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High Accuracy Reference Networks; A National Perspective[a]

By William E. Strange[1] and John D. Love[2]

Abstract: High Accuracy Reference Networks have been, or are being, established in a large number of states. These networks consist of stations spaced at 25 to 100 km intervals, whose positions relative to the NAD83 reference coordinate system and to one another are known with much higher accuracy than is the case with the existing network. These upgrades to the National Geodetic Reference System are being undertaken to meet expressed user needs for greater accessibility and higher accuracy in the horizontal reference network in the era of the Global Positioning System (GPS). The increased use of kinematic and pseudo-kinematic GPS field methods and fixed, automated reference stations, which lend themselves to direct GPS positioning relative to a single reference network site, as well as three dimensional positioning, will make High Accuracy Reference Networks increasingly important in the future. The National Geodetic Survey is working closely with surveyors in states to provide the fundamental coordinate system, to support survey planning, observations, and data reduction, and to integrate the High Accuracy Reference Networks and the existing network to assure compatibility. The establishment of a High Accuracy Reference Network throughout the United States in the next few years seems inevitable. The question to be answered is how to achieve this result as rapidly and efficiently as possible.

INTRODUCTION

The surveying profession is currently in the midst of a revolution brought about by Global Positioning System (GPS)

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[1]Chief Geodesist, National Geodetic Survey, Coast and Geodetic Survey, National Ocean Service, NOAA, 11400 Rockville Pike, Rockville, Maryland 20852.

[2]Chief, Projects and Specifications Section, National Geodetic Survey, National Ocean Service, NOAA, 11400 Rockville Pike, Rockville, Maryland 20852.

measurement technology and the power of the Personal Computer (PC). This revolution is placing into the hands of the surveyor here-to-fore unattainable capabilities. Many state, county, and private surveyors, using commercial GPS receivers, can perform surveys extending over tens of kilometers with accuracies better than those achievable by a geodetic research organization using specialized equipment only a few years ago. Also, using their PC and commercially available software, these surveyors can now perform data reductions, coordinate transformations, and relatively large scale adjustments. In addition to providing increased capabilities, GPS and PCs have greatly reduced the cost of many types of surveys. Coincident with this increase in capability and reduction in cost, the increasing implementation of Geographic and Land Information Systems (GIS/LIS) and the use of positions to define land parcel boundaries have led to increased requirements for surveying. The conjunction of increased capabilities and increased requirements is leading to a substantial increase in the number of closely spaced horizontal reference stations being established and the accuracy of their positioning.

As might be expected, the revolutionary changes being experienced by the surveyor are having a substantial effect on the requirements being placed on the National Geodetic Reference System (NGRS), including the reference network of monumented stations. One important impact is the need for stations that are easily accessible (drive to stations) and have no obstructions which impede use by GPS. Another impact is the desire for greater accuracy for the NGRS reference network station positions. These impacts have led a broad spectrum of users to request upgrades in the NGRS reference networks in their states. These requests have already led to establishment of a High Accuracy Reference Network (HARN) in a number of states, with many more in progress or planned.

This paper has three objectives: (1) to explain what a HARN is; (2) to define why a HARN is needed; and (3) to describe the current status and future plans for GPS establishment of a nationwide HARN.

What is a High Accuracy Reference Network?

In order to clearly understand what a High Accuracy Reference Network (HARN) is (and what it is not), it is worthwhile to specify what a National Geodetic Reference System, of which the HARN is a part, is and how it is used. In particular, it is important to specify how GPS has modified the nature of the NGRS.

A NGRS is a set of parameters allowing measurements of horizontal positions and heights from different surveys to be related to one another in a consistent way with satisfactory accuracy. Conventional surveying techniques dictate that horizontal and vertical coordinates be determined almost independent of one another, resulting in independent horizontal and vertical reference systems. The conventional horizontal reference system has three components: a reference coordinate system, a reference ellipsoid, and a reference network of stations whose positions relative to nearby stations are known with a well defined proportional accuracy, but whose positions relative to the reference coordinate system are less well defined. The coordinate system and ellipsoid, taken together, are commonly referred to as a datum. The vertical reference system for leveled heights has two components: a reference equipotential surface, the geoid, whose geometry relative to a coordinate system has been, here-to-fore, ill defined, and a network of bench marks whose heights relative to the equipotential surface, called orthometric heights, are known to a high level of accuracy, but whose horizontal positions are, in most cases, known only approximately by scaling from a map.

