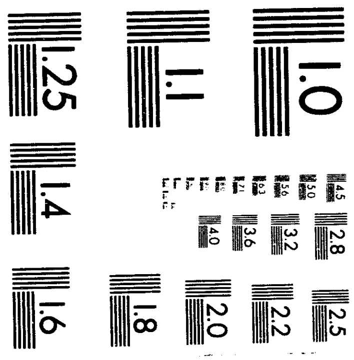
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USING THE GLOBAL POSITIONING SYSTEM IN SUPPORT OF ENVIRONMENTAL CHARACTERIZATION AT THE HANFORD SITE IN WASHINGTON STATE

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INTRODUCTION

The U.S. Department of Energy's 1,450 km^2 Hanford Site in southeastern Washington State accumulated hazardous wastes for more than 50 years. To support the Site's mission of environmental restoration and cleanup, the Global Positioning System (GPS) is being used to verify waste site locations and provide location information for field samples. Collected GPS data are stored for use in the Hanford Geographic Information System (HGIS).

THE GLOBAL POSITIONING SYSTEM - BACKGROUND

The NAVSTAR GPS is a space-based electronic navigation and positioning system designed and operated by the U.S. Department of Defense (DOD). The system consists of three major components: (1) the space segment, comprising 24 earth-orbiting satellites; (2) the control segment, made up of 5 control and monitoring stations placed around the globe; and (3) the user segment, which includes users worldwide. When declared fully operational by the DOD, the NAVSTAR GPS will allow users to identify their geographical position anywhere on earth at any time. There are no user fees for the service and anyone with a GPS receiver may use the system worldwide.

The one major hindrance to the system is the DOD policy concerning a security option called Selective Availability (SA). Selective Availability affects the usability of the system by intentional manipulation of the GPS signals to degrade the accuracy of the user's positions. The period and magnitude of degradation is solely a DOD privilege. The DOD policy on SA is to vary the error in position calculated from the Standard Positioning Service code to approximately 100 m root-mean squared (RMS). With SA on and other possible errors included, users may know their location to within a few hundred meters. While this accuracy is good for many applications, it is too inaccurate for others.

GPS receivers rely on signals sent from satellites to calculate positions. Simultaneous signals from at least three satellites are required to calculate a two-dimensional position that is horizontal only, and signals

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from four satellites to calculate a three-dimensional position that includes the height or elevation value. Up to six coded or uncoded signals may be broadcast on two carrier frequencies from each satellite. The GPS receivers can decipher one or more of these signals to calculate positions.

Some receivers, called code-phase receivers, can decipher only the uncoded signals broadcast by the satellites. These receivers calculate a position based on a distance to each satellite called a pseudorange. A pseudorange distance contains errors and is not the true distance. The majority of error in pseudorange is caused by SA. Other receivers are designed to use carrier signals, and some receivers use both types of signals. Carrier-phase receivers do not rely on the coded signals alone and are not as subject to the SA errors.

Resourceful users have developed GPS techniques of circumventing SA and eliminating or reducing other errors at the same time. The best technique is called differential GPS, which can be capable of calculating a geographical position to within millimeters. Differential GPS operates on the principle that two receivers calculating positions from the same satellites, at the same time, in the same relative location on earth, will obtain similar errors. That is, any errors introduced by SA or signal inconsistencies will be the same for both units during that period. If the location of one of the units is known, the difference between the position calculated and the known position is easily computed. This difference, generally called the DELTA, is then applied to the position calculated by the unknown receiver, usually resulting in the errors being eliminated.

In practice, many variations of differential GPS have been developed to increase accuracy. Two methods are widely used for differential corrections: (1) Radio Frequency (RF) corrections can be calculated and broadcast in real-time so that the receiver at the unknown location can receive the corrections and display and store the corrected position almost instantly; and (2) post-processed differential, where data are collected in the field and saved, and then differential corrections are processed on a computer at a later time. This post-processing technique allows for the greatest accuracies. Both code-phase and carrier-phase receivers can use differential correction processing.

