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THE INFLUENCE OF REFERENCE SYSTEM DISPARITY ON
NAVIGATION AND POSITIONING(U) DEFENSE MAPPING SCHOOL
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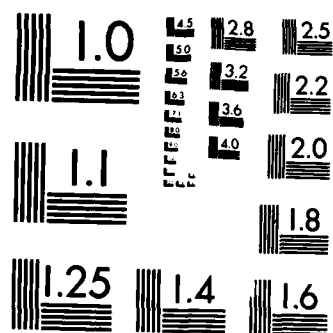
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the position of the center of an ellipsoidal model relative to the center of the mass of the earth is not known. The positions determined on one datum cannot be related accurately to positions on another datum. The development of absolutely-oriented datums incorporating satellite and gravity data has led to the development of datum transformations to relate positions on one datum to those on another.

Sophisticated new electronic navigation and targeting technology requires highly precise input data to obtain output on the order of design accuracies. To obtain positions on the order of ± 1000 feet, care should be taken by the users of such equipment that the datum to which positions are referred is taken into account. If positions are located on two different datums, then the user should know that one set of coordinates should be transformed into the other system prior to their input into the inertial navigation system as a point of departure and a destination.

This paper reviews some basic practical and theoretical concepts of datum development and evaluates errors that may be encountered if a datum transformation is required but is not used. Hardware and software alone cannot minimize the occurrence of these errors. The user community must be educated in the basic concepts of position determination.

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The Influence of Reference System Disparity on
Navigation and Positioning

Captain Gregory A. Robinson
and
Chief Warrant Officer David E. Miller

Defense Mapping School
Department of Topographic Sciences
Fort Belvoir, Virginia



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ABSTRACT

There are many geodetic datums in use throughout the world today. Each of these datums serves as a reference surface for the mapping, charting and geodetic work done in a specific geographical area. Each datum is defined by fitting a specific ellipsoid to the earth in such a manner as to minimize departures of this reference model from the geoid over the area of concern. Historically, these datums have been relatively oriented. Consequently, the position of the center of an ellipsoidal model relative to the center of mass of the earth is not known. The positions determined on one datum cannot be directly related to positions on another datum. The development of absolutely-oriented datums incorporating satellite and gravity data has led to the development of datum transformations to relate positions on one datum to those on another.

Sophisticated new electronic navigation and targeting technology requires highly precise input data to obtain output on the order of design accuracies. To obtain positions on the order of ± 1000 feet/300 meters, care should be taken by the users of such equipment that the datum to which positions are referred is taken into account. If positions are located on two different datums, then the user should know that one set of coordinates should be transformed into the other system prior to their input into the inertial navigation system as a point of departure and a destination.

This paper reviews some basic practical and theoretical concepts of datum development and evaluates errors that may be encountered if a datum transformation is required but is not used. Hardware and software alone cannot minimize the occurrence of these errors. The user community must be educated in the basic concepts of position determination. Therefore, this work is presented in such a manner as to be readily adapted to teach users of varying backgrounds, education and expertise.

INTRODUCTION

The material covered in this paper is not new. The Defense Mapping Agency and systems developers insure that products and systems are designed to minimize problems with datums. However, it has become apparent to the Defense Mapping School that this material is not common knowledge in the user community. To obtain maximum system capabilities, it is essential that users understand this problem if they are expected to enter coordinates into an interactive system.

In order for one to navigate from one point to another on the earth, the locations of both the starting point and the destination must be known. These locations may be determined utilizing one of several coordinate systems. Geographic, universal transverse mercator or military grid reference system are three of these. Each of these reference systems is based on a mathematical model of the earth which, when oriented to the earth at a specific point or "origin", is known as a geodetic datum. An ellipsoid is used as this model, since its shape more closely approximates that of the earth than does a sphere.