With the advent of GPS, it is possible to have a single reference system for both horizontal and vertical positions. A satisfactory NGRS in the GPS era consists of five components: a reference coordinate system, which is as nearly as possible geocentric; a reference ellipsoid; a set of monumented points whose three dimensional positions relative to nearby points and to the chosen coordinate system are known with high accuracies; a set of positions for GPS satellites as a function of time; and a reference geoid whose heights relative to the reference ellipsoid are known with a well defined accuracy.

Surveyors generally use the NGRS reference network stations for three purposes: (1) to permit station positions they derive from their survey to be related to a common coordinate system, and thus related to positions for points derived by others; (2) to serve as a means of evaluating the accuracy of their survey and detecting blunders; and (3) to improve their overall survey results by holding fixed the more accurate positions of the reference network stations included in the survey when performing adjustments.

With the above background in mind, we will now address the question of what a HARN is. A high accuracy reference network (HARN) is a set of stations, usually with 25 to 100 km station spacing, whose horizontal positions, relative to one another and to the NAD83 reference coordinate system, are known with very high accuracy. Figure 1 shows the HARN established in California. Nominally, the horizontal accuracies for stations of a HARN are given as 8 mm + 1:1,000,000, B Order as defined by the Federal Geodetic Control Committee. However, GPS is not a proportional accuracy system and 8 mm + 1:1,000,000 does not express the true accuracy of the station positions. A non-rigorous, but more correct, description of HARN accuracy is to say that differential horizontal positions of stations no more than 100 to 200 km apart will be accurate at the 1 to 3 cm level, while the absolute horizontal accuracy relative to the NAD83 coordinate system will be no worse than 10 to 15 cm. Vertical positions can be expected to be differentially accurate to 3 to 7 cm locally and no worse than 20 cm relative to the reference coordinate system.

Because there can be misunderstandings, it is worth discussing the relationship between the HARN and NAD83. To do this we must distinguish between NAD83 itself (i.e., the datum consisting of a coordinate system and an ellipsoid) and the NAD83 reference network, consisting of a set of monumented stations across the nation and their assigned coordinates. The horizontal coordinates derived for the HARN stations by NGS are NAD83 coordinates; that is, they are relative to the NAD83 reference coordinate system with latitudes and longitudes computed using the NAD83 reference ellipsoid. Where a station that was part of the original NAD83 reference network is included in the HARN, a new position will be obtained for the station. This does not mean that a new datum , i.e., a new coordinate system and/or ellipsoid has been introduced. The stations' latitudes and longitudes will change because a more accurate horizontal position relative to the NAD83 coordinate system has been obtained. In essence, the objective of a HARN is to remove to the maximum extent possible the remaining distortion in the positions assigned to NAD83 reference network stations.

Currently, HARNs are being established on a state by state basis. When a HARN is established in a state, numerous ties are made to stations of the existing NAD83 reference network. The more accurate HARN station positions are then held fixed and a complete readjustment of previously existing observations (conventional and GPS) are performed to provide upgraded positions for all previously established horizontal reference network stations in the state that are not contained in the HARN. The result is a set of more accurate, internally consistent coordinates for all horizontal reference network stations in the state.

From the above discussion two of the misconceptions concerning a HARN can be put to rest.

• The establishment of a HARN does not imply the abandonment of the NAD83 coordinate system and reference ellipsoid, i.e., a new datum has not been established.

• The establishment of a HARN does not imply abandonment of the existing NGRS reference network; it does imply improved NAD83 coordinates for the stations of the existing network.

Another misconception which should be addressed at this point is the idea that the establishment of a HARN, with its station spacing of 25 to 100 km, amounts to a decision that a denser spacing of reference stations is not needed. In fact, the establishment of a HARN makes no statement whatsoever about the density of monumented reference stations that might be required for various applications. What the HARN does do is make the establishment of a denser network, if one is desired, easier and cheaper to establish with more accurate results.

Why Have a High Accuracy Reference Network (HARN)?

Some of the reasons for the establishment of a HARN are clear and obvious. Others require a more in depth look at characteristics of GPS surveying and how these characteristics will impact surveying over the next few years and beyond.

If one talks to those who were instrumental in establishing a HARN for their state and those who are using it for GPS surveying, two points are brought up almost universally.

(1) The existing NGRS reference station network was difficult to use with GPS because of (a) a sparsity of stations, (b) difficulty in accessing many existing stations, and (c) unsuitability of many existing stations for use by GPS because of obstructions. The GPS surveyors wanted a reasonably spaced network of easily accessible, drive-to stations that were free of any obstructions which might prevent or degrade GPS observations.