DATA QUALITY OBJECTIVES

At the Hanford Site, multiple organizations are using equipment from 5 different manufacturers in 15 separate working groups independently collecting geographic data. The need for accurate position reporting mandates standardization and user training. The initial effort for GPS evaluation was to gain an understanding of the NAVSTAR system. Secondly, the need for Data Quality Objectives (DQO) for GPS data was addressed. After the DQO have been identified for any given GPS mission, the appropriate equipment can be selected and evaluated for accuracy, precision, reliability, and cost. This process identifies the specific geographic accuracy required. The key factor in determining the accuracy available is the GPS methodology. Depending on the method of GPS data collection and post processing, positional accuracy may vary from hundreds of meters to within millimeters. The DQO may also require GPS data collectors to supply other GPS information about the mission or project. Elements from the list below are suggested as a minimum set of "metadata" to be included in the GPS results.

- GPS data collector's name
- Collection period date and times
- Position identification method (naming conventions)
- Equipment used, by type and manufacturer (hardware and software)
- A list of the GPS equipment settings used and options, specifically the datum used and the elevation method used (height above ellipsoid, or altitude)
- Type of GPS data collected (pseudorange, carrier phase, or both)
- Raw or differentially corrected data
- Control locations used (if differential)
- Statement of accuracy
- Statement of confidence in accuracy
- Copies of software analysis of the data and differential solutions.

EQUIPMENT UPGRADE

Equipment testing and evaluation identified weaknesses in the existing NAV 1000 PRO* receiver capabilities and endorsed an upgrade to the NAV 5000 PRO models through an upgrade option offered by Magellan Systems. Three results of the upgrade were: (1) increased internal memory for both buffer (200 points to 1,500 points) and key reference positions known as waypoints (60 points to 500 points) storage; (2) conversion from a 1-channel receiver to a 5-channel receiver for continuous satellite tracking; and (3) the ability to use carrier-phase differential. The augmentation of memory was beneficial, but the addition of the extra channels and carrier phase were essential to acquire submeter accuracy.

TESTING

Test results provided a performance model for the use of GPS equipment to meet the DQO defined by any given project within the scope of environmental restoration work on the Hanford Site. Various GPS modes of operation were tested and results compared for accuracy, precision, repeatability, and ease of use. Three types of tests were conducted in the field: navigation, general locations, and precise location.

Navigation testing consisted of a single receiver (autonomous) using the navigation feature built into the NAV 5000 PRO. Using the GPS receiver for navigation is relatively straightforward; it requires the user to input

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*NAV 1000 PRO and NAV 5000 PRO are trademarks of Magellan Systems Corporation.

locations of reference points (waypoints) into the receiver and build a route from those waypoints. Up to 10 routes may be put into the system at one time. As the route is being traversed, the receiver displays information such as distance and direction to the next point, velocity, time left to travel at that velocity, and a measure of how far off the route the user (i.e., receiver) is. The system can update new information as often as every second. Navigating routes between waypoints works well for long baseline distances, such as across the Site, with an accuracy of 100 m.

Another navigation method uses two receivers operating in field-differential mode. Field-differential navigation can maneuver a user to within 10 to 30 m of a waypoint, but requires at least two receivers and a communication link between the operators. Navigation techniques were used in field applications to find National Geodetic Survey (NGS) markers in remote areas of the Site as well as to establish stake locations for future well sites.

General location testing methods included autonomous as well as differential operations. The simplest operation on the NAV 5000 PRO GPS receivers is the determination of the user's geographical position. It can be a one-button activity once the unit is set up properly. However, the positional accuracy can be greater than 100 m horizontally. Testing the accuracy consisted of setting the receiver on an NGS monument whose location is known and calculating the error from the GPS position collected by the receiver. Accuracy measurements generally include the area within a circle with a radius of 100 m with the true or known position as the center. Accuracy statements reflect the measurement of the direct distance from the known point to the calculated GPS position. Improvements in accuracy can be achieved by averaging many single fixes at the same location.

Fig. 1 contains a horizontal (two-dimensional) view of GPS positions collected using a single receiver in both single-fix and averaging modes. The receiver was placed on a known NGS marker called PUG. At a rate of one each second, 397 position fixes were collected. Any single point could represent a single fix taken at random with a single receiver. The average of the positions collected is represented and the improvement in accuracy of the average position over the majority of single fixes is evident in the figure. Still, the average position is in error by 20 m. The GPS receivers calculate the vertical height of the location as well as the horizontal position, and the errors in vertical vary closely with the horizontal, but the vertical error is twice the horizontal error. Similar tests have provided information that indicates that the greatest improvement in accuracy for position averaging occurs between 20 to 100 fixes.

PLACE FIG. 1 HERE.

