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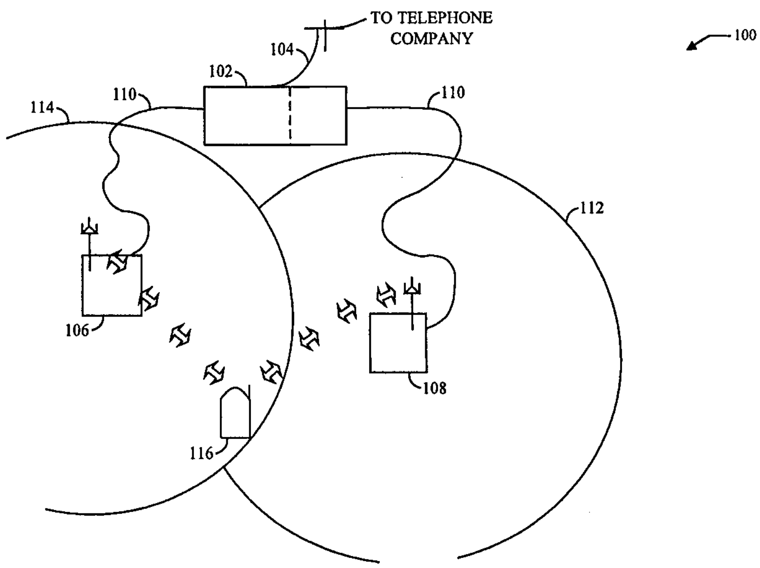

(57) Abstract

A method and apparatus to determine the position (116) of a remote station, such as a mobile cellular telephone using relative delay and absolute–range measurements. More particularly, the invention determines the position of a remote station (116) using a combination of forward link measurements made at the remote station (116) and reverse link measurements made at one or more base stations (106, 108). These measurements are used to perform calculations that yield the position of the remote station (116). An apparatus performing the calculations may use a–priori information on the exact location of all base stations participating in the mobile location determination, as well as inherent delay calibrations associated with the base stations.

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METHOD AND APPARATUS FOR DETERMINING THE POSITION OF A CELLULAR TELEPHONE

BACKGROUND OF THE INVENTION

I. Field of the Invention

Generally, the present invention relates to determining the location of a cellular telephone using forward and reverse link measurements. More particularly, the invention relates to a method to determine the position of a wireless mobile telephone - used in a code division multiple access system - using a combination of forward link measurements made at the mobile phone and reverse link measurements made at one or more base stations.

II. Description of the Related Art

The use of code division multiple access (CDMA) modulation techniques is one of several techniques used for wireless communications in which a large number of wireless telephone users are present. Standard terminology and methods for providing CDMA mobile communications in the United States were established by the Telecommunications Industry Association in TIA/EIA/IS-95-A entitled "Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System", generically referred to as IS-95.

A detailed discussion of the actual use of a CDMA wireless communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING SIGNAL WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM." These patents are assigned to the assignee of the present invention and are incorporated herein by reference.

In both of these patents, a multiple access technique is disclosed in which a large number of mobile phones - also referred to as remote stations, where each remote station has a transceiver – are used and communicate with other remote stations or other types of stations through satellite repeaters or terrestrial base stations using CDMA spread spectrum communication signals.

A terrestrial base station, also referred to as a base station, commonly receives communication signals from a remote station over a wireless *reverse* link and transmits communication signals to a remote station over a wireless *forward* link. The area over which a communication may be successfully transmitted by a base station and received by a remote station is referred to as a cell.

One problem with wireless remote stations is that the location of the remote station is not known when it is sending to and receiving signals from a base station. If a remote station user makes a 911 emergency call, assistance can not be sent to the user unless the user knows the exact location from which he or she is calling. Because of this problem, location technologies have been given high priority. Further, regulatory forces and phone service carriers' desires to enhance revenues by offering superior services than those of competitors have fueled location technology developments. For example, in June 1996, the Federal Communications Commission (FCC) mandated support for enhanced emergency 911 service, designated E-911, and mandated that the location of the cellular transceiver be sent back to a designated public safety answering point. To comply with the FCC mandate, at least 77,000 sites in the United States alone are to be equipped with automatic location technologies by the year 2005.

Several techniques are currently known to provide some degree of automatic location capability. One technique, disclosed in U.S. patent number 5,646,632, titled "Methods and Apparatus for a Portable Communication Device to Identify Its Own Location," invented by K.H. Khan, et al and assigned to Lucent Technologies, involves measuring the relative delays of communication signals sent from at least three base stations and received by a remote station. These signals are used to determine a range difference between the various base stations and the remote station. Unfortunately, an increase in transmission power in the reverse link is usually also required due to the fact that in a typical wireless system, each telephone transmits the minimum required power to send a communication to a single receiving base station. For three base stations to receive the signal, the remote stations transmission power needs to increase over the favored level. Further, the extrapolation techniques used require communication with at least three base stations, requiring the concentration of cell sites to be increased or, as mentioned above, the transmission power of each remote station to be increased.

This type of location technology has significant drawbacks. Increasing the number of base stations is extremely expensive. Alternatively, increasing remote station transmission power increases the likelihood of interference between remote stations, and may require additional hardware to be added to the remote station. Lastly, these known techniques do not appear to offer the accuracy required by the FCC mandate.

What is needed is a method and apparatus that can determine the location of a remote station by taking measurements from the forward and reverse links connecting a remote station with a minimum number of base stations. The invention should at least be compatible with CDMA modulated communication systems, and preferably also be compatible with the other communication techniques used in large mobile communication systems, such as time division multiple access (TDMA), frequency division multiple access (FDMA), and amplitude modulation (AM) techniques.

SUMMARY OF THE INVENTION

Broadly, the present invention determines the position of a remote station, such as a mobile cellular telephone, using a combination of forward link measurements made at the remote station and reverse link measurements made at one or more base stations. The forward link measurements are taken from signals transmitted from two or more base stations and received by the remote station. More particularly, the invention relates to a method, apparatus and article of manufacture used to determine the position of a remote station using a combination of measurements, such as the relative delay from two or more base stations and round-trip-delay of a communication made between the remote station and one or more base stations. These measurements are used to perform calculations that yield the position of the remote station. The apparatus performing the calculations may use a-priori information on the exact location of all base stations participating in the mobile location determination, as well as inherent delay calibrations associated with the base stations.

One embodiment of the invention provides a <u>method</u> to determine the position of a remote station using a combination of forward link measurements made at the remote station, with reverse link measurements made at one or more base stations. The forward link measurements are taken from signals transmitted from two or more base stations and received by the remote station. These measurements include at least one round-trip-delay for a communication made between the remote station and a base station, and relative delay measurements taken at the remote station. The measurement results are received at a central processing station – also referred to as a "primary" base station, where a primary base station is the base station primarily handling the communication initiated by the remote station. The central processing station performs calculations to determine the remote station position, and may use a-priori information on the exact location of all the participating base stations, as well as the delay calibrations, if any, associated with such base stations.

In another embodiment, the invention may be implemented as an apparatus used to determine the position of a remote station using the combination of forward link and reverse link measurements. The apparatus may include processors, controllers, data storage, receivers, transmitters, and a variety of other hardware depending upon the configuration for each embodiment. In another embodiment, the invention may comprise an article of manufacture, such as a digital signal bearing medium, tangibly embodying machine-readable instructions executable by a digital processing apparatus and used to determine the position of the remote station using the combination of forward and reverse link measurements.

The invention provides its users with numerous advantages. One advantage is that the number of base stations required to locate the remote station is reduced. Another advantage is that if three or more base stations are used to locate the remote station, the location may be determined to a greater certainty than the location provided using prior art methods. Yet another advantage is that using the round-trip-delay measurement in determining the location of the remote station improves, sometimes dramatically, the geometric dilution of precision for a given set of base stations. As discussed below, good geometric dilution of precision means that the effect of any measurement error on position is small and often negligible.

Lastly, the invention further provides a number of other advantages and benefits that should become even more apparent to one schooled in the art after reviewing the following detailed descriptions of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The nature, objects, and advantages of the invention will become more apparent to those skilled in the art after considering the following detailed description in connection with the accompanying drawings, in which like reference numerals designate like parts throughout, and wherein:

FIGURE 1 is a block diagram of hardware components and interconnections of a telecommunications system incorporating wireless links in accordance with one embodiment of the invention;

FIGURE 2 is an illustration of an article of manufacture pursuant to the invention;

FIGURE 3 shows a block diagram depicting the general operating steps used to control the operational characteristics of an apparatus such as shown in Figure 1 in accordance with one embodiment of the present invention;

FIGURE 4 is a block diagram of further defining method step 308, shown in Figure 3; and

FIGURES 5-14 illustrate performance characteristics in accordance with one embodiment of the present invention and includes comparisons with known prior art.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGURES 1 through 4 illustrate examples of the various apparatus, article of manufacture, and method aspects of the present invention. Figures 5-14 illustrate performance characteristics for one embodiment of the present invention and compares these characteristics to other known methods. For ease of explanation, but without any limitation intended, these examples are described in the context of a digital telecommunication system incorporating wireless links, one example of which is described below.

HARDWARE COMPONENTS AND INTERCONNECTIONS

Figure 1 illustrates one type of telecommunications system 100 including wireless links as used in the present invention. Basically, a communication, typically a telephone call or data transfer such as a facsimile, is sent from a telephone via a telephone company's link 104 to a base station controller (MSC)

102. The MSC 102 generally comprises hardware known in the art and used to perform switching functions. These switching functions are used to coordinate the transfer of one or more communications to a remote station 116. The link 104 may comprise any type of communication link known in the art for transporting an information signal, such as a wireless link, a fiber optic cable, or copper or aluminum wire. The MSC may include a transceiver sub-system referred to as a base station or BS. The BS --such as BS 106 or 108-- provides a radio link between a remote unit 116 and the MSC 102.

Regardless, the BS also provides a signal generation protocol, such as CDMA or TDMA, or any of the types mentioned above, whereas a MSC provides switching functions to coordinate the receipt and continued transfer of a communication to a remote station 116. As used in this application, a remote station 116 refers to all types of telecommunication units, generically referred to as telephones, using a wireless link as a primary means for transferring a communication, such as a cellular, mobile, portable, wireless local loop, or subscriber unit. As such, the remote station comprises a transceiver unit and other circuitry well known in the art and used to receive and transmit a communication. The remote station may include a processor – configured in part to calculate desired information as discussed in the method section below - and storage, both used to measure designated characteristics of a communication, such as the relative delay of a signal received from a base station. This information, or a representative value, may be transmitted to a base station.

MSC 102 may be coupled to a base station such as BS 106 or 108 by a link 110. Link 110 may be of the same or similar construct as link 104. The BS may include a processor and storage used to measure selected communication characteristics, such as any delay (D) between the time a communication is sent to and a responsive communication is received from a remote station 116. When a designated BS receives a communication to be transmitted, the BS attempts a radio link between the BS and the remote unit 116. However, each BS has a limited range, as shown by area 114 for BS 106, and area 112 for BS 108. If the remote unit 116 is located within the transmission range of BS 106 and BS 108 as shown, then both BSs may transmit signals that are received by the remote station 116. If remote station 116 moves out of area 114 and is still within area 112, then BS 106 may discontinue transmitting a signal intended for remote station 116.

As remote station 116 moves out of area 114 and into area 112, the call must be transferred or "handed-off," to BS 108 from BS 106. Hand-offs are generally divided into two categories- hard handoffs and soft handoffs. In a hard handoff, when a remote station leaves an origination base station, such as BS 106, and enters a destination base station, such as BS 108, the remote station breaks its communication link with the origination base station and thereafter establishes a new communication link with the destination base station. In soft handoff, the remote station completes a communication link with the destination base station prior to breaking its communication link with the origination base station. Thus, in soft handoff, the remote station is redundantly in communication with both the origination base station and the destination base station for some period of time.