(2) The NAD83 positions of existing NGRS stations were often of lesser accuracy than the GPS survey being performed, leading to problems when performing constrained adjustments. The GPS surveyors wanted reference network positions that were of sufficient accuracy that they did not introduce substantially greater distortions in constrained adjustments than were present in free adjustments of their GPS data.

The above concerns were raised because of real, practical considerations. The lack of readily accessible and usable reference stations made reconnaissance more difficult and costly. In some cases it was simply impossible to find sufficient usable and accessible stations in a survey area. The use of pack stations might be required, or establishment of an offset mark for use with GPS, an undesirable approach from both an accuracy and cost viewpoint. Because of accuracy concerns with NGRS positions, more existing stations than otherwise might be necessary were used; the objective being to identify any bad position for an existing station and reject that station in the final constrained adjustment. The level of error in NAD83 positions in existing reference network stations also added to the effort required to perform adjustment and analysis of a survey. Numerous adjustments were often required to determine which existing network station(s) had unsatisfactory positions and to be certain the problem was with existing network station positions and not with the current survey.

Even when the errors in the existing network were not sufficiently large to prevent the meeting of specifications for a survey they were troublesome to a surveyor. There is something inherently disturbing in attaining a high level of accuracy in one's work and then being told one must degrade the work to make it fit into the reference system network, even though it is known that the reference network, not the survey, is the source of the error. It was also time consuming and troublesome to resolve problems arising when positions for points common to two new surveys disagreed because each survey was constrained to different existing NGRS points.

If one combines the need for additional reference stations with the desire for higher accuracy, the establishment of a HARN is a natural consequence.

Although the above discussion indicates in a broad way why the desire for a HARN arose, it is by no means the whole story. As we move further into the GPS era, the existence of HARNs will be increasingly important for effective use of GPS. To understand this, we must first digress to discuss the characteristics of GPS surveying, how these differ from conventional surveying, and their impacts.

The important attributes of GPS surveying which differentiate it from conventional surveying are:

• GPS removes the need for line-of-sight between stations and causes ground station network geometry to no longer have the importance it had with conventional surveying.

• GPS permits direct high accuracy differential positioning between stations tens of kilometers apart.

• GPS eliminates the need to deal with local vertical coordinate systems in deriving horizontal positions.

• GPS provides the ability to perform three dimensional positioning using the same measurement.

The impact of these attributes on GPS surveyors and the users of their results are:

• The competent GPS surveyor can obtain observations capable of providing differential station position accuracies in the 2 to 10 cm range with relative ease.

• With the advent of PCs and commercially available software, the competent GPS surveyor can reduce and adjust the data to obtain final positions accurate to 2 to 10 cm.

• The GPS surveyor can tie a survey to stations tens of kilometers away with high accuracy at reasonable cost.

• The lowered costs associated with GPS surveying allow the ultimate users of survey information to obtain more stations and request higher accuracy than was previously possible. This is important since it encourages users to upgrade their surveys so they can serve multiple purposes.

Let us now ask two questions: How will the reference network evolve? and How will GPS survey methods change?

The evolution of reference networks over the remainder of this decade seems reasonably clear and is presaged by what is already underway. The major trends relative to reference networks are:

• In many areas, particularly developed areas, a denser reference network will appear with stations spaced at 1 to 6 mile intervals.

• The accuracy of the positioning of stations will be at the few centimeter level.

• A combined horizontal and vertical reference network will become a reality.

• Surveying and navigation will become inter-related through the use of common base stations.

Also GPS field methods will change. The two changes in GPS field methods are:

• Increased use of kinematic and pseudo-kinematic (rapid static) field procedures.

• Increased use of unmanned, base station receivers to work with field receivers.

With the above discussion as background, we are in a position to address the question of why a HARN is increasingly important to effective use of GPS in the near term future. Up to the present, the bulk of GPS surveying has involved static positioning and network observing schemes similar to those used in conventional surveying; but this is already in the process of changing. As we move toward the full satellite constellation, kinematic and pseudo-kinematic methods are being increasingly used because of the potential for increased productivity and, therefore, lower cost per station. Also, permanent automated reference stations are coming into increasing use in static, kinematic, and pseudo-kinematic GPS surveying because they result in reduced personnel and travel costs. Static positioning using an automated reference station and kinematic and pseudo-kinematic positioning methods, with or without an automated reference station, have a common characteristic. They lend themselves to what I term "direct positioning," i.e., positioning of a new station by direct determination of its differential position relative to a single known station, with redundancy obtained by multiple determinations of the chosen differential position. The known station can, and often will, be tens of kilometers distant from the station being positioned.