Precise location evaluation requires at least two GPS receivers operating simultaneously in differential mode. Test methods for evaluating accuracies for precise measurements included setting up two GPS receivers, each one on a known monument, and alternately post processing data files of each receiver as base station (known position) and rover (unknown position).

Because both locations were precisely known, it was a simple matter to calculate the GPS errors based on the results. Precise location testing showed field errors of 5 m in code phase mode, and 2 m in carrier-phase mode with a collection time of 20 minutes per point. The positions shown in Fig. 2 display the accuracies achievable using two NAV 5000 PRO receivers in carrier-phase operation and post processing the data sets. Each receiver was set up on a known NGS marker and the data collected by logging directly to laptop computers. Each data set represents approximately 20 minutes of carrier-phase raw data along with pseudorange positional data and requires about 750 kilobytes of disk space. After processing, the data are reduced to a single position with X, Y, and Z values.

PLACE FIG. 2 HERE.

FIELD APPLICATIONS

The Environmental Restoration Surface Disposal Facility (ERSDF) Project needed surface locational information concerning the placement of future monitoring wells to be drilled around the facility's perimeter. The boundary was digitized onto a map of the area and locations were selected for four new wells. The Environmental Restoration GPS staff was brought in to locate and stake the field locations. The area selected for the site was chosen partly because of its lack of surface features, which meant that there was no simple way to measure to the well sites from existing features.

The project planning session defined the DQO; DQO accuracy required navigating to within 5 m of the desired well site, driving a stake, and then collecting the position of the stake to within 1 m. This determined the GPS equipment and methodology to be used. Two NAV 5000 PRO GPS receivers would be used in differential mode using code-phase processing for the navigation phase, then carrier-phase post-processed differential would be used for the higher precision measurement. A known NGS high-precision marker was within 5 km of the GPS operational area, and mobile two-way radios could be used for communication between the roving crew and the base crew.

Initially each desired well location had been placed into the roving GPS receiver as a waypoint. Navigation from the outer area to the general vicinity of each well was accomplished with autonomous mode. This positioned the rover crew to within 100 to 150 m of the desired site. The rover operators then switched to field differential techniques and began communications with the base station operator. By adjusting the rover's position in accordance with the corrected positions, the rover was able to move to within 5 m of the desired site in two to three steps. Once within the 5-m range, the geologist chose a level spot to stake the well. The stake was driven and a 15-minute carrier-phase differential session was initiated, with the antenna directly over the newly staked location. The information from each GPS receiver was logged to laptop personal computers and later post processed to further improve the accuracy of the location. Two wells were staked on each of two consecutive days. The location task took three days and produced six staked well locations that have geographic locations that are known to an accuracy of 1 m.

Fig. 3 is a view of the data collected for the ERSDF project. "True" position is the result of the carrier-phase evaluation, and "Average" is the average of the 300 to 400 pseudorange measurements.

PLACE FIG. 3 HERE.

General-location GPS testing has been used on the Hanford Site's North Slope area, which is considered a remote part of the Site. In the late 1940's and early 1950's, the U.S. Army maintained military observation and control sites on the North Slope. Many waste sites have been identified in this area, most of which are burial dumps with unknown contents. Initial site discovery crews used single GPS receivers to collect locational information about physical anomalies. Instances such as pipes or cables protruding from the ground, or regularly shaped mounds and depressions were located for further investigation. From the GPS positions collected, researchers occasionally found historical aerial photography that further helped identify the site or the contents. As investigation continued, individual burial site boundaries were identified and staked. Ground-penetrating radar was used to classify certain locations within those boundaries where anomalies may indicate possible buried waste or contaminants. Sampling crews took borehole samples and further staked each site. When sampling was completed, GPS field differential with two receivers gathered positions of each of the sample locations with an estimated accuracy of 3 m for each stake. A GPS technician and three trainees collected 74 geographical positions in three days. Post processing and inclusion into an ARC/INFO* geographical information system (GIS) took an additional four hours.

The consequences of using GPS with untrained people or without proper planning is evident when the data collected are unusable for the intended purpose. In the spring of 1992, a group of field samplers used a single GPS receiver to collect positional data on naturally occurring hydraulic springs along the shore of the Columbia River adjacent to a waste site. Fourteen springs were located along the western bank in an area approximately 4,500 m in length. The river varies in width from about 675 m to more than 800 m along this area. Geographic positions were collected and a report issued stating the locations of the spring sites. The geographical positions were brought to a GIS shop to be placed into an existing database containing spatial information of the area.