Soft handoffs are far less likely to drop calls than hard handoffs. In addition, when a remote station travels near the coverage boundary of a base station, it may make repeated handoff requests in response to small changes in the environment. This problem, referred to as ping-ponging, is also greatly lessened by soft handoff. The process for performing soft handoff is described in detail in U.S. Patent No. 5,101,501, entitled "METHOD AND SYSTEM FOR PROVIDING A SOFT HANDOFF IN COMMUNICATIONS IN A CDMA CELLULAR TELEPHONE SYSTEM," and U.S. Patent No. 5,267,261, entitled "MOBILE STATION ASSISTED SOFT HANDOFF IN A CDMA CELLULAR COMMUNICATIONS SYSTEM", both of which are assigned to the assignee of the present invention and incorporated by reference herein. In the system of the '261 patent, the soft handoff process is improved by measuring the strength of "pilot" signals transmitted by each base station at the remote station. These pilot strength measurements assist in the soft handoff process by facilitating identification of viable base station handoff candidates.

A fuller discussion concerning the processing of signals for transmission in a telecommunications system may be found in Electronic Industry Association standard TIA/EIA/IS-95 entitled "Mobile Station-Based Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular Systems, and other transmission standards well known in the art.

Despite the specific foregoing descriptions, ordinarily skilled artisans having the benefit of this disclosure will recognize that the apparatus discussed above may be implemented in a telecommunications system of different construction without departing from the scope of the present invention. As a specific example, a BS may be integral to BSC 102, or a public switched telephone network, commonly referred to as a PSTN, may be included in the system.

OPERATION

In addition to the various hardware embodiments described above, a different aspect of the invention concerns a *method* for determining the position of a remote station. Such a method may be implemented, for example, by operating a digital signal processor (not shown) to execute a sequence of machine-readable instructions. These instructions may be inherent to the processor or may be contained within one or more data storage units coupled to the processor.

Data Storage Unit

The sequence of machine-readable instructions may reside in whole or in part in various types of data storage units. As such, one aspect of the present invention concerns an article of manufacture comprising a data storage medium tangibly embodying a program of machine-readable instructions executable by a processor, such as a digital signal processor, to perform method steps to determine the position of a remote station using a relative delay and a RTD measurement, as discussed below, for a communication made between the remote station and two or more base stations.

The data storage medium may comprise, for example, memory units contained within the base station 106. These memory units may be located in whole or part within the controller 102 or the remote station 116, or any other location within communicative access with the telecommunications system 100. Alternatively, the instructions may be contained within another type of data storage medium, such as a magnetic storage diskette 200 (Figure 2), or any other type of data storage medium, such as a direct access storage device (DASD), electronic read-only storage (CD-ROM or WORM), or even paper punch cards. Further, the machine-readable instructions may comprise lines of compiled "C-type" or other source code language.

Overall Sequence of Operation

Figure 3 shows a basic method 300 for determining the position of a remote station 116 using the present invention. Figure 4 shows step 308 of the basic method 300 in greater detail, providing a method for position determination using the relative delay and a RTD measurement for communication exchanged between the remote station 116 and at least two base stations, shown as base stations 106 and 108 in Figure 1.

The method 300 shown in Figure 3 starts at task 302 when forward link measurements for a communication are made at the remote site 116 shown in Figure 1. In this context and as discussed above, the forward link is the wireless communication link between a BS and the remote station 116. These measurements yield in task 304 the relative delays of communication signals received by the remote station 116 from two or more BSs, such as base stations 106 and 108. The relative delays correspond to a range-difference between the various BSs and the remote station 116.

In task 306, at least one RTD measurement - taken for a communication between a serving base station and remote station 116 - is added to the relative delays of task 304. This RTD measurement is inherently available at the serving base station, that is, a base station in communication with the remote station 116. Each RTD measurement corresponds to a measured absolute-range between the remote station 116 and the serving base station, and is defined in one embodiment as RTD=D*C/2. If the remote station 116 is in hand-off mode, additional RTD measurements are available for communications made between the remote station 116 and other base stations. These additional measurements may be used in other embodiments of the invention to calculate the position of the remote station 116 and refine the location accuracy as discussed below.

The position calculations are made at a base station in one embodiment of the invention. However, in other embodiments, the position calculation may be made at any location having access to the relative delay and RTD measurements, such as the controller 102 shown in Figure 1. Assuming the position calculation occurs at BS 106, the base station receives all available RTD measurements from the other base stations, as well as relative delay measurements from the remote station 116. In this embodiment, the remote station 116 does not store base station information, such as the location of a BS, or delay calibrations, and does not perform the position calculations. Usually it is the communications system 100 that needs to know the phone position (e.g., for 911 calls), therefore a base station makes the position determination. If needed, the calculated position can be transmitted to the remote station 116.

In other embodiments, the remote station 116 may store some or all of the measurement information, or may perform some or all of the calculations required to determine its location, thereby making the position determination more efficient, hence faster. For example, the remote station 116 may perform some processing in order to average and reduce the many repetitions of the relative delay measurements into a representative relative delay value for each base station. This "pre-processing" helps reduce any measurement error and allows transmitting the minimum necessary information to the serving base station. A less desirable alternative is for the remote station 116 to transmit to the serving base station the repetitious raw relative delay measurements.

As discussed with respect to Figures 4-14, using a RTD measurement improves -sometimes dramatically over prior art methods - a Geometric Dilution of Precision (GDOP) for a set of base stations. Good GDOP minimizes the affect any measurement errors may have on determining position location for a remote station. This RTD measurement reduces the minimum number of base stations required to determine the location of the remote station 116, and reduces ambiguity inherent in determining the location using two or more base stations. For example, in one embodiment, two base stations are required for a location with minor ambiguity. In another embodiment, three base stations are required for an "all-but" or ambiguity-free location.

<u>Calculating GDOP</u>

The location of a remote station may be anywhere within a three-dimensional area defined by the cells of the base stations, such as areas 114 and 116 for BSs 106 and 108, respectively, shown in Figure 1. To make the position determination 308 as detailed in Figure 4 using a minimal set of measurements, a two-dimensional scenario is assumed in task 402 where the base stations and the remote station are all in the same horizontal plane. This plane has an eastward coordinate x and a northward coordinate y. Unless the remote station or a base station is very high off the ground with respect to the other, this two-dimensional scenario works very well.

The forward link relative delay measurements yield what is known as pseudo-ranges in task 404. These pseudo-ranges are used extensively in global positioning system (GPS) methods and are well known in the art. Using pseudo-ranges, the location of a remote station is fixed by a vector, the vector defined by coordinates x and y, and a range bias δ. This vector may be expressed as $\boldsymbol{\theta} = [x \ y \ \delta]^T$, where $[\ ]^T$ indicates the transpose of a matrix.

The measurements available from the relative delays yield pseudo-range measurements. Assuming a noise-free environment, the relationship between the noise-free pseudo-range measurement to an ith BS and the three unknowns of the vector defined above is given by

$$PR_i = R_i + \delta \quad , \quad i = 1, \ldots, N$$

where

$$R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad , \quad i = 1, \ldots, N$$

and x_i and y_i are the coordinates of the ith BS, and N is the total number of BSs used. An RTD measurement associated with a first BS yields a true range to the first BS. Assuming a noise free environment, the relationship between a RTD measurement and the location of a remote station may be given by

$$RTD = \sqrt{(x - x_1)^2 + (y - y_1)^2}$$

The partial derivatives of the above calculations with respect to the three unknowns – x, y, and δ are determined in task 406:

$$\frac{\partial PR_i}{\partial x} = \frac{x - x_i}{R_i} \quad ; \quad \frac{\partial PR_i}{\partial y} = \frac{y - y_i}{R_i} \quad ; \quad \frac{\partial PR_i}{\partial \delta} = 1 \quad ;$$
$$\frac{\partial RTD}{\partial x} = \frac{x - x_1}{R_1} \quad ; \quad \frac{\partial RTD}{\partial y} = \frac{y - y_1}{R_1} \quad ; \quad \frac{\partial RTD}{\partial \delta} = 0$$

In task 408, a derivative matrix H is arranged where:

$$\mathbf{H} = \begin{bmatrix} \frac{\partial PR_1}{\partial x} & \frac{\partial PR_1}{\partial y} & \frac{\partial PR_1}{\partial \delta} \\ \frac{\partial PR_2}{\partial x} & \frac{\partial PR_2}{\partial y} & \frac{\partial PR_2}{\partial \delta} \\ \vdots & \vdots & \vdots \\ \frac{\partial PR_N}{\partial x} & \frac{\partial PR_N}{\partial y} & \frac{\partial PR_N}{\partial \delta} \\ \frac{\partial RTD}{\partial x} & \frac{\partial RTD}{\partial y} & \frac{\partial RTD}{\partial \delta} \end{bmatrix}$$

A GDOP may be obtained in task 410 from the first two diagonal elements of a matrix G defined as:

$$\mathbf{G} = \left(\mathbf{H}^{T}\mathbf{H}\right)^{-1}$$

and

$$\text{GDOP} = \sqrt{\mathbf{G}_{11} + \mathbf{G}_{22}}$$

GDOP can be easily converted to random positioning error standard deviation (STD), if it is assumed that any random measurement errors are independent and identically distributed (iiD) with an error STD of σ_R. In that case, the STD of the horizontal positioning error is simply GDOP $\cdot\, \sigma_R$.

In another embodiment, the N pseudo-range measurements may be replaced with the N-1 range-difference measurements and eliminate δ from the unknown vector, yielding substantially similar positioning results. However, this substitution makes the GDOP calculation more complex because the errors in the range-difference measurements are not independent. Therefore, the calculation of the matrix G involves a non-diagonal error covariance matrix.

Once the GDOP has been calculated, the position of the remote station is determined in task 412 using iterative least-squares algorithms. This algorithmic technique is well known in the art. The method ends in task 414.

GDOP Contour Maps – Equilateral Triangle Arrangement

To help understand the important accuracy improvements of the present invention over the prior art, and to highlight the contribution of using one or more RTD measurements, contour maps of the GDOP are shown in Figures 6-8, and 10-14. The first example uses three base stations arranged in an equilateral triangle as shown in Figure 5. For comparison purposes, the contour map of

Figure 6 represents a remote station position solution using only relative delays (pseudo-ranges) as suggested in the prior art, such U.S. patent No. 5,646,632 referenced above. The contour map of Figure 7 represents a solution using relative delays plus one RTD , according to our method.

Comparing Figure 7 to Figure 6, significant GDOP improvements are shown outside a hypothetical triangle (not shown) connecting the three base stations, and near the base stations. For example, at 6000N by 6000E, the prior art yields a value of 6. The present invention produces a value of 1.9. This improvement is even more dramatic when only two base stations, such as BS #1 and #2 of Figure 5, are available. The prior art method fails completely while the present invention yields reasonable accuracy, over a large area, with slight ambiguity due to the symmetry relative to a hypothetical line (not shown) connecting the two base stations (baseline). The GDOP contours for the present invention when there are only two base stations in communication with the remote station are shown Figure 8. For example, the presence of only two base stations still yields large areas with a GDOP smaller than 2.5 on both sides of the baseline. In the above example, at 6000N by 6000E the GDOP increases slightly – to approximately 2.3 – from the three base station resolution of 1.9 shown in Figure 7.