Because of the fundamental importance of network geometry in conventional surveying, its relative unimportance in GPS surveying may seem surprising. However, the reason for this difference is straightforward. With conventional horizontal control surveying, observations of geometric quantities are observations of angles and distances made between ground stations. With GPS surveying, while the result obtained from a set of measurements is the vector between two ground stations, the actual geometric measurements used to derive the vector are between ground stations and satellites. As a result, the more important geometry in GPS positioning accuracy is ground station-satellite geometry, not ground station-ground station geometry.

Obviously, the use of GPS for positioning does not negate the need to evaluate the accuracy of position determinations and detect systematic errors and blunders. With direct positioning using GPS, evaluation of random measurement error is accomplished by multiple occupations of the new stations being positioned and, therefore, multiple determinations of the differential vector being used to position a new station. However, detection of blunders and systematic errors caused by such factors as error in the base station position and in antenna height corrections must be tested for by occupation of one or more reference stations of known position by the roving receiver. Clearly, such a blunder detection test can be made only to the level of accuracy with which the base station-reference network station differential position is known. If the base station-reference network station separation were 30 km, for example, and the reference network were First-Order one could not, with any certainty, detect systematic survey errors of 30 cm or less, since errors as large as 30 cm could be present in the differential reference network positions. This amounts to saying that in many cases the present reference network cannot serve as a meaningful blunder detector for the most cost effective methods of GPS surveying now coming to the fore.

Another important consideration relative to reference network accuracy is that we are rapidly moving to the time when GPS will be used to provide height information as well as horizontal information. For this purpose new, relatively dense, high accuracy GPS reference networks are essential. To be meaningful for vertical applications, these networks must, of necessity, be accurate vertically at the few centimeter level. To achieve this level of vertical accuracy equal or greater horizontal accuracy will be obtained. It is thus certain that reference networks will be established in the next few years, using GPS, which are capable of providing very high horizontal accuracies. Without HARNs in place there will be no way to take full advantage of the accuracy of the horizontal information arising from these surveys.

Where Do We Stand in Establishing HARNs?

Figure 2 shows the current status in the establishment of HARNs. Over a third of the states have, or are in the process of establishing, a HARN. By the end of 1992 over half of the land area of the United States will have a HARN in place. Substantial use of GPS in surveying is less than 5 years old. It is truly amazing how rapidly the upgrading of reference networks through the establishment of HARNs has proceeded, particularly given the built-in delays associated with the budgeting process of government entities and the need to reach a consensus relative to a new technology. This section of the paper explores how this tremendous effort has come about and the role played by the National Geodetic Survey (NGS) at the national level.

The impetus for the upgrading of the existing reference networks through the establishment of HARNs has been very much user generated. In state after state, users of the new GPS technology identified deficiencies in the existing horizontal reference network, and initiated efforts to establish HARNs in order to alleviate these deficiencies. Often these efforts have been focused by the establishment of GPS users groups, whose membership encompassed a broad spectrum of users. Three examples of users groups are those in the states of Florida, Washington, and New Mexico. In Florida the GPS users group was initially an ad hoc group but later became a formal practice section of the

Florida Society of Professional Land Surveyors. In New Mexico the establishment of a HARN is the primary project of the GPS committee of the New Mexico Geographic Council, an advisory board to the Governor. In Washington the users group was associated with the state surveyors organization. The broad participation in these groups is illustrated by the current membership of the New Mexico GPS Committee which includes representatives from three state agencies (State Highway and Transportation Department, Bureau of Mines and Mineral Resources, State Engineers Office), Federal agencies (NGS, U. S. Forest Service, Bureau of Land Management, U. S. Geological Survey), the City of Albuquerque, and five private surveying firms.

In other states the primary impetus for a statewide HARN has come from a single organization. For example, in California the primary impetus for a HARN has come from the California Department of Transportation (Caltran). However, this does not mean that other groups are not involved. Even before observations for a HARN began, survey organizations in seven counties, the City of Los Angeles, and the Los Angeles Water Authority had already indicated the desire to integrate local high accuracy reference networks they were establishing into the California HARN. In Tennessee where the Department of Transportation was primarily responsible for the establishment of the first statewide HARN, every major city having a GPS reference network established to support LIS/GIS activities has tied to the Tennessee HARN.