The GPS data points were converted to Washington State Plane coordinates using GIS software. The first problem was that no metadata accompanied the GPS positions. There was no information about the datum, GPS method or equipment, setup, or who had collected the data or estimated accuracies. Without at least some of this information, the positions were almost impossible to plot against existing data. The GPS operator was contacted and remembered that the datum had been NAD27, but none of the original data had been saved. Furthermore, the operator could not remember any of the equipment settings.

GIS plots were created and the GPS data overlaid on the river and area boundaries. Each position appeared to lie from 40 to 150 m east of the river bank (that is, in the Columbia River). Circles with the possible error radius of 200 m were plotted using the GPS position as the center and the area map as a background. Assuming that SA was active, and that the probable error could be as great as 200 m in any direction, there were several of the GPS positions where the error circles overlapped each other. Further GIS processing reduced the error probability low enough to identify the majority of the spring sites to within ±100 m along the shoreline. Six positions remained ambiguous. To resolve the spring locations to the satisfaction of the environmental restoration organization, another GPS survey will be conducted, with proper planning and users trained in the GPS techniques to meet the DQO.

Fig. 4 shows the initial locations of the GPS spring sites relative to the Columbia River bank. The circles represent a circular error possible of 200 m from the GPS position. Where the circles overlap and two points lie within both circles, there is no definite resolution of which GPS position belongs to which spring site.

PLACE FIG. 4 HERE.

One successful application of GPS precise location collection at the Hanford Site is the Hanford Environmental Information System (HEIS) database. More than 3,900 locations for wells and other single-point sample locations with monitoring information are stored in the HEIS database. There have been many sources for the geographic locations in the database, and some of the locations are incorrect. The GPS is being used in the field to verify locational data. Magellan GPS receivers are being used in carrier-phase post-processed differential mode. Several wells in an area central to the Hanford Site that is located near a carbon-tetrachloride waste site have been verified to an accuracy of 1 m of the published locations with no positional database errors. When two published positions for the same sample location disagree by more than 1 m, GPS is used to resolve the discrepancy. In two such cases so far, the GPS position collected agreed closely with one of the associated database positions; the other position was deemed in error.

Because of growing widespread use of GPS on the Hanford Site, a special group has been established to facilitate site-wide GPS applications. A GPS base station has been engineered and procured that will provide differential correction capabilities to most Site contractors. The system provides real-time radio frequency (RF) broadcast correction data in the Radio Technical Commission for Maritime Service (RTCM) standard format. Another service will be logging differential satellite information to a network server, which will make differential data available for post processing. Successful implementation of a base station may reduce GPS operational costs up to 50% by reducing the need for current levels of equipment and personnel. The base station is presently being purchased and is expected to be in operation by December 1993.

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*ARC/INFO is a trademark of Environmental Systems Research Institute, Inc.

LESSONS LEARNED

(1) Potential GPS users should first decide on their own data requirements to successfully evaluate and purchase the proper GPS equipment: How accurate will the GPS position need to be? How quickly is that accuracy needed? What is a reasonable cost?

(2) Manufacturers' sales brochures may be misleading in terms of accuracy. Accuracy statements including terms like RMS or CEP, SEP 1σ or 2σ, and without SA are confusing to beginners and casual users.

(3) The required accuracy is a prime product of the DQO process.

(4) Planning is critical for a successful GPS mission. Items to be planned include the DQO, equipment, GPS logistics, and Hanford Site logistics. DQO must be determined in the planning stage, before any data have been collected. The DQO must define the accuracy of GPS data needed. This in turn should define GPS methods required, which then define GPS equipment to be used and personnel skills required.

(5) Managers and supervisors need to know what to expect from the system and operators. Occasional users who require accuracy of 100 m may require only brief training. Operators who require high accuracy GPS will need not only GPS training for equipment, but survey and/or cartographic training as well. Most GPS operators in ER have other primary duties; GPS positioning is only part of their workload. It is difficult to coordinate training classes with the schedules of many workers. Frequently, new users are eager to use the equipment and impatient about the planning phase. Users comment that the manufacturers' operating manuals are either too simple or too difficult.

(7) Most GPS equipment requires additional peripheral gear to perform anything but the simplest operations. Gear can range from special cables, batteries, and antennas, to data loggers, including laptop computers. Differential GPS requires at least two GPS receiver equipment sets. Minor problems with equipment and/or connectivity can cause major problems in data collection. Few missions go as planned, and many times a whole day's work is lost because of equipment malfunctions. Users need equipment dedicated for GPS use, which has been proven functional in the field.

