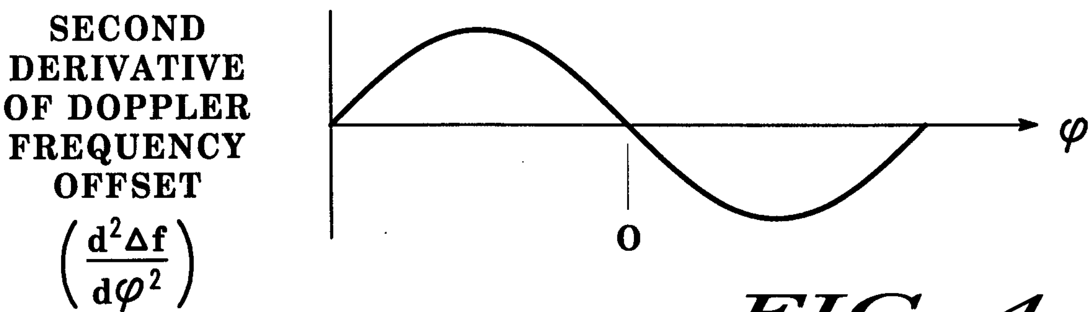

FIG. 4

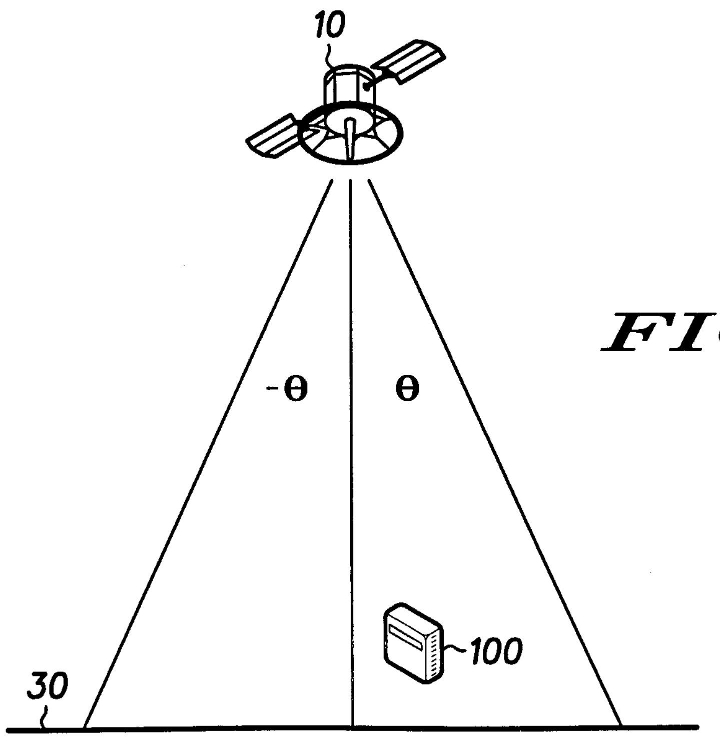

FIG. 5

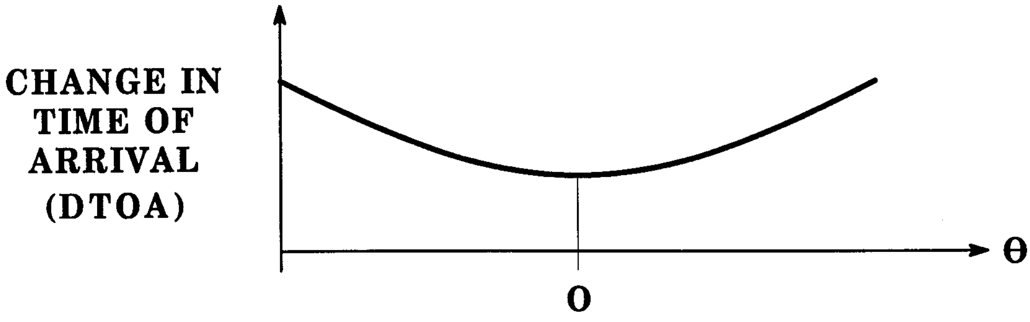