NGS has participated in the establishment of statewide HARNs in response to requests from state groups for support. The objective of NGS in cooperating with state groups is to assist users in meeting their requirements for upgrading their existing state horizontal reference networks while maintaining the integrity and consistency of the network on a nationwide basis. The activities being undertaken by NGS in cooperation with state groups can be summarized as follows:

a. Provide a nationwide high accuracy framework;

b. Participate in planning, observation, and data reduction related to the GPS surveys used to establish the HARN;

c. Adjust the resulting vectors to produce high accuracy NAD83 coordinates for the HARN stations;

d. Readjust pre-existing conventional and other GPS observations in the state while holding the HARN station positions fixed to produce a compatible statewide reference network.

Because HARNs are established on a state-by-state basis, it is important to assure compatibility between states as new HARNs are added. To provide this assurance, NGS has implemented the definition of the NAD83 coordinate system at the few centimeter level and provided a means of accessing it at that level nationwide. The coordinate system definition was accomplished by using NAD83 positions of Very Long Baseline Interferometry (VLBI) stations derived in the original NAD83 reference network adjustment. The differential positions of these VLBI stations (based on analysis of incoming signals from radio stars) are known at the 1 to 3 cm level. Thus they define the NAD83 coordinate system to the same level. To provide access within each state to the defined coordinate system, GPS reduction methods involving correction of satellite orbits, simultaneous with estimation of station positions, are used to compute positions of 3 to 6 stations in each state. These stations, known as A Order stations, by being differentially positioned relative to the VLBI stations have positions relative to the NAD83 coordinate system at the 5 cm or better level. When performing a final adjustment of the HARN network in a state, these A Order stations are held fixed, thus assuring accurate relation of the HARN station positions to the NAD83 coordinate system. Figure 3 shows the current Order A station network in the United States.

To some degree NGS has participated in HARN implementation in all of the states which have established HARNs. However, the amount of NGS participation has varied widely in the observation and reduction phases of HARN development. For example, in Florida NGS performed all observations and data reduction for the B Order HARN network. In Wisconsin observations and reductions of the B Order HARN network were performed by a contractor to the state, with NGS only performing quality checks. As ownership of GPS receivers have become more widespread, observations have been performed jointly by state and NGS field teams as was the case in California. One can anticipate all of these modes of operation continuing in the future.

To assure consistency and proper relation to a common coordinate system, NGS is performing all final computations of positions of A Order stations and final adjustment of the B Order HARN networks in each state.

There are distortions in the existing NAD83 reference network relative to the NAD83 coordination systems. These distortions are usually at the few decimeter level, but have occasionally been found to locally be as large as 1.5 meters. Since the HARN's level of distortion relative to the NAD83 coordinate system is a few centimeters, the discrepancy between HARN and published NAD83 coordinates is of the same order of magnitude as the distortions in the published values. These discrepancies prevent the use of HARN reference stations with their high accuracy NAD83 coordinates in conjunction with the remainder of the existing reference network stations having lesser accuracy NAD83 coordinates. To reintroduce compatibility, while at the same time improving the accuracy of the positions of the remainder of the existing network stations, NGS is undertaking complete readjustments of all previously existing observations in a state. These readjustments hold fixed the previously derived HARN station positions, resulting, not only in bringing about compatibility, but also in improving the accuracy of the positioning of the existing network stations relative to the NAD83 coordinate system.

A Look Ahead

Over the next few years one can foresee an acceleration in the establishment of statewide HARNs until all, or nearly all, of the United States is covered. This acceleration will occur for several reasons. As use of GPS becomes more widespread and the direct positioning procedures come into more common use, there will be an increased recognition of the value of and need for a HARN. Adding to this increased recognition of the value of a HARN will be increasing awareness of the positive experiences of surveyors in states already having HARNs. Also, as more state organizations acquire GPS receivers they will be able to participate in the observation phase of the HARN establishment, thus reducing costs. Given that in a relatively short time frame (< 5 years) almost all of the country will be covered by HARNs, there is much to be said for completing the process as rapidly as possible. Completing the entire upgrade process as soon as possible will minimize the need to make special adjustments at state boundaries. More importantly it will allow counties, cities, etc. to position their more dense reference networks relative to the HARNs initially, removing the need to change coordinates at a later time.

Thus far the question of station spacing for HARNs has been considered entirely in the context of horizontal positioning. However, we should now begin to consider the question of how

HARNs might serve vertical reference network needs. This question will need to be addressed from two directions. The first direction is the determination of how accurately orthometric heights can be determined from GPS using various observation procedures (static, kinematic and pseudo-kinematic) after taking into account the accuracy of the available geoid height information for converting GPS derived ellipsoid heights to orthometric heights. Improvements in satellite orbits and computations of tropospheric refraction corrections give real promise for substantial improvement in GPS derived ellipsoid heights in the next few years. Also, NGS has underway a vigorous program aimed at improving geoid height determinations. Taken together, these two factors provide real promise of the ability to determine orthometric heights at the 3.0 to 6.0 cm (0.1 to 0.2 ft.) level. This is less accuracy than can be provided by leveling, except where extremely large distances are involved. However, it is not clear as to how many requirements for orthometric heights exceed 3.0 cm (0.1 ft.), given varying station separations (1, 5, 10, ... km). This question needs to be carefully addressed.