Optical methods of navigation and target acquisition were long relied on to compensate for charting and positioning discrepancies. Computerized navigation and weapon delivery systems require input commensurate to the output accuracies desired. The users of maps, charts and other geodetic products must have some knowledge of the use of datums and be able to apply that knowledge to satisfy this requirement for greater accuracy. This work defines geodetic datums, describes their application, and illustrates some of the concerns about them that must be shared by all users of mapping, charting and geodetic products. It is written so as to be easily adapted to educate a wide spectrum of users.

HISTORICAL DEVELOPMENT

The majority of the ellipsoidal models presently in use as datums were derived during the nineteenth century. At that time, most travel was conducted within national boundaries. Prior to the advent of the telegraph and radio time signals, and, more recently, the acceptance of the Greenwich Meridian as a time standard, astronomic longitude determinations were very inaccurate. Therefore, they were referred to each country's national observatories, not to an international standard (Gunther, 1978). The combination of these factors resulted in the development of many datums which fit the earth well only over the area of each nation's mapping effort. Consequently, there is a large number of datums in use throughout the world today. This proliferation of geodetic datums has been easily perpetuated: when one nation maps the area of another for its own use, the nation doing the mapping relies on source material from the nation mapped. It is far easier and less expensive to produce such maps on the other datum than to derive another datum which fits all areas of concern to a nation.

Since World War II, a concerted effort has been made to derive a practical World Geodetic System to overcome some of the problems encountered when working with points located on more than one datum. Initially, such worldwide systems were derived using gravimetric methods and data (Heiskanen and Vening Meinesz, 1958). Much more refined models can now be developed using a combination of gravimetric, astronomic-geodetic, and satellite methods and data.

DEFINITION OF TERMS

A datum is simply a basis for measurement. Therefore a geodetic datum is a basis for the determination of geodetic quantities. Geodetic quantities are various in type. Horizontal positions, vertical positions and gravity values are the three most general categories. In this paper we are principally concerned with positions and the geometric relationships between these positions, i.e. distance and direction. Subsequently, this treatment must be concerned with both horizontal and vertical datums.

A horizontal datum is a reference for specifying the positions of points on the earth's curved surface, that is, latitude and longitude. A vertical datum is a reference for specifying the elevations of these points. Horizontal and vertical datums are further categorized by geographical extent of applicability. A local or regional datum is one of less than global applicability, typically used as a national or continental datum. A global datum is one which is defined such that discrepancies between the surface of the earth and the model are averaged out over the entire earth. Due to this characteristic, such a datum has world-wide applicability, although it may be a better model in some areas than in others.

An important distinction between regional and global datums is the relationship between the model and the earth. The orientation of a global datum is performed in such a way that the center, or intersection of the axes, of the model corresponds to the center of mass of the earth. This is also referred to as "absolute orientation." Regional datums are "relatively" oriented at a point on the surface of the earth, usually the starting point of the control net used to determine horizontal positions in the area of concern. Therefore, even though the ellipsoid used for a regional datum may closely approximate the earth in size and shape, the position of the center of this model relative to the center of mass of the earth cannot be determined from the orientation process.

We have discussed the ellipsoid, our mathematical reference surface, and have alluded to the topography. Neither of these surfaces reflects the true shape of the earth. Therefore, we must define a new surface, the geoid, which is an equipotential surface. An equipotential surface is one on which the potential of gravity is a constant. At every point on this surface, the direction of gravity is normal to the surface, that is, along the plumbline. Since there is an infinite number of equipotential surfaces, it is further stated that the geoid is the equipotential surface which "coincides with that surface to which the oceans would conform over the entire earth if free to adjust to the combined effect of the earth's mass attraction and the centrifugal force of the earth's rotation" (Burkard, 1968). The geoid is that equipotential surface which most closely represents the true shape of the earth.

Since the geoid is a complex surface, the reference surface does not everywhere coincide with it. The vertical departures of the ellipsoidal model from the geoid are called geoidal undulations or geoidal separations (Fig 1), and are measured along the plumbline. The angular departures are deflections of the vertical (Fig 1, 2). A deflection, also known as a deviation of the vertical, is the angle between the plumbline through the point on the geoid, and the normal through the corresponding point on the ellipsoid. A deflection angle is separated into its two components, one in the observer's meridian and the other in the prime vertical (Fig 2).