FIG. 6

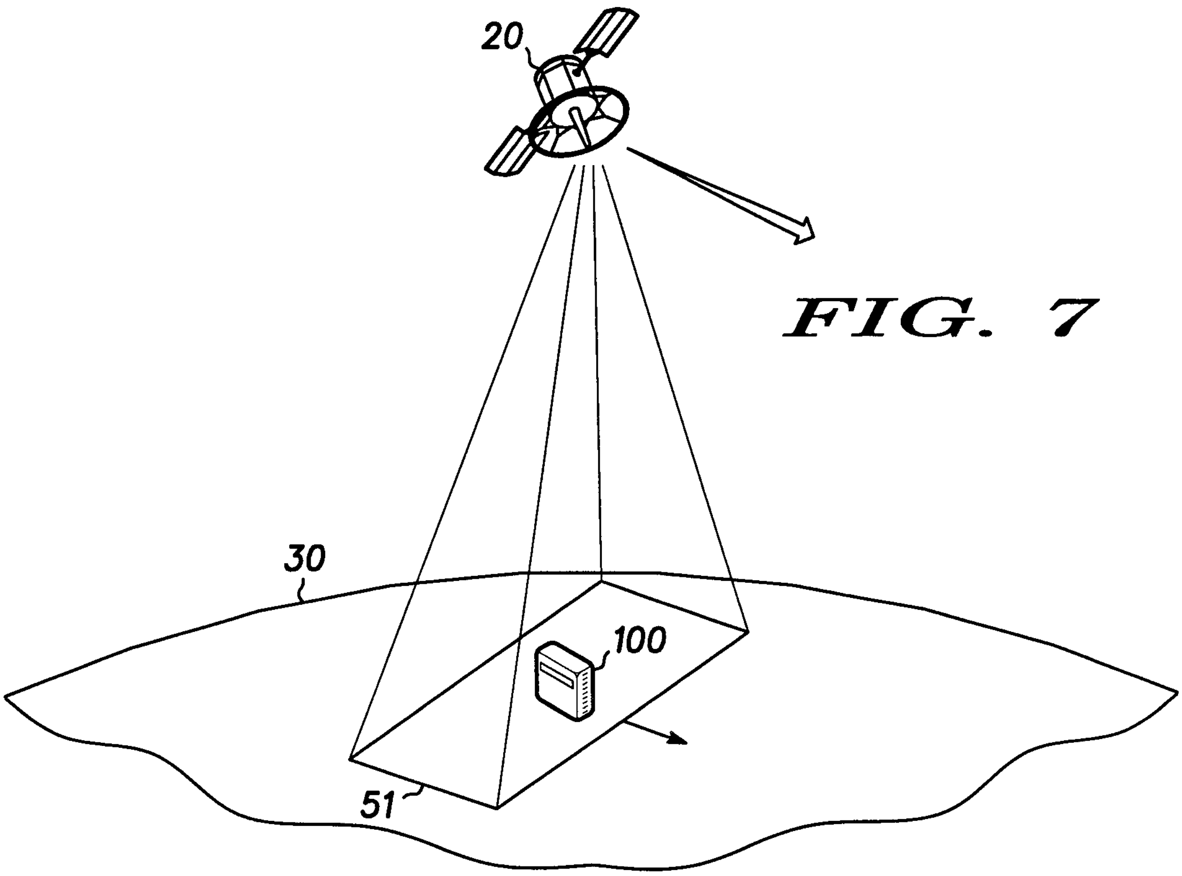

FIG. 7

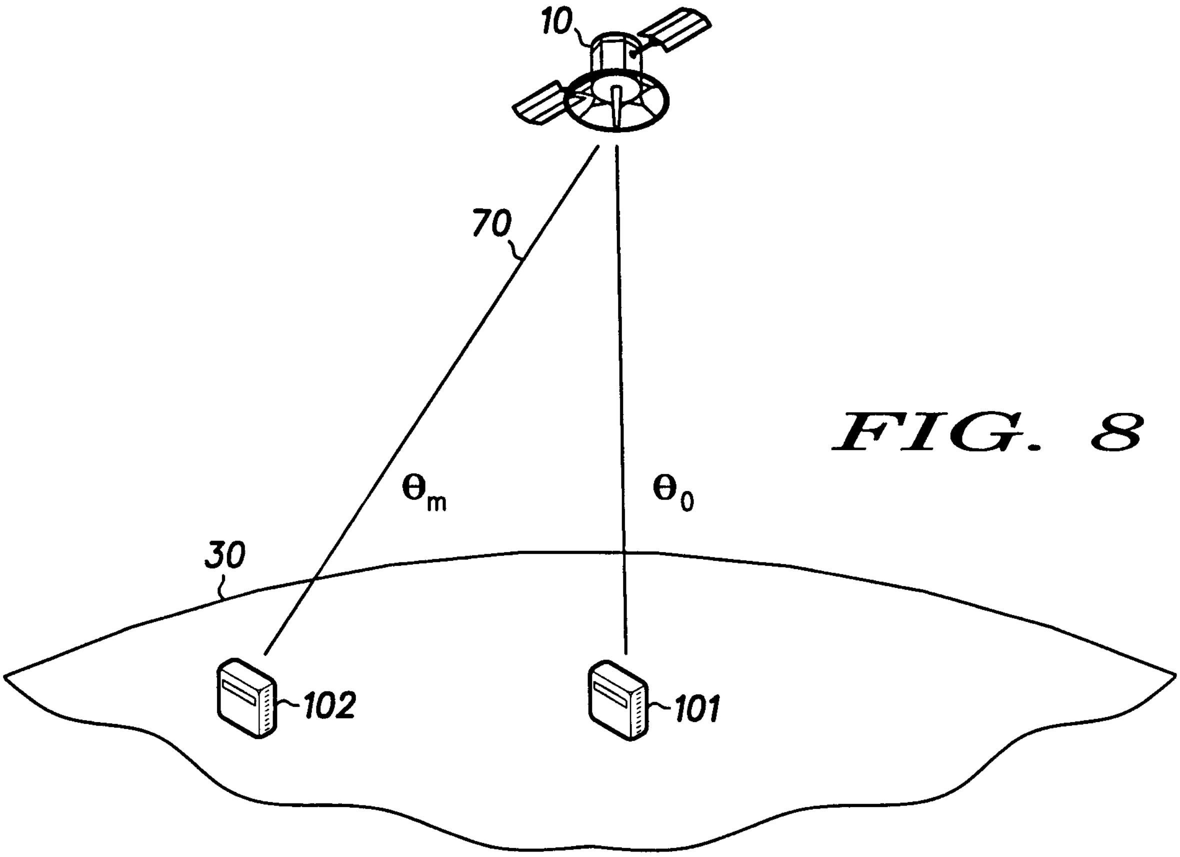
10
70
θ_m
θ_0
30
102
101

