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The Defense Mapping Agency (DMA) has developed World Geodetic System 1984 (WGS 84) as a replacement for WGS 72. The defining parameters and reference frame orientation of the WGS 84 Ellipsoid, and the WGS 84 Ellipsoidal Gravity Formula, are those of the internationally-sanctioned Geodetic Reference System 1980 (GRS 80). The WGS 84 Earth Gravitational Model (EGM), complete through degree (n) and order (m) 180, was developed using various types of data. The low degree and order portion of the WGS 84 EGM (through n=m=41) was developed from a weighted least squares solution based on the use of surface gravity data, satellite radar altimetry, laser and Doppler satellite tracking data, range difference data (from NAVSTAR Global Positioning System Satellites), and "lumped coefficient" data. The WGS 84 EGM coefficients above n=m=41 were determined from a spherical harmonic analysis of a worldwide residual 1°x1° mean free-air gravity anomaly field from which the effect of the coefficients through n=m=41 had been removed. The WGS 84 Geoid was formed using a spherical harmonic expansion and the WGS 84 EGM (through n=m=180). Local geodetic-to-WGS datum shifts are available for converting the geodetic coordinates

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WGS 84 Earth Gravitational Model
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Local Geodetic-to-WGS 84 Datum Shifts
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Regression Equations
Multiple Regression Equations
Abridged Molodensky Datum Transformation Formulas
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WORLD GEODETIC SYSTEM 1984

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SUMMARY

The Defense Mapping Agency (DMA) has developed World Geodetic System 1984 (WGS 84) as a replacement for WGS 72. The defining parameters and reference frame orientation of the WGS 84 Ellipsoid, and the WGS 84 Ellipsoidal Gravity Formula, are those of the internationally-sanctioned Geodetic Reference System 1980 (GRS 80). The WGS 84 Earth Gravitational Model (EGM), complete through degree (n) and order (m) 180, was developed using various types of data. The low degree and order portion of the WGS 84 EGM (through n=m=41) was developed from a weighted least squares solution based on the use of surface gravity data, satellite radar altimetry, laser and Doppler satellite tracking data, range difference data (from NAVSTAR Global Positioning System Satellites), and "lumped coefficient" data. The WGS 84 EGM coefficients above n=m=41 were determined from a spherical harmonic analysis of a worldwide residual $1^{deg} \times 1^{deg}$ mean free-air gravity anomaly field from which the effect of the coefficients through n=m=41 had been removed. The WGS 84 Geoid was formed using a spherical harmonic expansion and the WGS 84 EGM (through n=m=180). Local Geodetic System-to-WGS 84 datum shifts are available for converting the geodetic coordinates of approximately 80 local geodetic systems to WGS 84. Since most of the local geodetic systems either had no local geoids or those available were of poor quality, local geoids were prepared as part of the WGS 84 development effort and are available for use when converting local geodetic systems to WGS 84. The geocentric coordinate system of the Navy Navigational Satellite System, modified in origin, scale, and longitude reference, provided the WGS 84 coordinates for the datum conversion stations used in developing Local Geodetic System-to-WGS

84 datum shifts. The parameters/products that define and form WGS 84 are now available for use in developing mapping, charting, geodetic, and gravimetric products and supporting various applications.

1.0 INTRODUCTION

Numerous mapping, charting, geodetic, gravimetric, and digital products are produced by the Defense Mapping Agency (DMA). It is advantageous to reference these products to a world geodetic system due to the large number and variety of such products and their users, the need for commonality in relating information from one product to another, increasingly stringent accuracy requirements, and the need to support space age activities worldwide. Such a world geodetic system provides a basic reference frame and geometric figure for the earth, models the earth gravimetrically, and provides the means for relating positions on various local geodetic systems to a single earth-centered, earth-fixed coordinate system. To date, three such systems, World Geodetic System 1960 (WGS 60), WGS 66, and WGS 72, each successively more accurate, have been developed by DMA. The purpose of this paper is to report on a new more accurate and extensive system, WGS 84, which has been developed as a replacement for WGS 72. The new system represents DMA's modeling of the earth from a geometric, geodetic, and gravitational standpoint using data, techniques, and technology available through early 1984.

2.0 THE WGS 84 REFERENCE FRAME

In keeping with the international geodetic community's definition of the reference frame for Geodetic Reference System 1980 (GRS 80) [1]: the origin of the WGS 84 coordinate system is the center of mass of the earth; the WGS 84 Z-axis is parallel to the direction of the Conventional International Origin (CIO) for polar motion, as defined by the Bureau International de l'Heure (BIH) on the basis of the latitudes adopted for the BIH stations; the X-axis is the intersection of the WGS 84 reference meridian plane and the plane of the mean astronomic equator, the reference meridian being parallel to the zero meridian defined by the Bureau International de

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l'Heure on the basis of the longitudes adopted for the BIH stations; and the Y-axis completes a right-handed, earth-fixed orthogonal coordinate system measured in the plane of the mean astronomic equator 90° east of the X-axis. The WGS 84 Coordinate System origin and axes also serve as the geometric center and the X,Y, and Z (rotational) axes of the WGS 84 Ellipsoid.