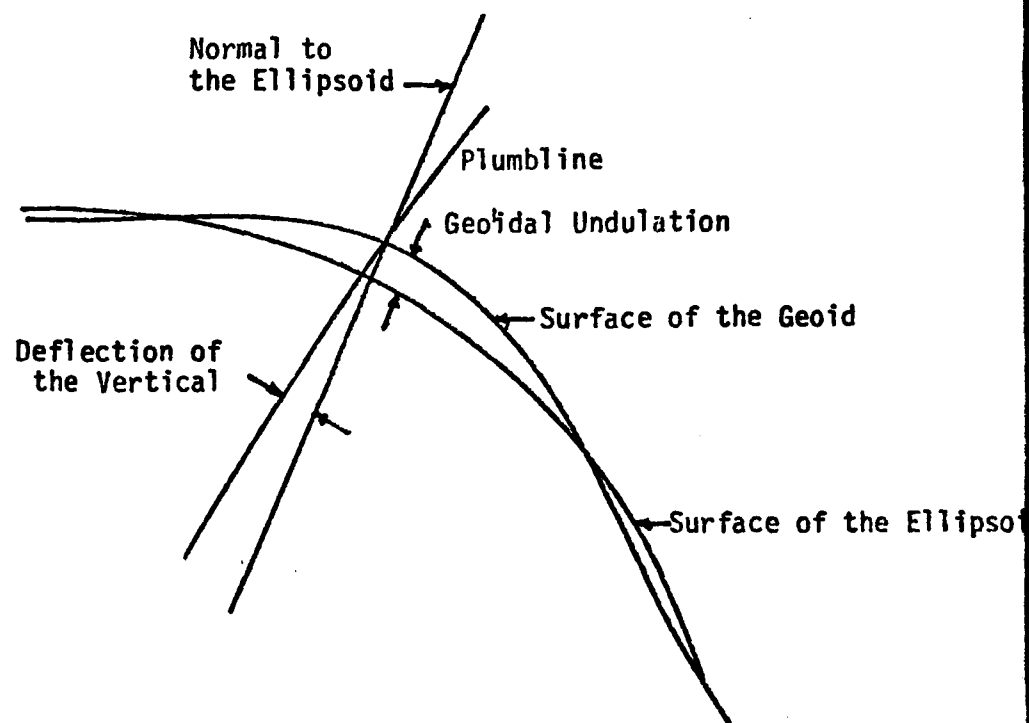


Figure 1. Geoid-Ellipsoid Relationship

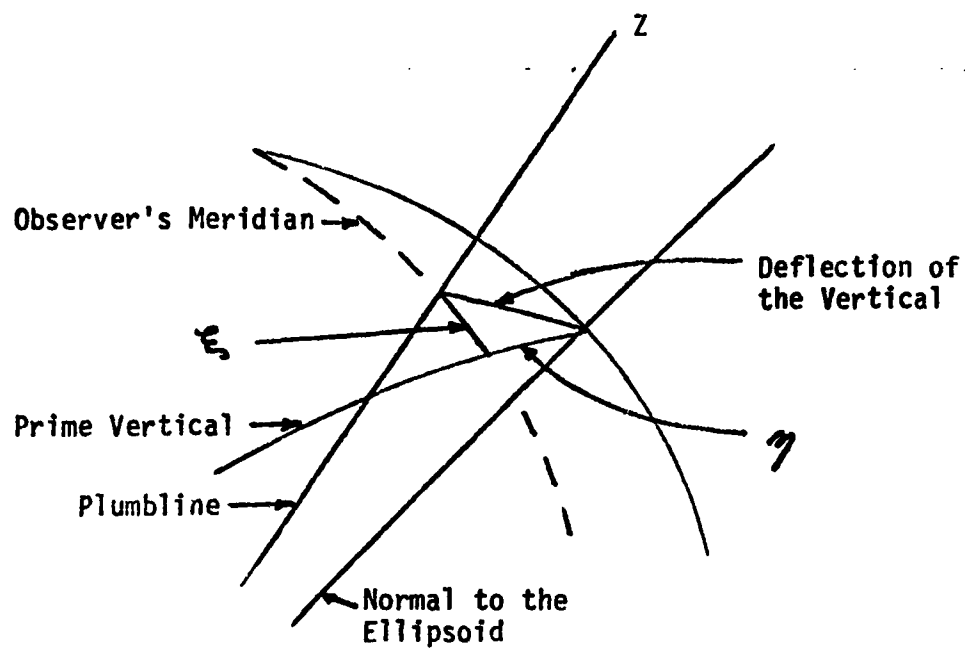


Figure 2. Components of Deflection of the Vertical

HORIZONTAL DATUM ORIENTATION

The geoid is a mathematically complex figure unacceptable as a surface for computations. We, therefore, select a reference surface that is mathematically regular and is of approximately the same shape as the geoid: an ellipsoid. In order to use the model, we must define its relationship to the geoid, that is, establish a datum. The objective of establishing this datum is to fit a particular ellipsoid to the geoid so that its departures from the geoid are principally random and any departures, systematic or random, are small. A regional horizontal datum is established by fitting the ellipsoid to the geoid using seven orientation parameters. It is of particular importance to note that the ellipsoid itself does not constitute a datum. These parameters are:

- 1) a = the semi-major axis (equatorial radius) of the ellipsoid;
- 2) f = ellipsoidal flattening;
- 3) ξ = deflection of the vertical, prime vertical component, at the origin;
- 4) η = deflection of the vertical, meridian component, at the origin;
- 5) N = geoidal undulation, at the origin;
- 6) α_0 = geodetic azimuth of initial line, defined by astronomic azimuth;
- 7) The condition that the rotational axis of the ellipsoid is parallel to the rotational axis of the earth.

If the astronomically determined position of the origin is not assumed to be the geodetic position, then geodetic latitude, longitude, and height are also required. Detailed discussion of the derivation and discussion of several methods of orientation may be found in Rapp (1981).

Practically speaking, there are two general methods for performing a datum orientation. For small areas, such as islands, the astronomic position is defined to be the geodetic position, $\xi = \eta = N = 0$, and the geodetic azimuth is defined by the astronomic azimuth. This method is unsatisfactory for large areas because ξ , η and N systematically increase with increasing distance from the origin.

The orientation of a datum for a large area requires estimates of the first six parameters and the geodetic position of the origin. These may be determined by the method given above. A preliminary adjustment of the survey is then done. The results are analyzed and better values are determined for the positional and ellipsoidal parameters.

The datum, as established, is a best fit for the area of concern. If the same datum were used elsewhere, the results may not be acceptable. Specifically, large deflections of the vertical and geoidal undulations could result. An ellipsoid may be suitable for more than one area, but the other datum orientation parameters must be re-determined. Table 1 gives parameters for some preferred regional datums. A preferred datum is a regional datum used for areas of continental extent or for large areas over adjoining continents. Figure 3 illustrates positional differences between the ellipsoids used for two datums and the center of the earth (Burkard, 1968).