FIG. 8

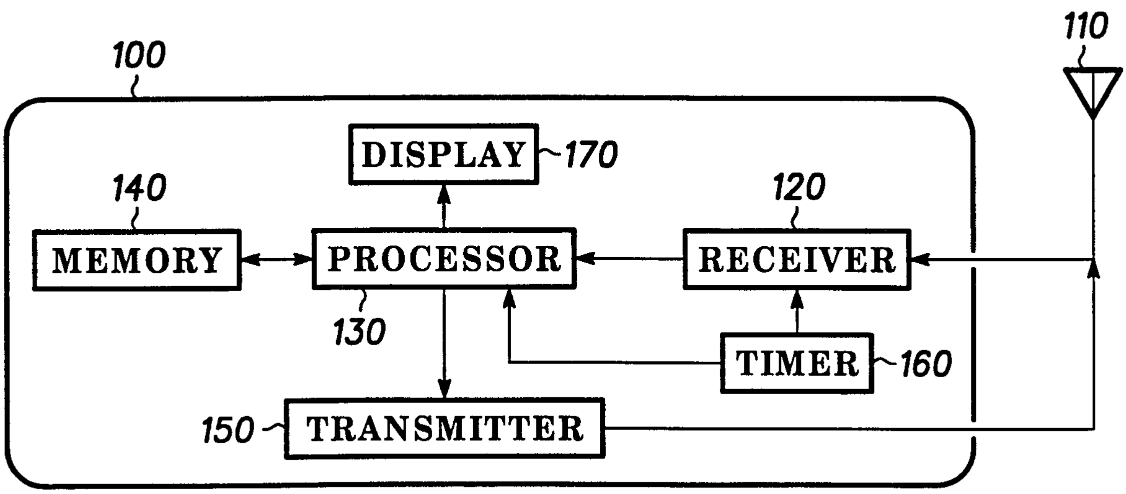
100
110
DISPLAY
170
140
MEMORY
PROCESSOR
130
120
RECEIVER
TIMER
160
150
TRANSMITTER