In the longer time frame, 5 years and beyond, the question of the density of HARN stations needed is a matter that is currently debated. As noted, rather dense reference networks are being established in some counties and cities. This is done with the view of making control available to surveyors using conventional surveying equipment. Some argue that by the end of the decade even 25 to 50 km spacing of the HARNs will not be needed; everyone will operate from automated base stations located perhaps 200 km apart. The question of how dense a monumented network will be required a decade or more from now is far from certain. What is certain is that the final decision will be based on economics, i.e., What is the cheapest way for users to meet their requirements? It is too early in the development of GPS to say what the capabilities will be a decade from now, and thus to answer the economic question. However, it is difficult at present to imagine that monumented stations at densities at lease as great as those provided by statewide HARNs will not be required in the foreseeable future. Even if a 200 km spacing base station network were to come into common use, the need to ensure the integrity of local positioning would still exist. Thus, the statewide HARNs that are being established should play an important reference system role into the next decade regardless of how GPS technology evolves.

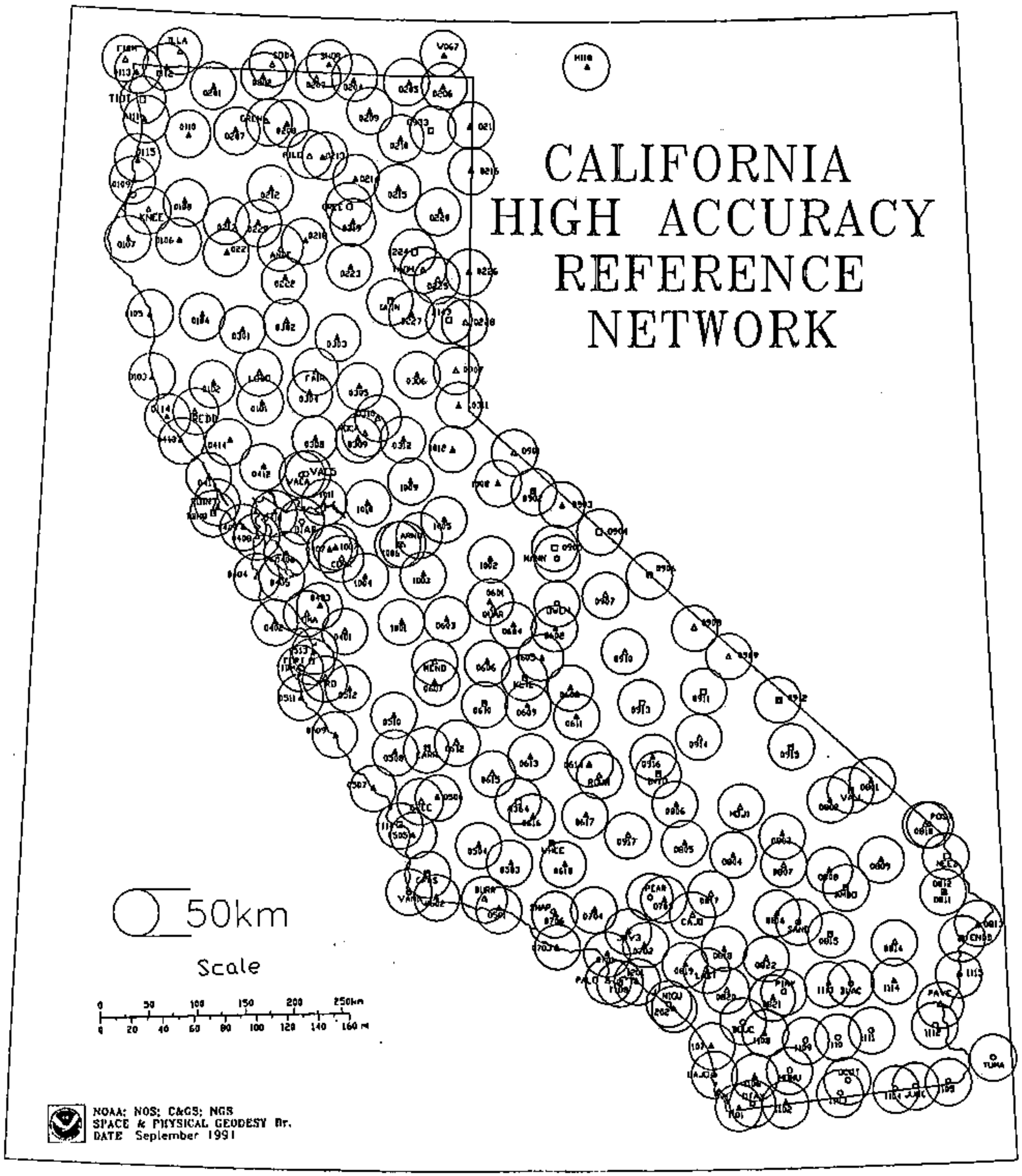
CALIFORNIA
HIGH ACCURACY
REFERENCE
NETWORK
50km
Scale
0 50 100 150 200 250km
0 20 40 60 80 100 120 140 160 mi
NOAA: NOS: C&GS: NGS
SPACE & PHYSICAL GEODESY Br.
DATE September 1991