CONCLUSION

Although the GPS has been in development for many years, it is still a fledgling industry. The NAVSTAR system is very successful in achieving its original purpose: navigation. However, at the Hanford Site, users push the design limits when they attempt to collect highly accurate positional data. Using the GPS to work beyond the original design capabilities dictates the need for a greater understanding of the underlying technology. There is a need for technical training, operation, data quality standards, and field procedures to ensure that others may effectively use the GPS data they collect. A substantial amount of the Hanford Site's environmental work requires positional data accuracy on the order of 1 m with a confidence level of 95%. The GPS is capable of providing data of even higher quality when used with properly trained operators and suitable equipment.

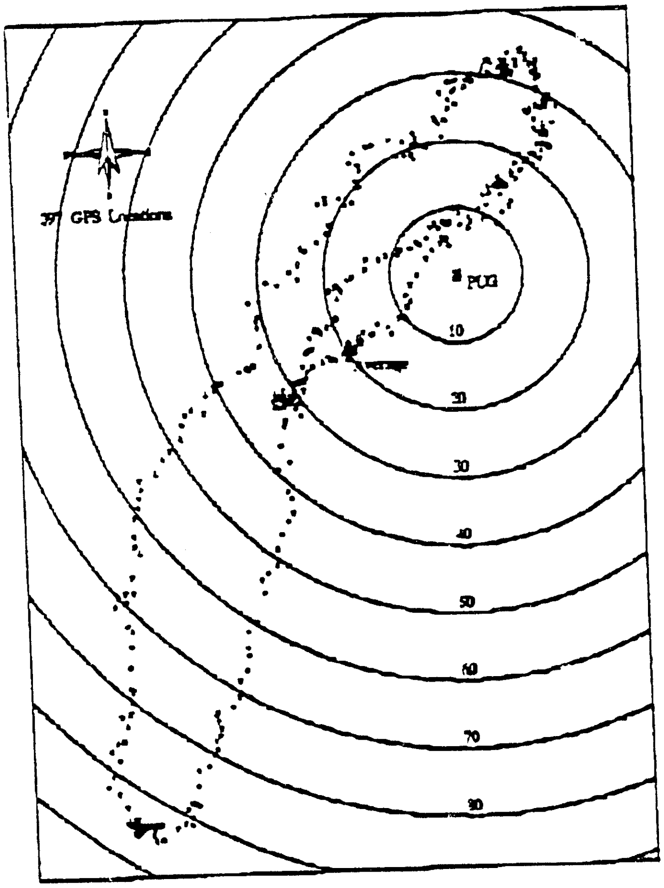
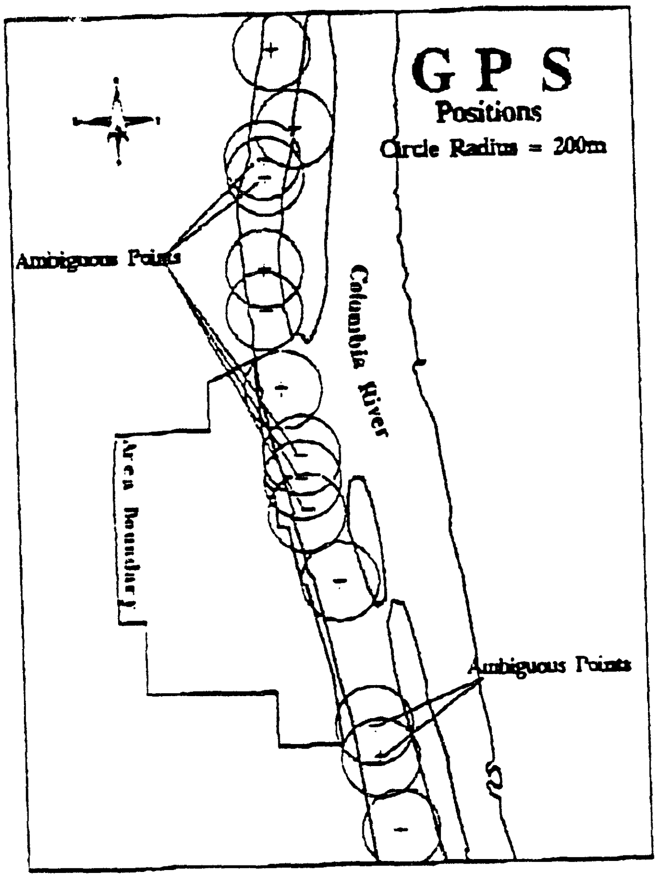
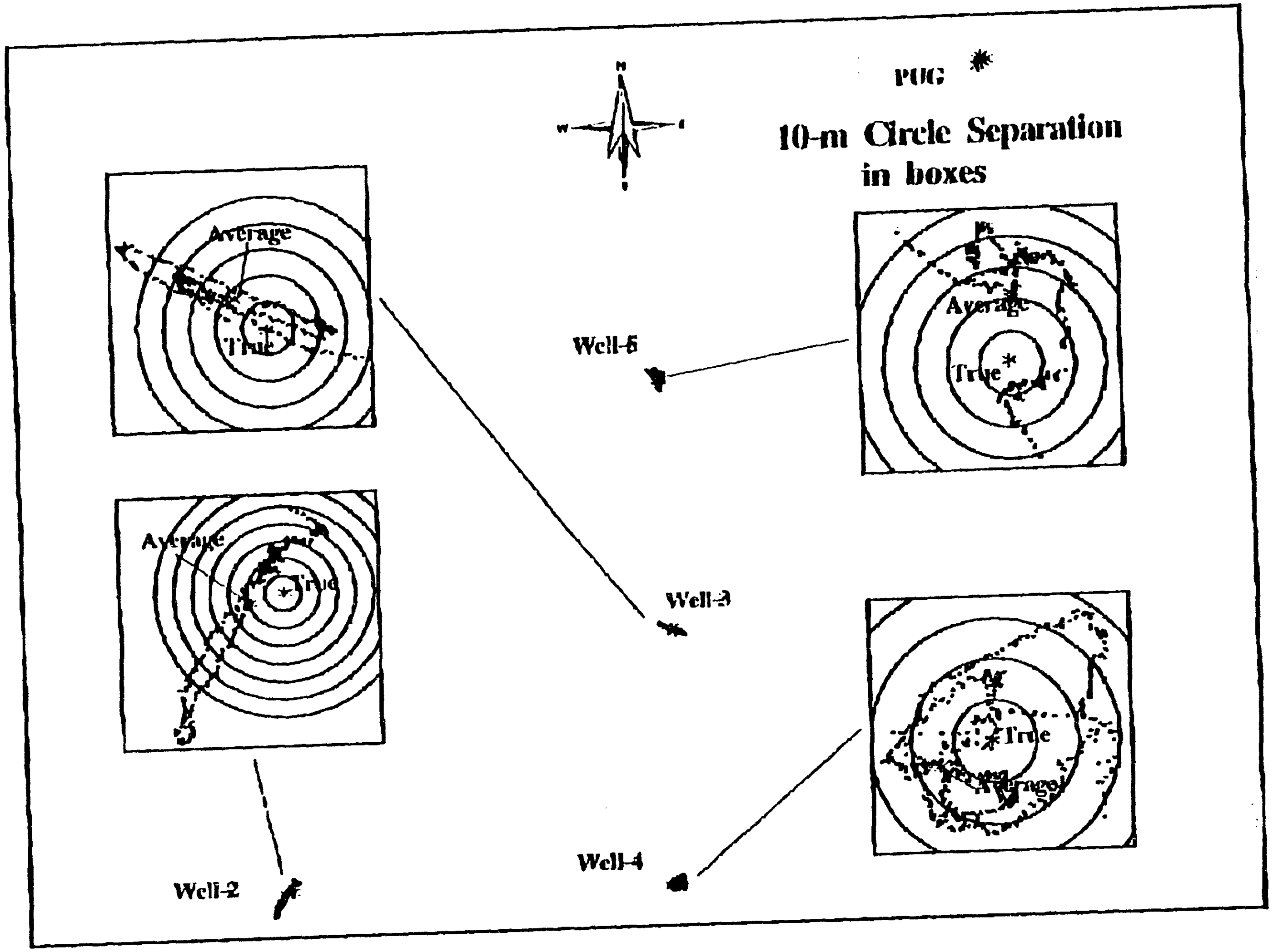


Figure-1 Horizontal Positions Relative To Known Location



G P S
Positions
Circle Radius = 200m
Ambiguous Points
Columbia River
Area Boundary
Ambiguous Points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