FIG. 10

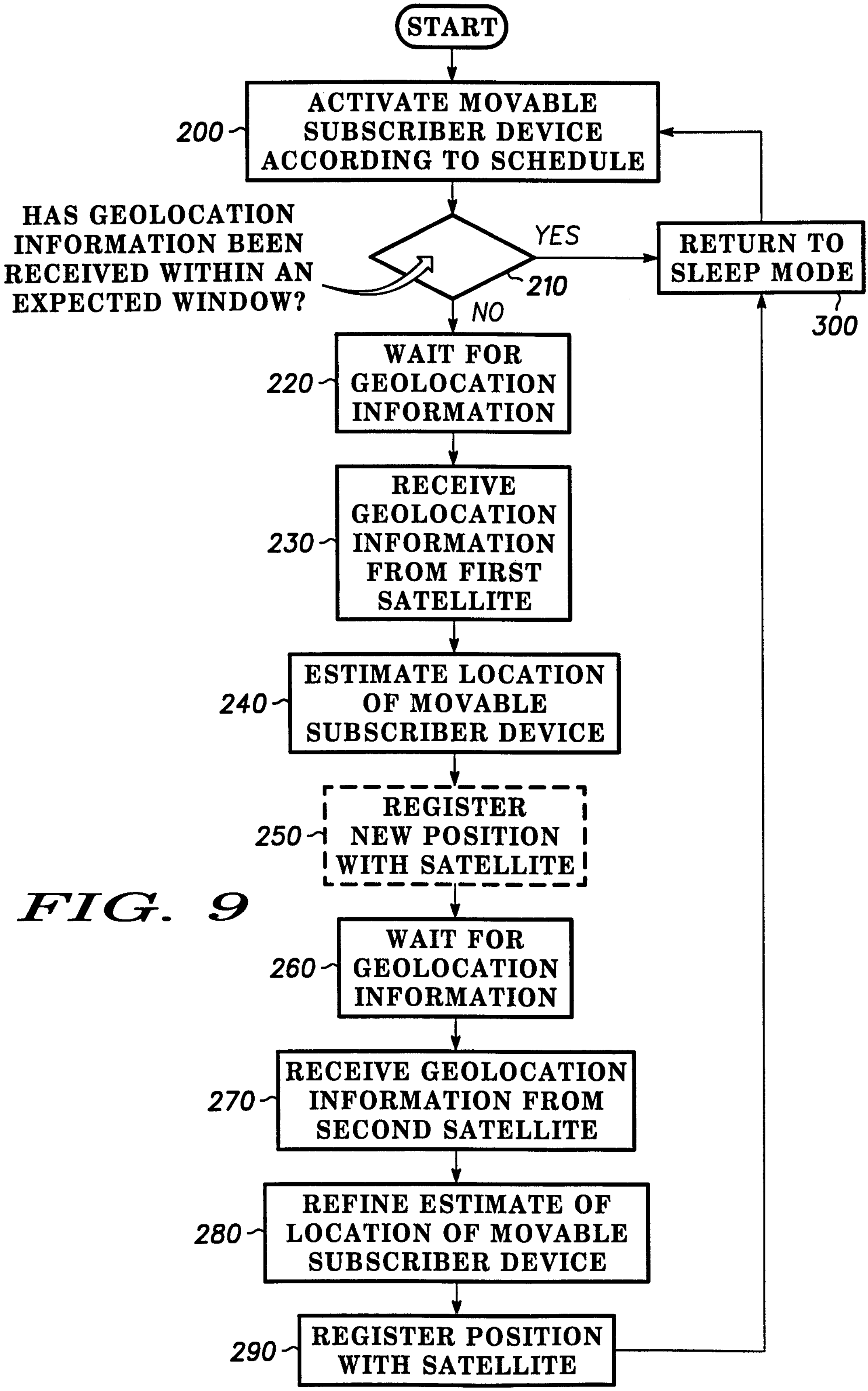
START
200
ACTIVATE MOVABLE SUBSCRIBER DEVICE ACCORDING TO SCHEDULE
HAS GEOLOCATION INFORMATION BEEN RECEIVED WITHIN AN EXPECTED WINDOW?
210
YES
NO
RETURN TO SLEEP MODE
300
220
WAIT FOR GEOLOCATION INFORMATION
230
RECEIVE GEOLOCATION INFORMATION FROM FIRST SATELLITE
240
ESTIMATE LOCATION OF MOVABLE SUBSCRIBER DEVICE
250
REGISTER NEW POSITION WITH SATELLITE
260
WAIT FOR GEOLOCATION INFORMATION
270
RECEIVE GEOLOCATION INFORMATION FROM SECOND SATELLITE
280
REFINE ESTIMATE OF LOCATION OF MOVABLE SUBSCRIBER DEVICE
290
REGISTER POSITION WITH SATELLITE

FIG. 9