Figure 1

Statewide High Accuracy Reference Networks

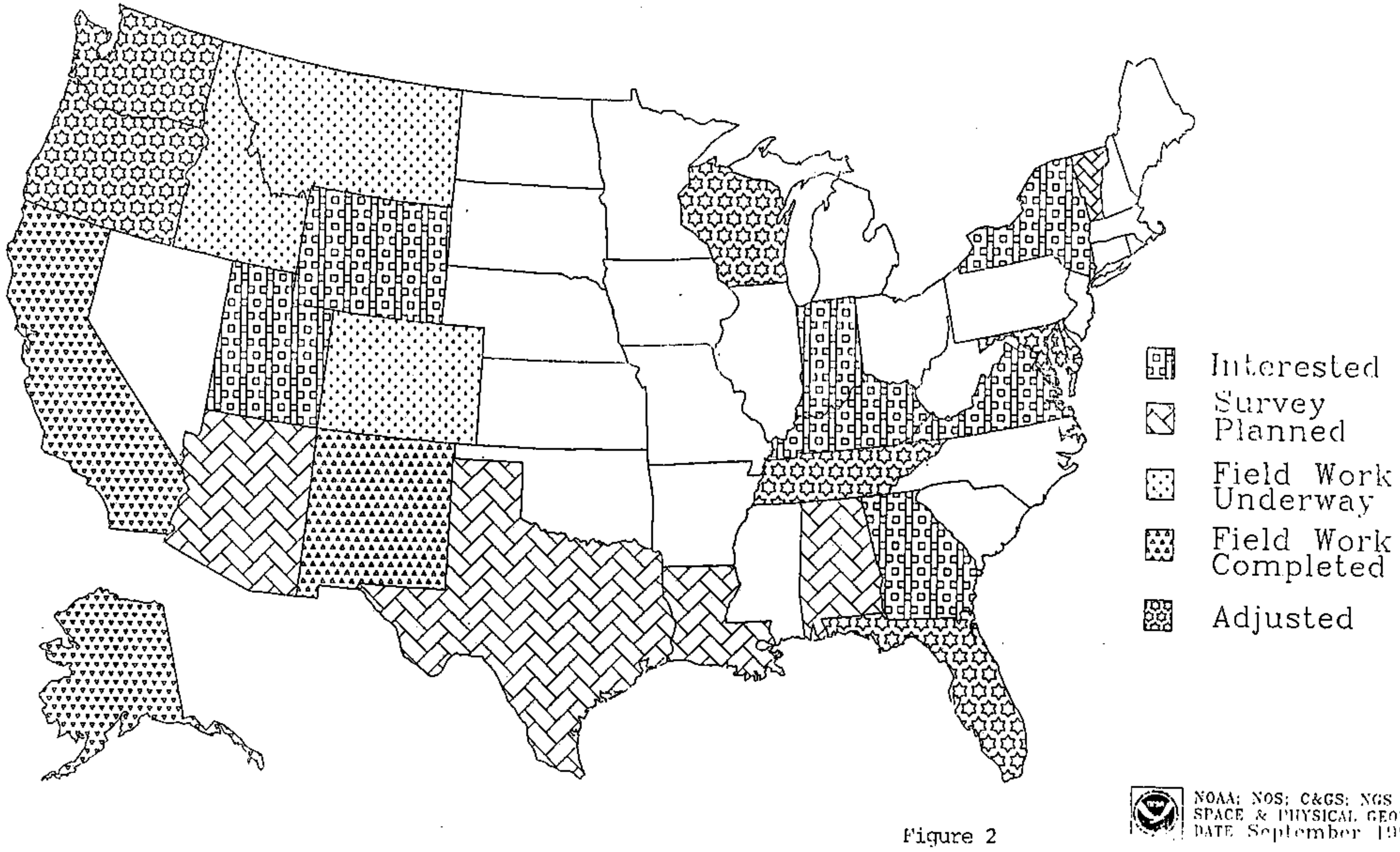

Figure 2