<u>GDOP Contour Maps - Obtuse Triangle Arrangement</u>

The improvement in GDOP realized from using a RTD measurement in location determination is even more pronounced in an obtuse triangle layout of the base stations. This arrangement is shown in Figure 9. The GDOP contours for the prior art invention using only relative delays is shown in Figure 10, whereas the present invention including RTD is presented Figure 11.

Comparing the figures, a dramatic improvement in GDOP is shown in Figure 11, especially below the obtuse triangle, that is, at approximately -2000N and below. As seen from comparing the lower left quadrant of the figures, the GDOP dropped from 10 in Figure 10 where a RTD measurement is not used, to approximately 2 in Figure 11 where a RTD measurement is used, in calculating GDOP. Recall from above that the smaller the value of GDOP, the greater accuracy in determining the location of a remote station using known algorithmic techniques.

Remote Station Position Determination

As mentioned, the position of the remote station is obtained using iterative least-squares algorithms. However, the resulting position solution also corresponds to the intersection points between iso-curves generated from the available measurements. As shown in Figure 12, the intersections for the prior art method using relative delay (range-difference) measurements only are displayed for the equilateral triangle arrangement of the base stations. These iso-range-difference curves are hyperbolas. Note that outside the hypothetical triangle (not shown) connecting the base stations, and especially near the edges of the figure, the intersecting hyperbolas are nearly tangential. This tangential characteristic represents the cause for the inferior GDOP values noted in these areas for the prior art.

Iso-range-difference curves for the present invention are shown in Figure 13. Including at least one RTD measurement between the remote station and, in this example, BS #1 adds iso-RTD curves represented by the circles centered at BS #1 and extending outward therefrom. These "circles" add favorable (nearly perpendicular) intersections with the iso-range-difference curves, resulting in a lower GDOP.

Two Station Ambiguity

The slight ambiguity inherent in one embodiment of the invention, where two base stations are in communication with the remote station 116 instead of three base stations, is demonstrated using iso-curves in Figure 14. This figure and discussion is only offered to distinguish these two embodiments of the invention. In Figure 14, any intersection between an iso -RTD curve (the circles) and an iso-range-difference curve (the hyperbolas) has a "twin" or "mirror" intersection that is symmetric with respect to a hypothetical line (not shown) connecting the two base stations, in this example BS #1 and BS #2. This twin intersection may cause ambiguity in determining the location of the remote station 116. If necessary, this ambiguity can generally be resolved using antenna sector information. For example, if two possible solutions are determined for the location of the remote station 116, it may be possible to eliminate one based on the transmission characteristics of the antenna used for that sector or area.

OTHER EMBODIMENTS

While there have been shown what are presently considered to be preferred embodiments of the invention, it will be apparent to those skilled in the art that various changes and modifications can be made without departing from the scope of the invention as defined by the appended claims.

What is claimed is:

CLAIMS

1. A method to determine the position of a wireless remote station using forward and reverse link measurements, comprising:

measuring a relative delay for communications received by said remote station from at least two base stations;

executing an absolute range (RTD) measurement for a communication between said remote station and at least one of said two base stations; and

determining the position of said remote station using said RTD and said relative delay measurements, wherein said RTD and said relative delay measurements are communicated to said location.

2. The method in accordance with claim 1, wherein said position determination is made at one of said at least two base stations.

3. The method in accordance with claim 1, wherein said position determination is made at said remote station.

4. The method in accordance with claim 1, wherein said relative delay corresponds to a range-difference between said remote station and a base station, and wherein said remote station reduces the number of relative delay measurements communicated to said location by averaging said relative delay measurements for each base station.

5. The method in accordance with claim 1, wherein the position of said remote station is represented by a vector θ, where $\theta = [x\ y\ \delta]^T$, and x and y are coordinates representing the position of said remote station, $[\ ]^T$ represents the transpose of a matrix, and δ is a range bias, and wherein said position calculation comprises:

determining a pseudo-range measurement (PR) from said relative delay measurements, wherein the relationship between PR to an ith base station and θ is

$PR_i = R_i + \delta$, $i = 1, 2, \ldots, N$ where $Ri = \sqrt{(x-x_i)^2 + (y-y_i)^2}$, $i = 1, 2, \ldots, N$, and where x_i and y_i are the coordinates of the ith base station, and N is the total number of base stations;

determining the partial derivatives of said RTD and said PR with respect to the elements comprising θ, comprising:

$$\frac{\partial PR_i}{\partial x}=\frac{x-x_i}{R_i}\ ;\quad \frac{\partial PR_i}{\partial y}=\frac{y-y_i}{R_i}\ ;\quad \frac{\partial PR_i}{\partial \delta}=1\ ;$$

$$\frac{\partial RTD}{\partial x}=\frac{x-x_1}{R_1}\ ;\quad \frac{\partial RTD}{\partial y}=\frac{y-y_1}{R_1}\ ;\quad \frac{\partial RTD}{\partial \delta}=0$$

arranging a derivative matrix H comprising:

$$\mathbf{H}=\begin{bmatrix} \frac{\partial PR_1}{\partial x} & \frac{\partial PR_1}{\partial y} & \frac{\partial PR_1}{\partial \delta} \\ \frac{\partial PR_2}{\partial x} & \frac{\partial PR_2}{\partial y} & \frac{\partial PR_2}{\partial \delta} \\ \vdots & \vdots & \vdots \\ \frac{\partial PR_N}{\partial x} & \frac{\partial PR_N}{\partial y} & \frac{\partial PR_N}{\partial \delta} \\ \frac{\partial RTD}{\partial x} & \frac{\partial RTD}{\partial y} & \frac{\partial RTD}{\partial \delta} \end{bmatrix}$$

determining the position of said remote station using an iterative least-squares algorithm, where the resulting position solution corresponds to intersection points between iso-curves corresponding to said RTD measurement or measurements and said relative delay measurements; and

determining a geometric dilution of precision (GDOP) from the first two diagonal elements of a matrix G, where G = $([H]^T[H])^{-1}$ and GDOP = $\sqrt{G_{11}+G_{22}}$, and using said GDOP to determine an accuracy of said position solution.

6. The method in accordance with claim 5, wherein the relationship between said RTD measurement between said remote station and one of said at least two base stations is given by RTD = $\sqrt{(x-x_i)^2+(y-y_i)^2}$, where x_1 and y_1 are the coordinates locating said one of said at least two base stations.

7. A communication apparatus capable of determining a position of a remote station using forward and reverse link measurements, comprising:

a remote station, said remote station including:

a remote station receiver;

a relative delay measurement unit coupled to said remote station receiver; a remote station transmitter;

a remote station processor coupled to said remote station relative delay

measurement unit and said remote station transmitter;

remote station storage coupled to said processor;

a first base station comprising a first receiver, a first transmitter, and a round-trip-delay determination unit;

at least one other base station, wherein said remote station is communicatively coupled to said first base station and said at least one other base station, and wherein each of said at least one other base stations comprise:

an other receiver; and

an other transmitter;

wherein said relative delay measurement unit of said remote station is configured to measure the delay of a communication signal received by said remote station from said first and said at least one other base stations, and

wherein one of said base stations includes a processor, said processor capable of determining the position of said remote station using delay measurements made by said round-trip-delay determination unit, and said relative delay measurements made by said relative delay measurement unit, and communicated to said processor.

8. The apparatus in accordance with claim 7, wherein said remote station reduces the number of relative delay measurements communicated to said base station by averaging said relative delay measurements for each base station.

9. The apparatus in accordance with claim 8, wherein said first base station is one of said at least one other base stations.

10. The apparatus in accordance with claim 8, wherein said delay measurements are used to determine an absolute range (RTD) from said remote station to a base station.

11. The apparatus in accordance with claim 10, wherein said processor determines the position of said remote station by:

determining a pseudo-range measurement (PR) from said relative delay measurements, wherein the relationship between PR to an ith base station and θ is $PR_i = R_i + \delta$, $i = 1, 2, \ldots, N$ where $Ri = \sqrt{(x - x_i)^2 + (y - y_i)^2}$, $i = 1, 2, \ldots, N$, and where x_i and y_i are the coordinates of the ith base station, and N is the total number of base stations;

determining the partial derivatives of said RTD and said PR with respect to the elements comprising θ, comprising:

$$\frac{\partial PR_i}{\partial x} = \frac{x - x_i}{R_i} \; ; \quad \frac{\partial PR_i}{\partial y} = \frac{y - y_i}{R_i} \; ; \quad \frac{\partial PR_i}{\partial \delta} = 1 \; ;$$

$$\frac{\partial RTD}{\partial x} = \frac{x - x_1}{R_1} \; ; \quad \frac{\partial RTD}{\partial y} = \frac{y - y_1}{R_1} \; ; \quad \frac{\partial RTD}{\partial \delta} = 0$$

arranging a derivative matrix comprising:

$$\mathbf{H} = \begin{bmatrix} \frac{\partial PR_1}{\partial x} & \frac{\partial PR_1}{\partial y} & \frac{\partial PR_1}{\partial \delta} \\ \frac{\partial PR_2}{\partial x} & \frac{\partial PR_2}{\partial y} & \frac{\partial PR_2}{\partial \delta} \\ \vdots & \vdots & \vdots \\ \frac{\partial PR_N}{\partial x} & \frac{\partial PR_N}{\partial y} & \frac{\partial PR_N}{\partial \delta} \\ \frac{\partial RTD}{\partial x} & \frac{\partial RTD}{\partial y} & \frac{\partial RTD}{\partial \delta} \end{bmatrix}$$

determining the position of said remote station using an iterative least-squares algorithm, where the resulting position solution corresponds to intersection points between iso-curves corresponding to said RTD measurement or measurements and said relative delay measurements; and

determining a geometric dilution of precision (GDOP) from the first two diagonal elements of a matrix G, where G = $([H]^T[H])^{-1}$ and GDOP = $\sqrt{G_{11} + G_{22}}$, and using said GDOP to determine an accuracy of said position solution.

wherein the position of said remote station is represented by a vector θ, where $\theta = [x \; y \; \delta]^T$, and x and y are coordinates representing the position of said remote station, $[\;]^T$ represents the transpose of a matrix, and δ is a range bias.

12. The apparatus in accordance with claim 11, wherein the relationship between said RTD measurement between said remote station and one of said at least two base stations is given by RTD = $\sqrt{(x - x_i)^2 + (y - y_i)^2}$, where x_1 and y_1 are the coordinates locating said one of said at least two base stations.

13. An article of manufacture tangibly embodying a program of machine-readable instructions executable by a digital processing apparatus and used to determine the position of a wireless remote station using forward and reverse link measurements by:

measuring a relative delay for communications received by said remote station from at least two base stations;

measuring a round-trip-delay for a communication between said remote station and at least one of said at least two base stations; and

determining the position of said remote station using said round-trip-delay and said relative delay measurements, wherein said round-trip-delay and said relative delay measurements are communicated to said location.

14. The article in accordance with claim 13, wherein said position determination is made at one of said at least two base stations.

15. The article in accordance with claim 13, wherein said round-trip-delay measurement corresponds to an absolute-range (RTD).

16. The article in accordance with claim 15, wherein said relative delay corresponds to a range-difference between said remote station and said at least two base stations, and wherein said remote station reduces the number of relative delay measurements communicated to said location by averaging said relative delay measurements for each base station.