DATUM TRANSFORMATIONS

As previously stated, we do not know the relative positions of the

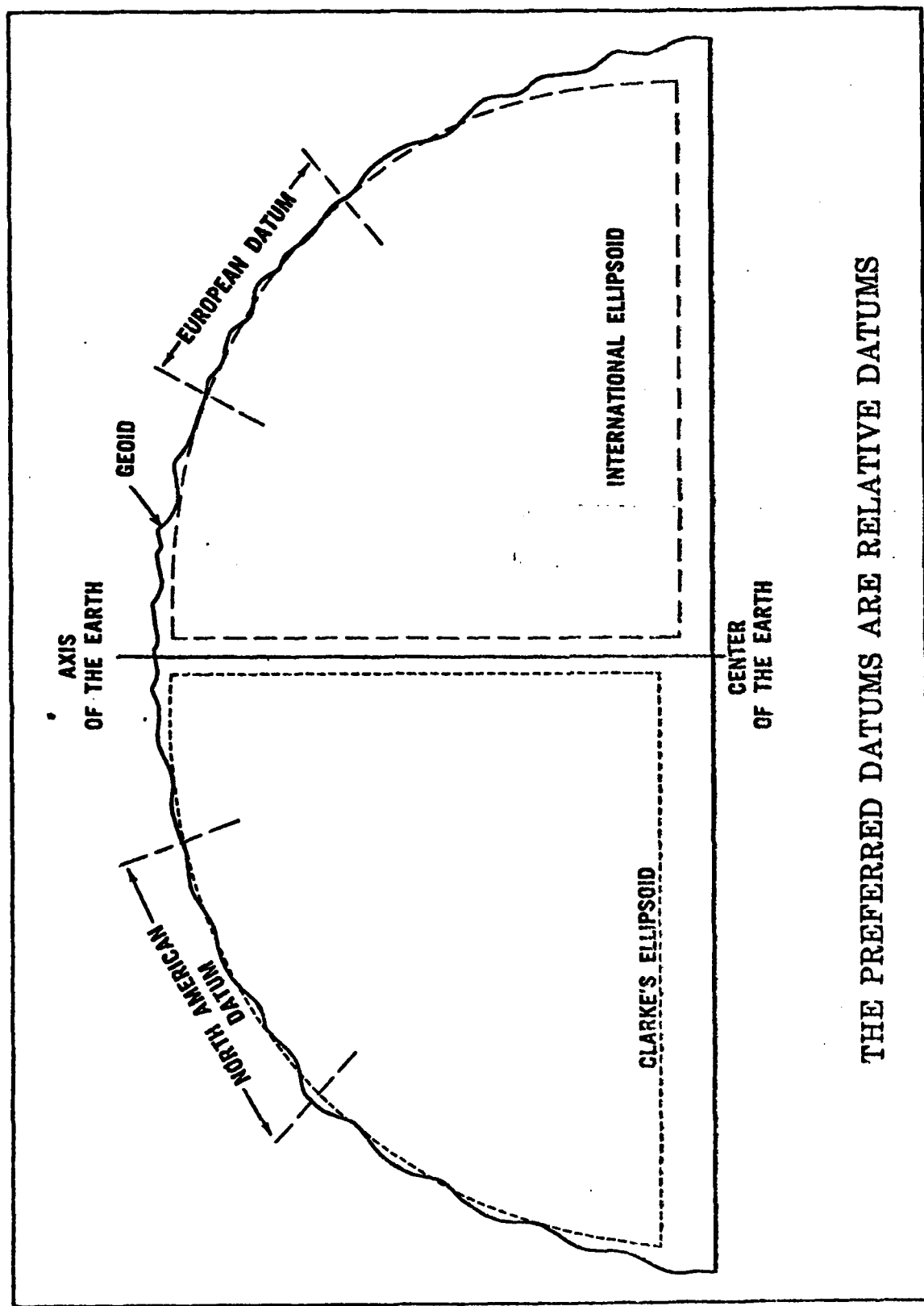
TABLE 1. Some Preferred Datums and Ellipsoid Parameters.

1-A. Preferred Datums.

DATUM	ELLIPSOID	ORIGIN	
		LATITUDE	LONGITUDE
Australian Geo Datum	Austr Natl	-25°56'54".55	133°12'30".08
European Datum 1950	International	52°22'51".446	13°03'58".928
Indian	Everest	24°07'11".26	77°39'17".57
NAD 27	Clarke 1866	39°13'26".686	261°27'29".494
Tokyo	Bessel	35°39'17".5148	139°44'40".90

1-B. Corresponding Ellipsoidal Parameters.