REGIONAL HIGH ACCURACY NETWORK

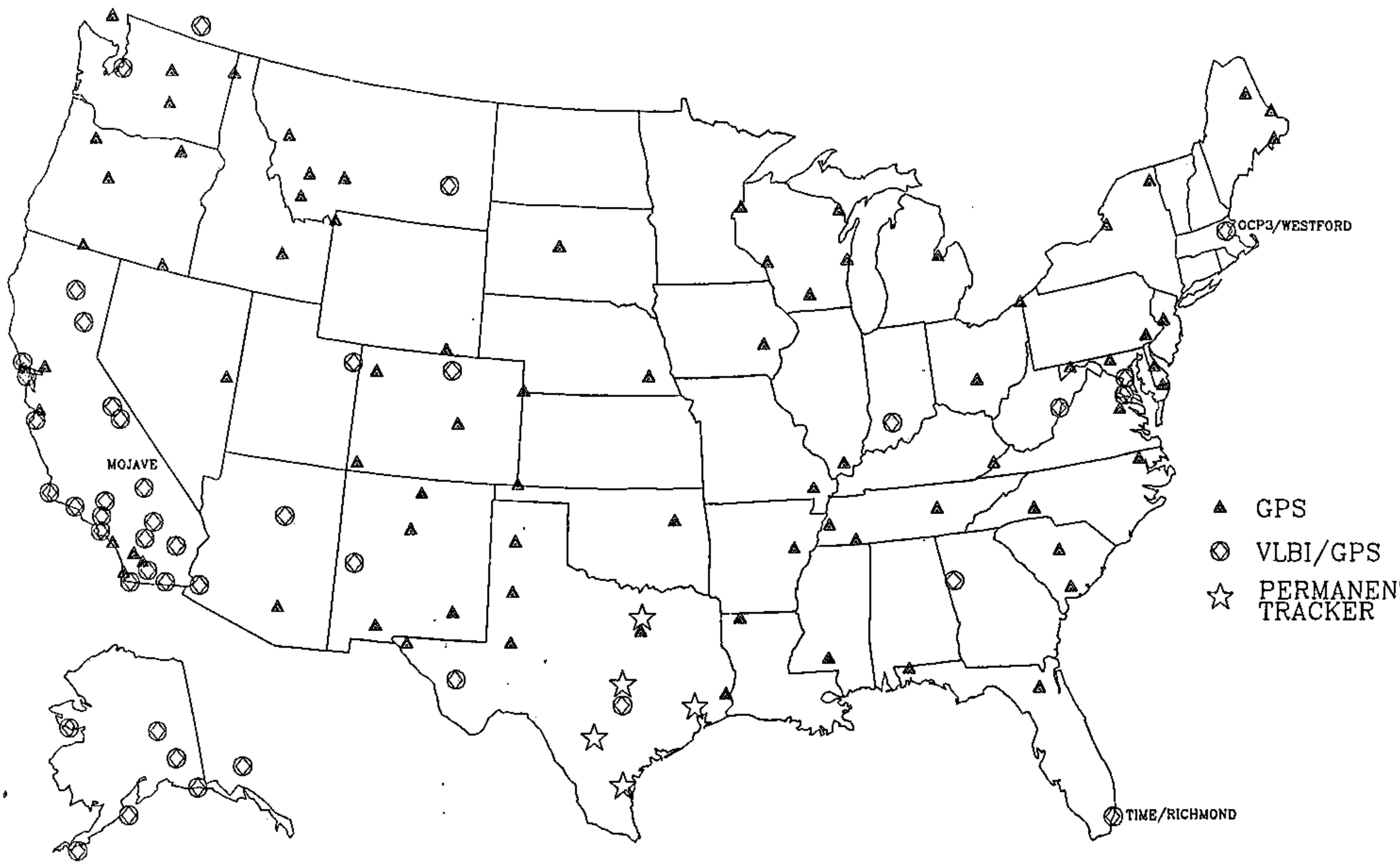

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Figure 3