17. The article in accordance with claim 15, wherein the position of said remote station is represented by a vector θ, where $\theta = [x\ y\ \delta]^T$, and x and y are coordinates representing the position of said remote station, $[\ ]^T$ represents the transpose of a matrix, and δ is a range bias, and wherein said position calculation comprises:

determining a pseudo-range measurement (PR) from said relative delay measurements, wherein the relationship between PR to an ith base station and θ is $PR_i = R_i + \delta$, $i = 1, 2, \ldots, N$ where $Ri = \sqrt{(x - x_i)^2 + (y - y_i)^2}$, $i = 1, 2, \ldots, N$, and where x_i and y_i are the coordinates of the ith base station, and N is the total number of base stations;

determining the partial derivatives of said RTD and said PR with respect to the elements comprising θ, comprising:

$$\frac{\partial PR_i}{\partial x} = \frac{x - x_i}{R_i} \quad ; \quad \frac{\partial PR_i}{\partial y} = \frac{y - y_i}{R_i} \quad ; \quad \frac{\partial PR_i}{\partial \delta} = 1 \quad ;$$

$$\frac{\partial RTD}{\partial x} = \frac{x - x_1}{R_1} \quad ; \quad \frac{\partial RTD}{\partial y} = \frac{y - y_1}{R_1} \quad ; \quad \frac{\partial RTD}{\partial \delta} = 0$$

arranging a derivative matrix comprising:

$$\mathbf{H} = \begin{bmatrix} \frac{\partial PR_1}{\partial x} & \frac{\partial PR_1}{\partial y} & \frac{\partial PR_1}{\partial \delta} \\ \frac{\partial PR_2}{\partial x} & \frac{\partial PR_2}{\partial y} & \frac{\partial PR_2}{\partial \delta} \\ \vdots & \vdots & \vdots \\ \frac{\partial PR_N}{\partial x} & \frac{\partial PR_N}{\partial y} & \frac{\partial PR_N}{\partial \delta} \\ \frac{\partial RTD}{\partial x} & \frac{\partial RTD}{\partial y} & \frac{\partial RTD}{\partial \delta} \end{bmatrix}$$

determining the position of said remote station using an iterative least-squares algorithm, where the resulting position solution corresponds to intersection points between iso-curves corresponding to said RTD measurement or measurements and said relative delay measurements; and

determining a geometric dilution of precision (GDOP) from the first two diagonal elements of a matrix G, where G = $([H]^T[H])^{-1}$ and GDOP = $\sqrt{G_{11} + G_{22}}$, and using said GDOP to determine an accuracy of said position solution.

18. The article in accordance with claim 17, wherein the relationship between said RTD measurement between said remote station and one of said at least one base stations is given by RTD = $\sqrt{(x - x_i)^2 + (y - y_i)^2}$, where x_i and y_i are the coordinates locating said one base station.

19. An apparatus used in a wireless communications system to determine the position of a remote station using forward and reverse link measurements, comprising:

first means for measuring a relative delay for communications received by said remote station from at least two base stations;

second means for measuring an absolute range (RTD) for a communication between said remote station and at least one of said at least two base stations; and processing means for determining the position of said remote station using said RTD and said relative delay measurements, wherein said RTD and said relative delay measurements are communicated to said location.

20. The apparatus in accordance with claim 19, wherein said processor determines the position of said remote station by:

determining a pseudo-range measurement (PR) from said relative delay measurements, wherein the relationship between PR to an ith base station and θ is $PR_i = R_i + \delta$, $i = 1, 2, \ldots, N$ where $R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$, $i = 1, 2, \ldots, N$, and where x_i and y_i are the coordinates of the ith base station, and N is the total number of base stations;

determining the partial derivatives of said RTD and said PR with respect to the elements comprising θ, comprising:

$$\frac{\partial PR_i}{\partial x} = \frac{x - x_i}{R_i} \; ; \quad \frac{\partial PR_i}{\partial y} = \frac{y - y_i}{R_i} \; ; \quad \frac{\partial PR_i}{\partial \delta} = 1 \; ;$$

$$\frac{\partial RTD}{\partial x} = \frac{x - x_1}{R_1} \; ; \quad \frac{\partial RTD}{\partial y} = \frac{y - y_1}{R_1} \; ; \quad \frac{\partial RTD}{\partial \delta} = 0$$

arranging a derivative matrix comprising:

$$\mathbf{H} = \begin{bmatrix} \frac{\partial PR_1}{\partial x} & \frac{\partial PR_1}{\partial y} & \frac{\partial PR_1}{\partial \delta} \\ \frac{\partial PR_2}{\partial x} & \frac{\partial PR_2}{\partial y} & \frac{\partial PR_2}{\partial \delta} \\ \vdots & \vdots & \vdots \\ \frac{\partial PR_N}{\partial x} & \frac{\partial PR_N}{\partial y} & \frac{\partial PR_N}{\partial \delta} \\ \frac{\partial RTD}{\partial x} & \frac{\partial RTD}{\partial y} & \frac{\partial RTD}{\partial \delta} \end{bmatrix}$$

determining the position of said remote station using an iterative least-squares algorithm, where the resulting position solution corresponds to intersection points between iso-curves corresponding to said RTD measurement or measurements and said relative delay measurements; and

determining a geometric dilution of precision (GDOP) from the first two diagonal elements of a matrix G, where $G = ([H]^T[H])^{-1}$ and $GDOP = \sqrt{G_{11} + G_{22}}$, and using said GDOP to determine an accuracy of said position solution.

wherein the position of said remote station is represented by a vector θ, where

$\theta = [x\ y\ \delta]^T$, and x and y are coordinates representing the position of said remote station, $[\ ]^T$ represents the transpose of a matrix, and δ is a range bias.

21. The apparatus in accordance with claim 20, wherein the relationship between said RTD measurement between said remote station and one of said at least one base stations is given by RTD = $\sqrt{(x - x_i)^2 + (y - y_i)^2}$, where x_i and y_i are the coordinates locating said one base station.

22. The apparatus in accordance with claim 21, wherein said position determination is made at one of said at least two base stations, and wherein said first and second means for measuring are the same means.

23. The apparatus in accordance with claim 21, further comprising:

remote station processing means for reducing the number of relative delay measurements communicated to said location by averaging said relative delay measurements for each base station; and

remote station storage means for storing said relative delay measurements and coupled to said remote station processor.