ELLIPSOID	SEMI-MAJOR AXIS (meters)	1/FLATTENING
Australian National	6378160	298.25
Bessel	6377397.155	299.152813
Clarke 1866	6378206.4	294.978698
Everest	6377276.345	300.8017
International	6378388	297



THE PREFERRED DATUMS ARE RELATIVE DATUMS

Figure 3. Relative positions of two relatively-oriented datums (Burkard, 1968)

center of our relatively-oriented reference ellipsoid and the center of mass of the earth. Consequently, if we have geographic coordinates (ϕ_A, λ_A, H_A) of a point in one datum, for example NAD 27, we cannot directly determine the coordinates (ϕ_B, λ_B, H_B) in another datum, for example ED 50, unless we have ground points common to the two systems. The use of satellite data enables us to resolve this problem. These data, in combination with gravimetric and astro-geodetic data, have been used in the determination of absolutely-oriented worldwide geodetic systems. The one presently in use is DoD WGS 1972, soon to be replaced by DoD WGS 1984. These datums, by the nature of the data from which they are derived, have ground points in common with the regional horizontal datums. This fact enables us to transform positions from a regional datum to WGS and then to another regional datum. Rapp (1981) addresses several approaches to two methods of transformation. A general form of one method is:

$$X_B = X_A + dX + R(\omega, \epsilon, \psi) X_A + dA * R(\phi_0, \lambda_0)(X - X_1) + dS * R(\phi_1, \lambda_1, \alpha_1)$$

where, in matrix notation:

X_B are the desired rectangular coordinates in datum 2;
 X_A are the known coordinates in datum 1;
 dX are the translations in x, y, and z between the two origins;
 $R(\omega, \epsilon, \psi) X_A$ is the rotation of the axes of the first system (1) into those of the second;
 $dL * X_A$ is a scale change;
 $dA * R(\phi_0, \lambda_0)(X - X_1)$ corrects for orientation effects in the initial azimuth;
 $dS * R(\phi_1, \lambda_1, \alpha_1)$ corrects for system inconsistencies in distances S.

These values then must be converted to geographic coordinates in datum 2. Rapp (1981) gives equations for the complete transformation in section 2.76.

RESULTANT ERRORS

A datum transformation program developed by the Defense Mapping Agency Aerospace Center was used in a Hewlett-Packard 9825B desktop computer to demonstrate the magnitudes of errors that could result if Tokyo coordinates based on the Tokyo datum were input as destination coordinates to an electronic navigation system with the assumption that these coordinates were based on the same datum as the point of departure. The results are given in Table 2. It should be noted that these errors are due solely to a difference in datums. They do not reflect errors in the navigational system. For civilian commercial aviation, errors of this magnitude are insignificant at this time. However, such errors are critical in attempts to obtain positional accuracies of +/- 1000 feet or better.

Such errors can occur quite easily. Mixing the use of charts from different datums in flight planning could be one cause. In a military application, an aircraft could receive target coordinates based on one datum from a ground commander and use them as though they were based on the same datum as the flight charts when such was not the case. This latter mistake appears to have happened several times in the Viet Nam conflict. The failure of the German V2 rocket program during World War II was partly due to this problem.

SPHERICAL DATUMS

Spherical datums, because they do not approximate the shape of the earth as

TABLE 2. Positional Errors Due to Datum Difference.

Destination: Tokyo, 35°37'30"0 N, 139°45'00"0 E.

Data reflects errors in position due to coordinates being computed on datum of origin instead of Tokyo Datum with a datum transformation.

DATUM OF ORIGIN	$d \phi''$	$d \lambda''$	POSITIONAL ERROR (ft) / (m)
NAD 27	16.38	- 7.86	1778/542
ED 50	17.58	-17.34	2282/696
AGD	18.90	-16.43	1833/559
ARC 50 (1)	29.91	-19.34	3420/1042
S. AMER (2)	13.83	-13.94	1811/552
ALASKA (3)	16.05	- 8.07	1754/535