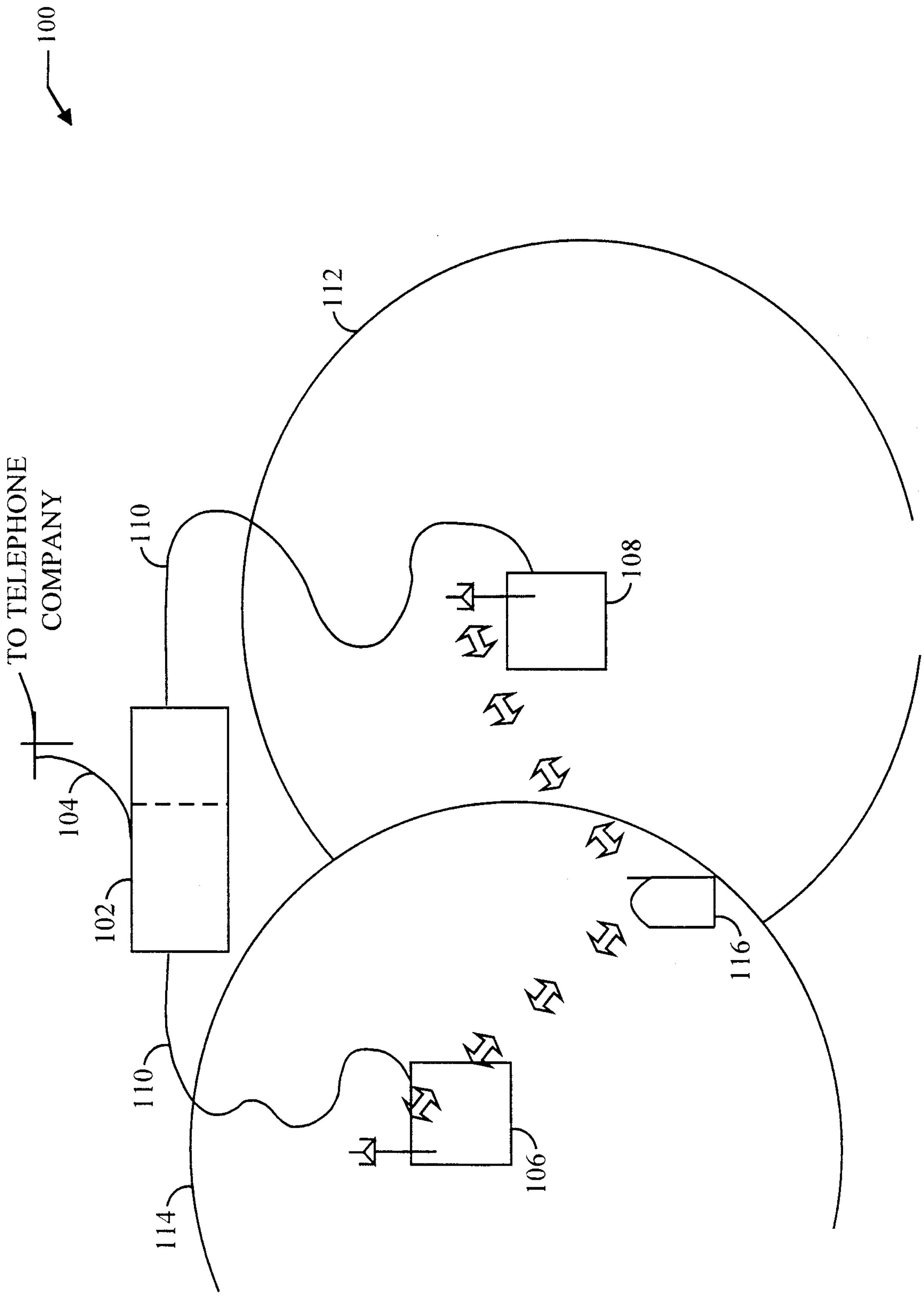


FIG. 1

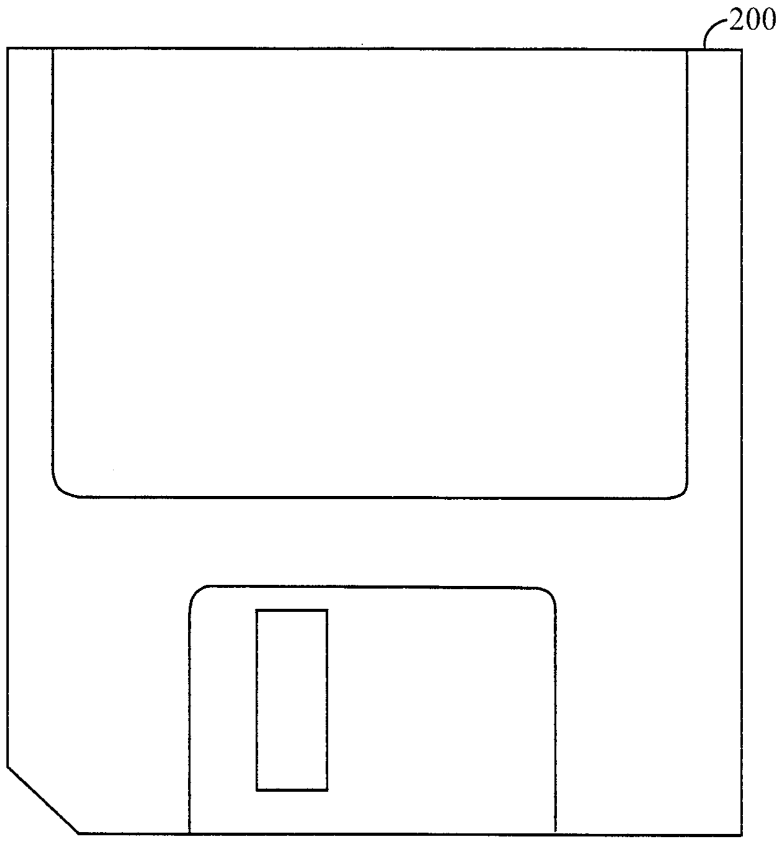


FIG. 2

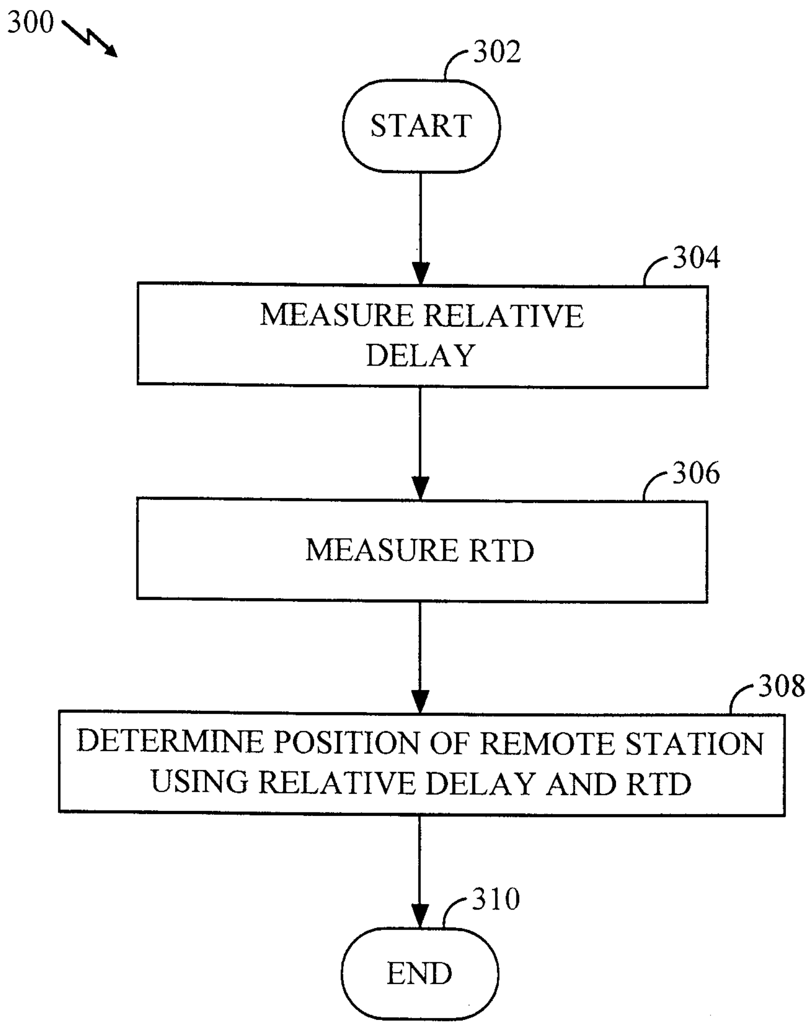

300
302
START
304
MEASURE RELATIVE DELAY
306
MEASURE RTD
308
DETERMINE POSITION OF REMOTE STATION USING RELATIVE DELAY AND RTD
310
END

FIG. 3

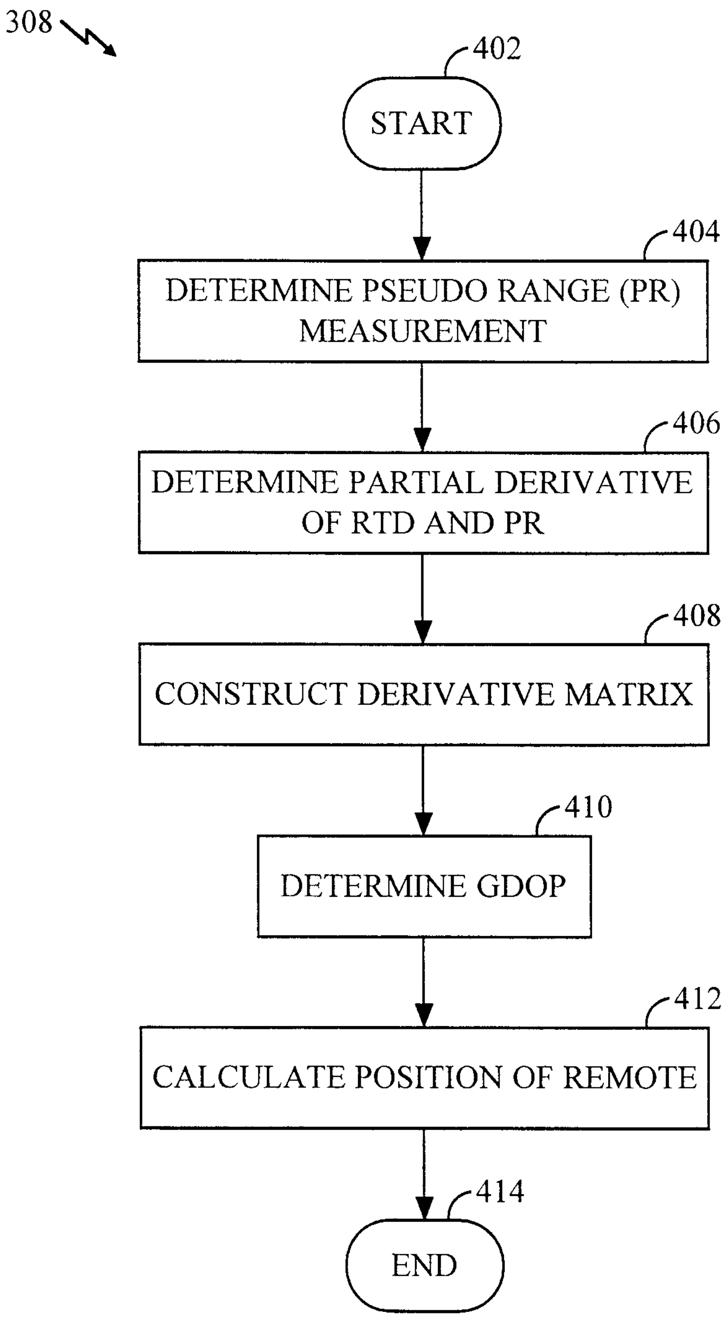
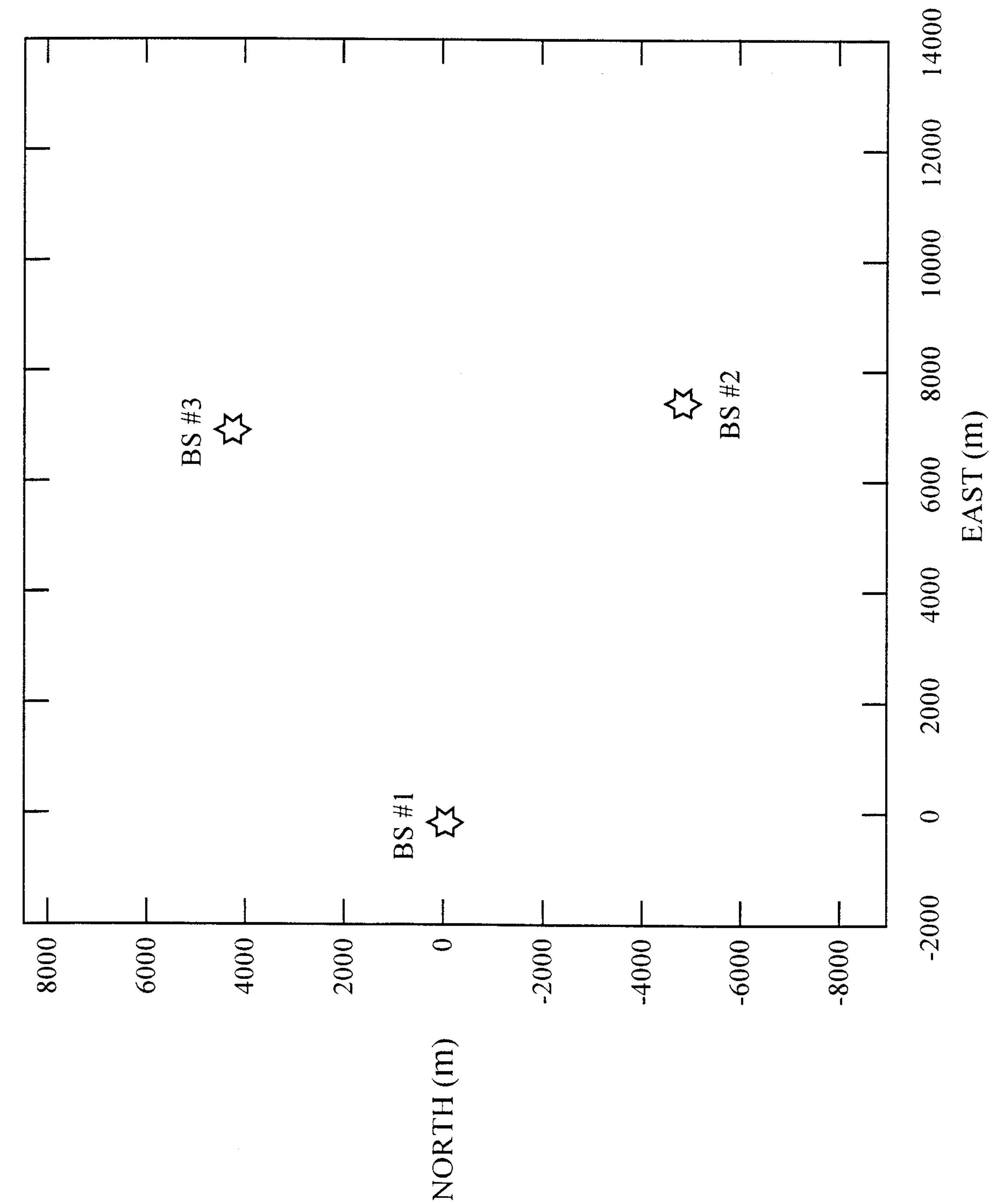

308
402
START
404
DETERMINE PSEUDO RANGE (PR) MEASUREMENT
406
DETERMINE PARTIAL DERIVATIVE OF RTD AND PR
408
CONSTRUCT DERIVATIVE MATRIX
410
DETERMINE GDOP
412
CALCULATE POSITION OF REMOTE
414
END

FIG. 4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BS #2
BS #3
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4000
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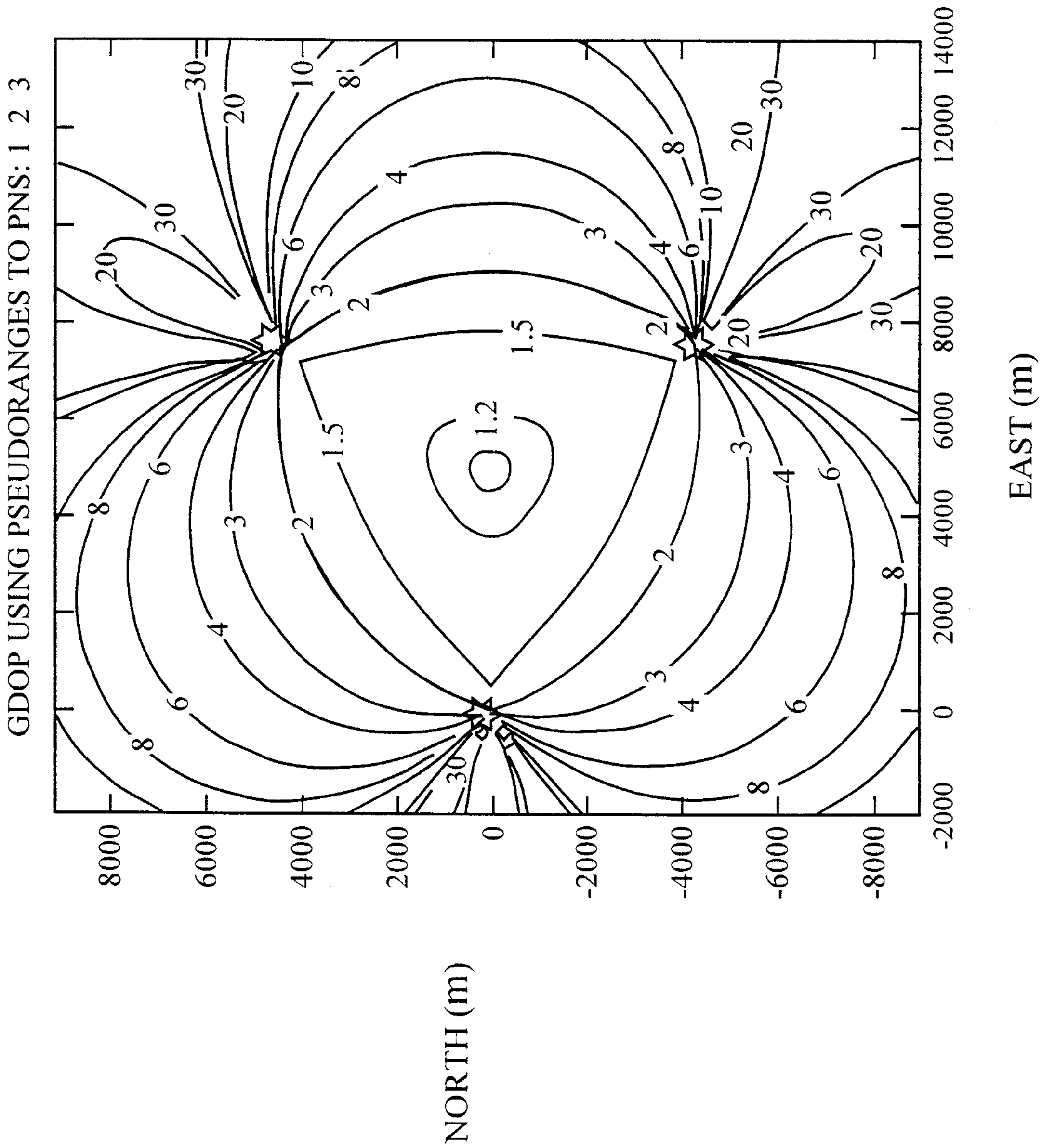
-2000
-4000
-6000
-8000
-2000
0
2000
4000
6000
8000
10000
12000
14000

FIG. 5

FIG. 6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12000
14000
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1.5
2
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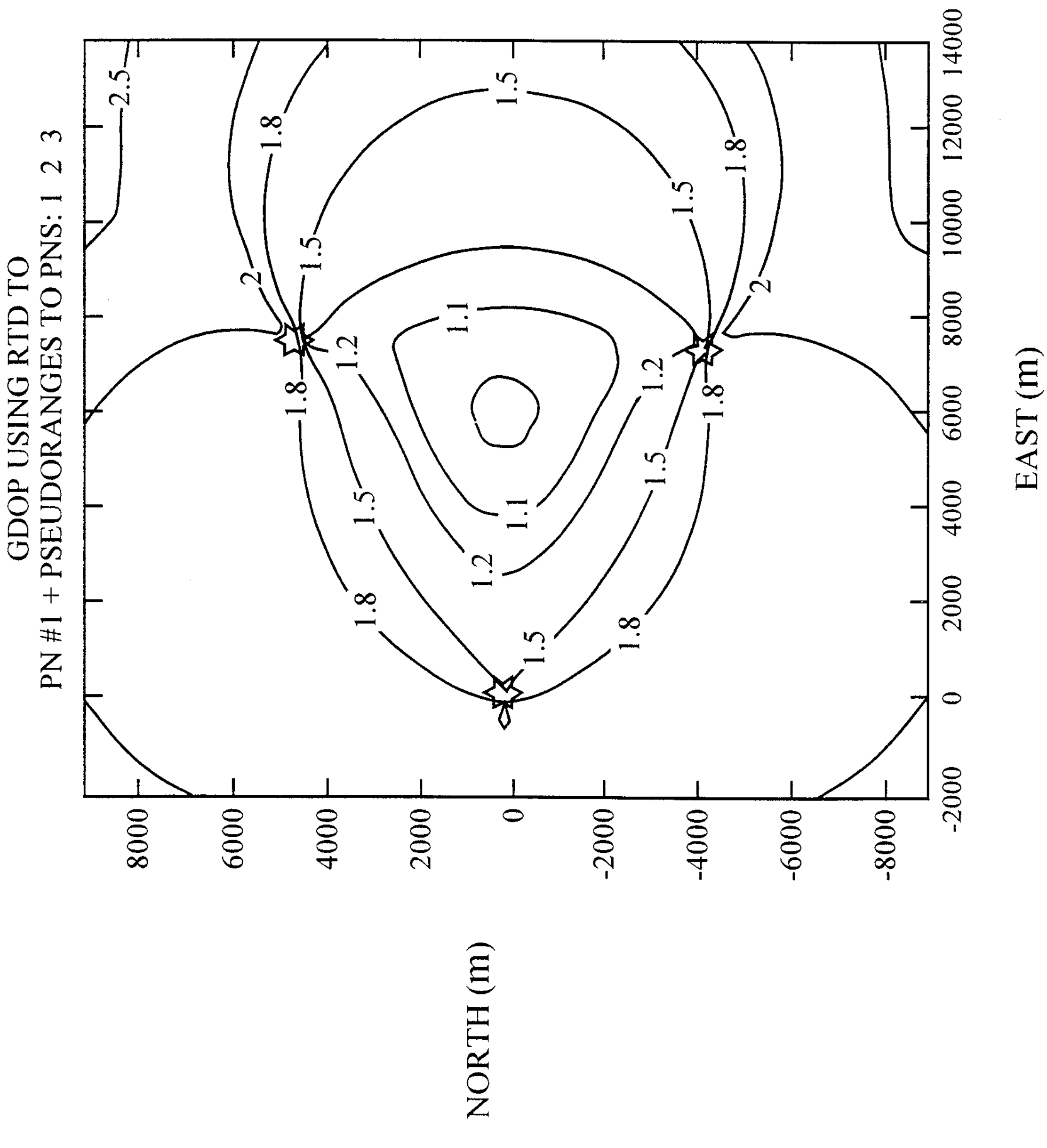
10
20
30

FIG. 7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-4000
-6000
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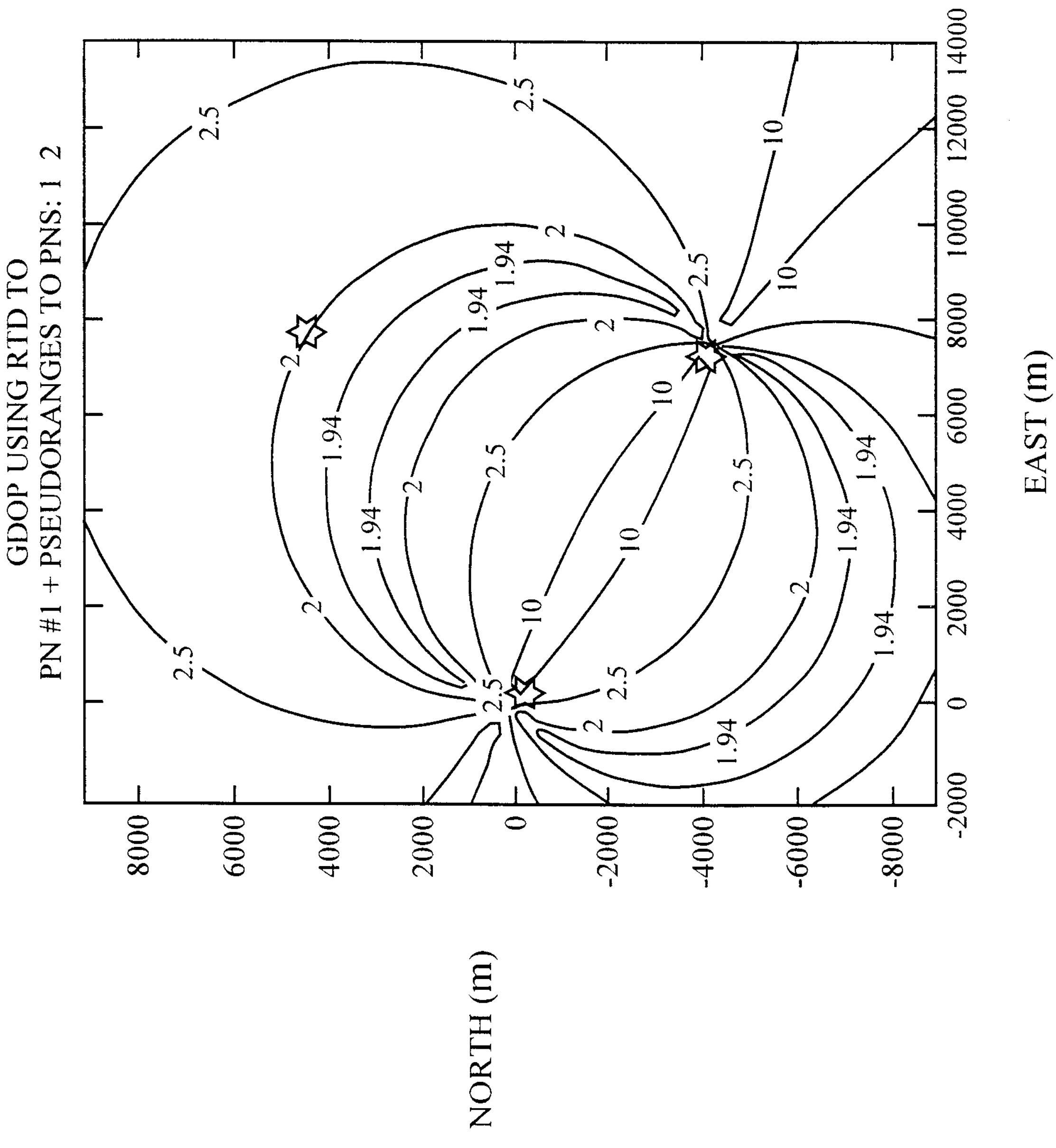
1.1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-6000
-8000
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6000
8000
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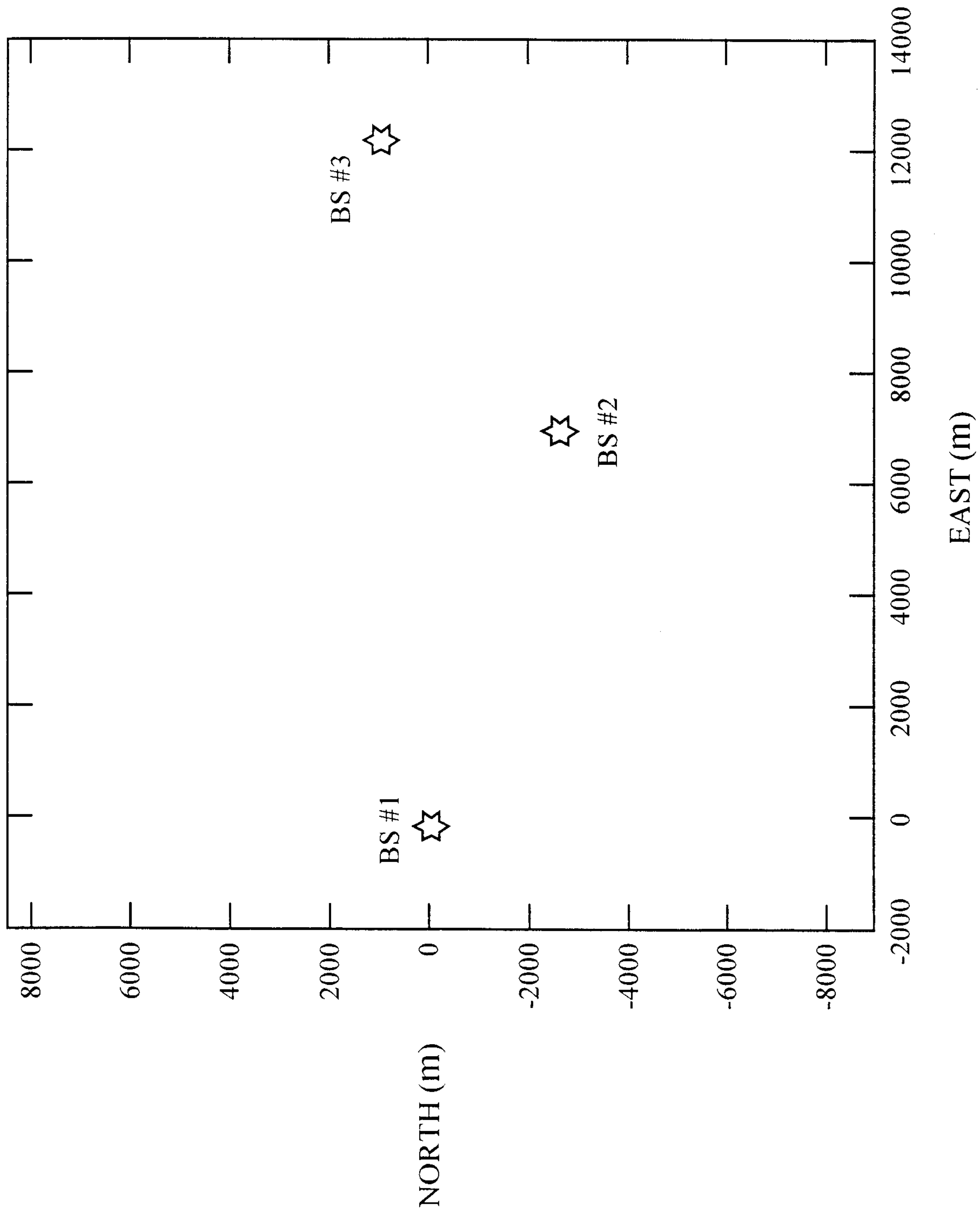
14000
2.5
2
1.94
10