(1) South Africa, uses Clarke 1880 ellipsoid

(2) South America, uses S. American ellipsoid

(3) Uses Clarke 1866 ellipsoid

closely as an ellipsoidal datum, will contribute some error to absolute positions. An attempt to mix datums will also yield errors of the nature shown for ellipsoidal datums. Additionally, errors will result if spherical datums of different radii are mixed. From Figure 4, using the law of cosines for a spherical triangle:

$$\cos(s/R) = \cos(d\phi)\cos(d\lambda)$$

and

$$ds = \cos^{-1}(\cos(d\phi)\cos(d\lambda))dR$$

where ds is the difference in distance between two points, $d\phi$ is the difference in their latitudes, and $d\lambda$ is the difference in their longitudes. This yields a maximum error of 0.77851328 times dR , of the difference in radii of the two datums. This value assumes that both are absolutely oriented with parallel rotational axes. If dR is as great as the difference in equatorial radii of ellipsoidal models, ds values in excess of one nautical mile would not be unreasonable to expect.

VERTICAL DATUMS

Elevation data are usually not given as geodetic heights, that is, height above the ellipsoid, since the varying relationship between the topography and the ellipsoid would usually make such information meaningless. The vertical datum for much of the world is a zero elevation corresponding to a local sea level. The problems of modelling inertial systems for heights and deflections of the vertical are recognized, but are outside the purview of this paper. Elevation differences between vertical datums are typically on the order of 1-2 meters (3-7 feet).

MOVEMENT TOWARD A RESOLUTION

The resolution of this problem with datums is not solely a function of hardware. The testing procedures used on inertial navigation systems within the Department of Defense ensure that the coordinates used are on the same datum. Education of the users of navigation systems and any other system relying on input from the MC&G community is the only certain method of reducing errors due to a lack of understanding of the function of datums and maximizing the effectiveness of technological advances.

SUMMARY

All geodetic positions are based on references called datums. Horizontal positions are referred to any of a large number of ellipsoids which are oriented to the geoid to develop horizontal datums. Positional errors on the order of 1550 to 3400 feet may occur if coordinates used are referred to different datums and transformed coordinates are not calculated. It is imperative that the users of mapping, charting and geodetic products be educated to minimize the occurrence of such errors.

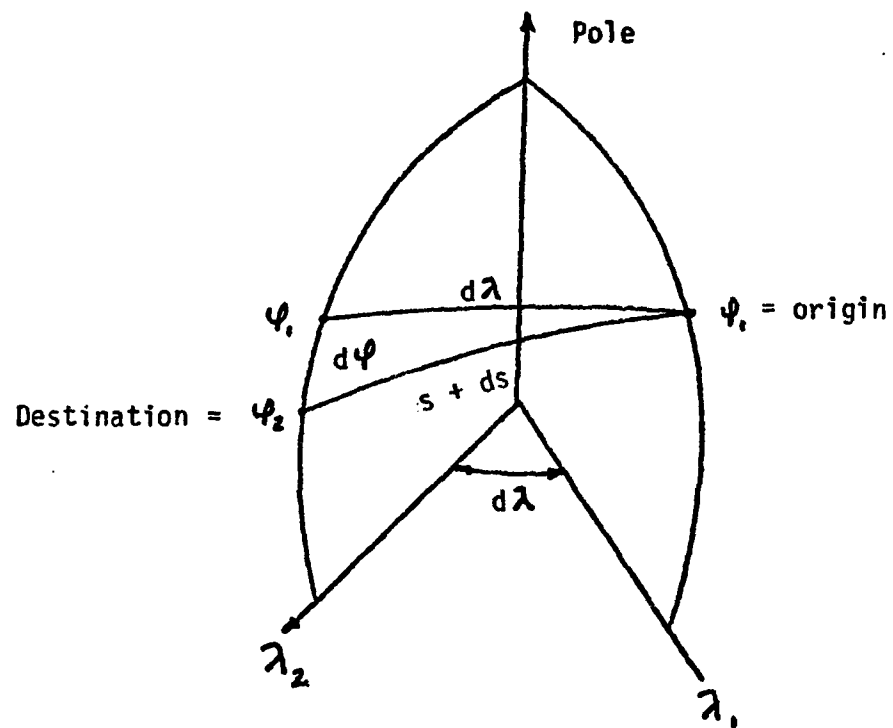


Figure 4. Distance Travelled on a Sphere

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