FIG. 8

FIG. 9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BS #3
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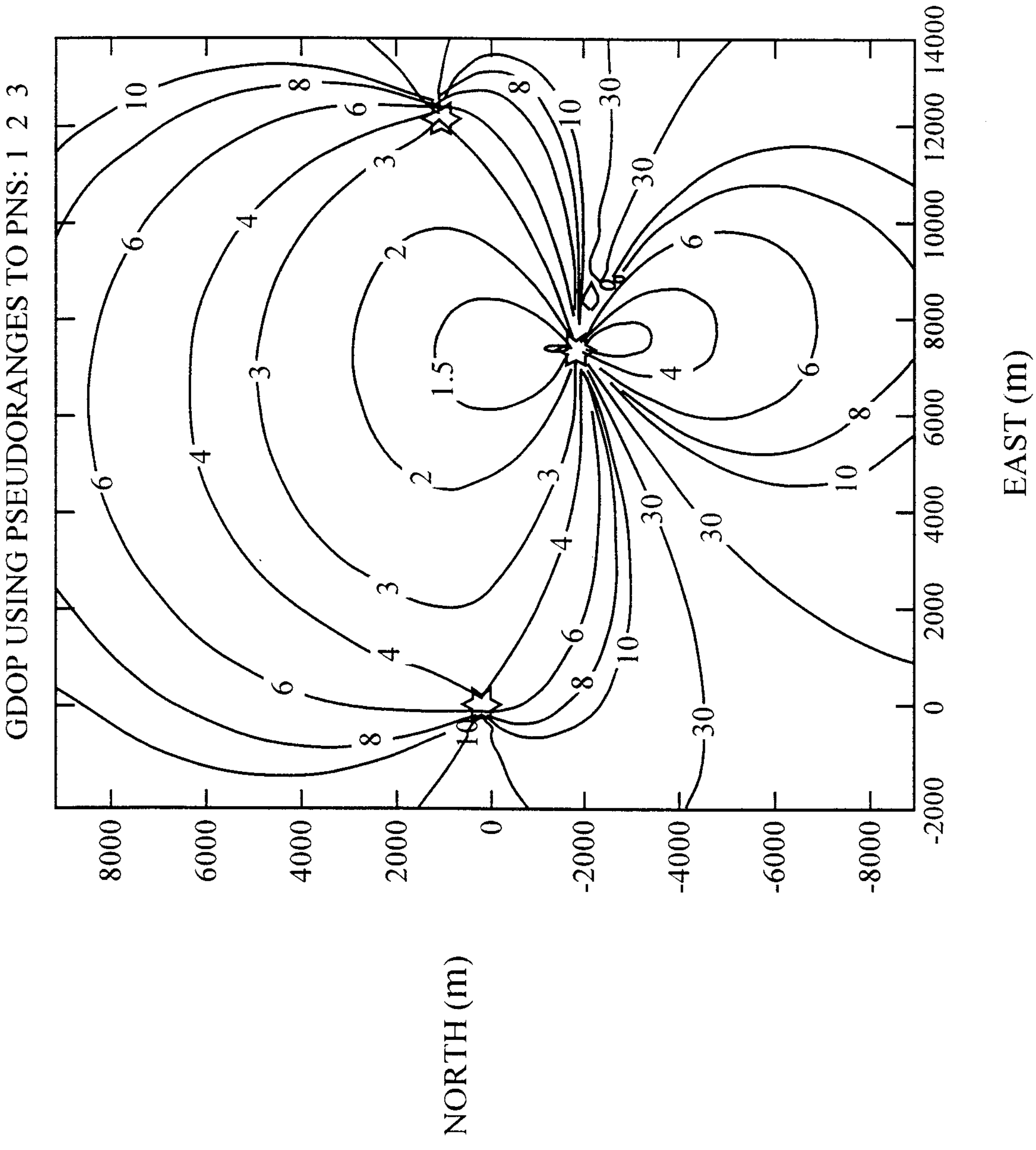
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12000
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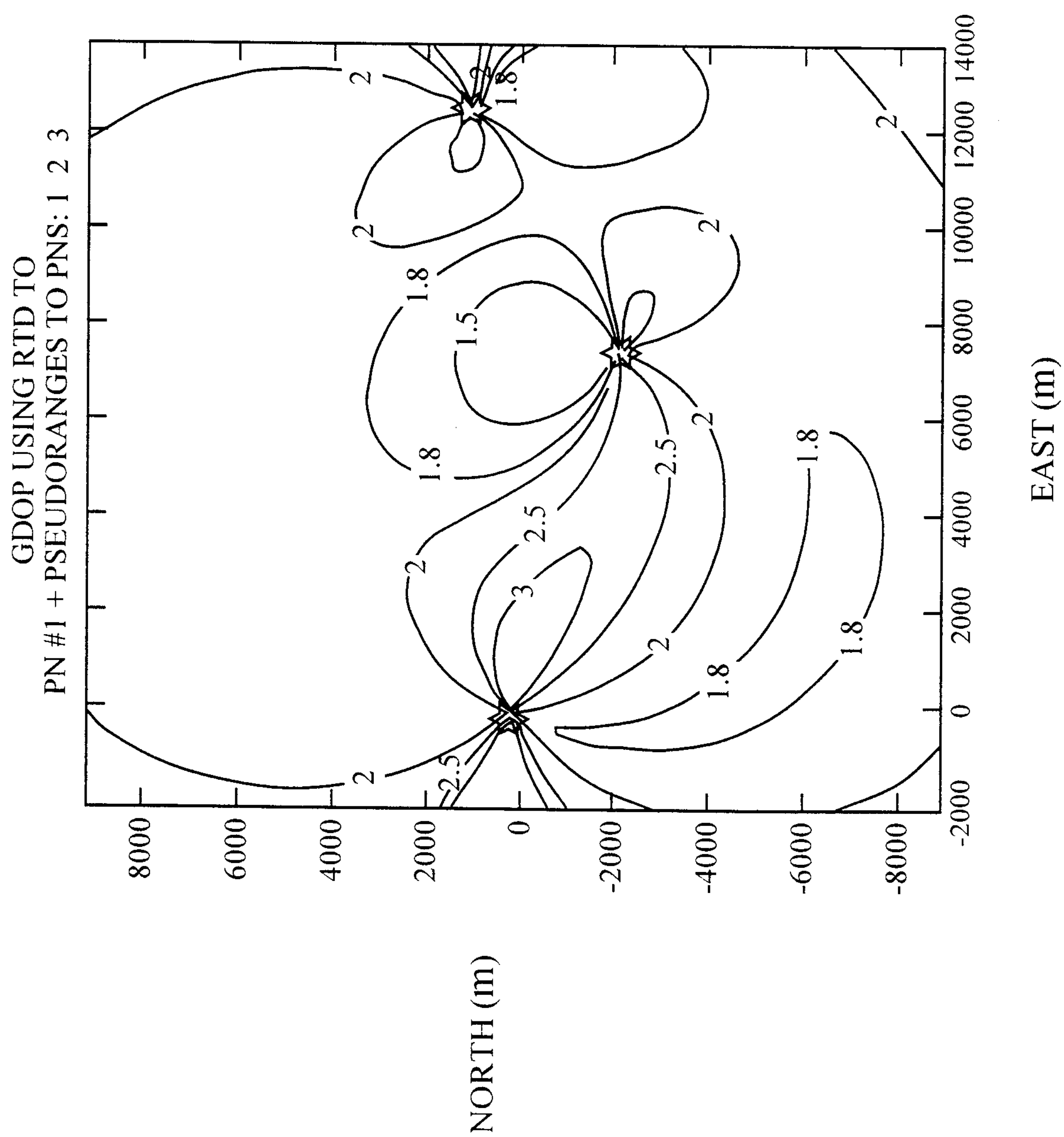
FIG. 10


GDOP USING RTD TO
PN #1 + PSEUDORANGES TO PNS: 1 2 3
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14000
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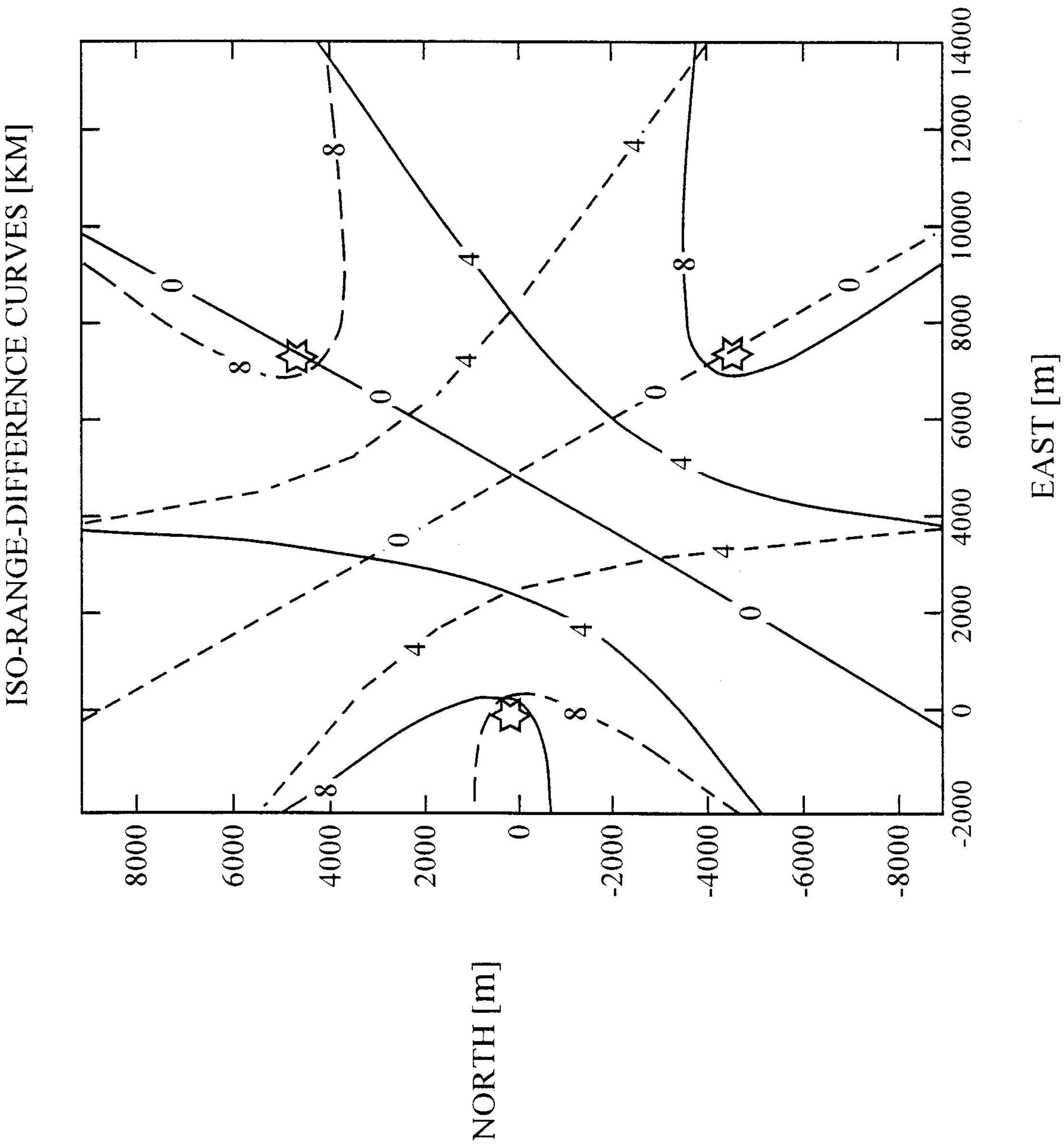
1.5
2.5
3

FIG. 11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12000
14000
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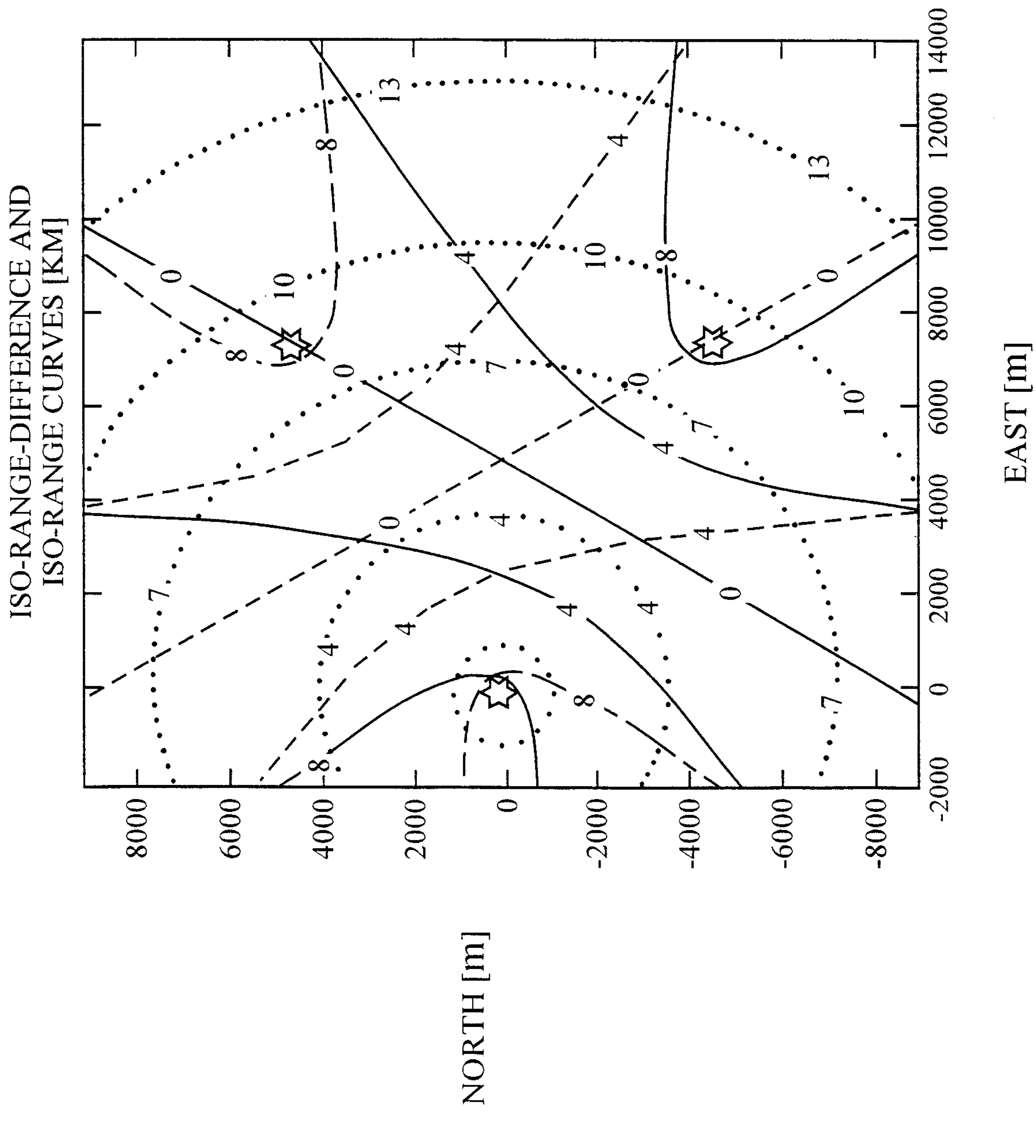
8

FIG. 12


ISO-RANGE-DIFFERENCE AND
ISO-RANGE CURVES [KM]
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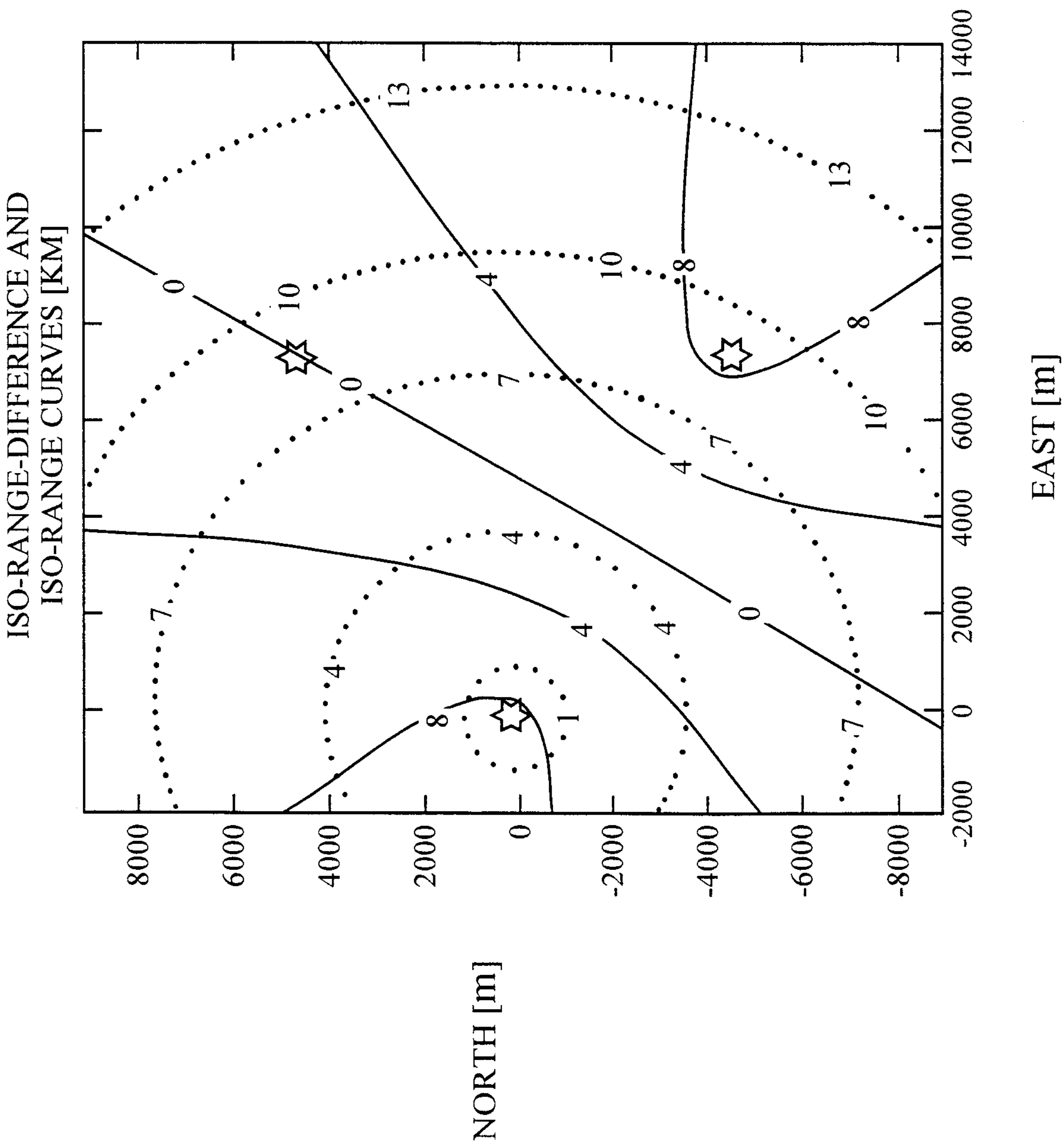
13

FIG. 13


ISO-RANGE-DIFFERENCE AND
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-8000
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4000
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10000
12000
14000
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4
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8
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13

FIG. 14

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/08508

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H04Q7/38

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H04Q G01S

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 98 48578 A (ERICSSON INC.) 29 October 1998 (1998-10-29) page 9, line 16 - line 25	1,7,19
A	CAFFERY ET AL.: "OVERVIEW OF RADIOLOCATION IN CDMA CELLULAR SYSTEMS" IEEE COMMUNICATIONS MAGAZINE, vol. 36, no. 4, 1 April 1998 (1998-04-01), pages 38-45, XP000752569 USA the whole document	1,7,19
A	US 5 884 215 A (BIRCHLER ET AL.) 16 March 1999 (1999-03-16) the whole document	1,7,19

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

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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

"P" document published prior to the international filing date but later than the priority date claimed

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

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 July 2000	24/07/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Danielidis, S

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

Interi nal Application No
PCT/US 00/08508

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9848578 A	29-10-1998	US 6040800 A	21-03-2000
		AU 6954898 A	13-11-1998
		EP 0977999 A	09-02-2000
US 5884215 A	16-03-1999	AU 5611998 A	25-08-1998
		BR 9709149 A	03-08-1999
		CA 2250236 A	06-08-1998
		CN 1215474 A	28-04-1999
		EP 0895600 A	10-02-1999
		WO 9834124 A	06-08-1998