The WGS 84 Coordinate System is the reference frame of a mean or standard earth rotating at a _constant_ rate around a mean astronomic pole (the CIO) fixed in time. Since the universe is in motion, the earth is non-standard, and events occur in an instantaneous world, the WGS 84 Coordinate System (Conventional Terrestrial System) must be related to an instantaneous terrestrial system and an inertial reference frame. The mathematical relationship between the WGS 84 Coordinate System and these associated reference frames can be expressed as:

$$CTS = [A] [B] [C] [D] CIS \qquad (1)$$

where the rotation matrices for polar motion (A), sidereal time (B), nutation (C), and precession (D) provide the relationship between the Conventional Inertial System (CIS), defined by the FK5 Star Catalog referenced to Epoch J2000, and the Conventional Terrestrial System (CTS) = WGS 84 Coordinate System. Proceeding from right-to-left in Equation (1) through matrices D, C, and B establishes the relationship between the CIS and what might be termed the Instantaneous Terrestrial System (ITS). However, since the ITS Pole (instantaneous axis of rotation) cannot be measured, the Celestial Ephemeris Pole (CEP) is actually used. The CEP is the mean axis of rotation of the earth over a 24-hour period [2] and thus closely approximates the ITS Pole. Matrix A provides the relationship between the CIO, or mean pole of the standard earth being modeled by WGS 84 (CTS), and the CEP (which approximates the instantaneous pole of the instantaneous earth).

3.0 THE WGS 84 ELLIPSOID AND ASSOCIATED CONSTANTS

The WGS 84 Ellipsoid is a geocentric equipotential ellipsoid of revolution defined by the semimajor axis (a), the universal

gravitational constant (GM), the normalized second degree zonal harmonic coefficient of the geopotential ($\overline{C}_{2,0}$), and the angular velocity (ω) of the earth (Table 1). To promote standardization and in the absence of any changes of significance, the values adopted for the four defining parameters of the WGS 84 Ellipsoid are those of the internationally sanctioned GRS 80 Ellipsoid [1]. However, to maintain consistency with the coefficient form used with the WGS 84 EGM, $\overline{C}_{2,0}$ rather than the GRS 80 J_2 is used with WGS 84. The WGS 84 $\overline{C}_{2,0}$ value was obtained from the GRS 80 J_2 value, $J_2 = 108263 \times 10^{-8}$, using the relationship $\overline{C}_{2,0} = -J_2/(5)^{1/2}$, and truncating the result to eight significant digits. The $\overline{C}_{2,0}$ value is defined to exclude the permanent tidal deformation. The four defining parameters were used to calculate the more commonly used geometric and physical constants associated with the WGS 84 Ellipsoid. Space limitations prevent their inclusion here.

The defining parameters and those of the WGS 72 Ellipsoid are listed in Table 2 along with their differences. Table 2 also contains a value for the earth's gravitational constant that does not include the mass of the earth's atmosphere (GM'), and an untruncated value for the earth's angular velocity (ω') which is consistent with the new definition of time [3]. For precise satellite applications, the untruncated angular velocity ω' rather than ω should be used in the formula $\omega^* = \omega' + m$ with the new precession rate in right ascension m [3] to obtain the angular velocity of the earth in a precessing reference frame (ω^*).

Other constants adopted for use with WGS 84 include the velocity of light in a vacuum (c) and GM_A of the atmosphere:

$$c = (299792458 \pm 1.2)\text{m s}^{-1} \qquad [4] \qquad (2)$$

$$GM_A = (3.5 \pm 0.03) \times 10^8 \text{m}^3 \text{ s}^{-2} \qquad [4] \qquad (3)$$

where the universal constant of gravitation (G) and the mass of the earth's atmosphere were taken to be

$$G = (6.673 \pm 0.001) \times 10^{-11} \text{m}^3 \text{s}^{-2}\text{kg}^{-1} \qquad [4]$$

and

$$M_A = (5.24 \pm 0.02) \times 10^{18} \text{kg} \qquad [5].$$

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4.0 THE WGS 84 ELLIPSOIDAL GRAVITY FORMULA

Values of theoretical (normal) gravity (γ) on the surface of the WGS 84 Ellipsoid can be computed using the closed form WGS 84 Ellipsoidal Gravity Formula

$$\gamma = \frac{978032.67714(1+0.001931851386 \sin^2\phi)}{(1-0.00669437999013 \sin^2\phi)^{1/2}} \text{ milligals} \qquad (4)$$

where ϕ is the WGS 84 geodetic latitude. The primary purpose of the WGS 84 Ellipsoidal Gravity Formula is to serve as a reference for gravity measurements when forming gravity anomalies (Δg) via the formula $\Delta g = g_0 - \gamma$. (In classical gravity reduction theory, g_0 in the preceding formula is a value for measured gravity after it has been reduced to the geoid by one of several available methods.)

4.0 THE WGS 84 EARTH GRAVITATIONAL MODEL (EGM)

The form of the WGS 84 EGM is a spherical harmonic expansion of the geopotential. The WGS 84 EGM, complete through degree (n) and order (m) 180, is comprised of 32755 geopotential coefficients. The coefficients through n=m=41 were obtained from a weighted least squares solution of a normal equation matrix developed by combining individual normal equation matrices formed from Doppler satellite tracking data, satellite laser ranging data, $3^o \times 3^o$ equal-area mean free-air gravity anomalies, oceanic $3^o \times 3^o$ equal-area mean geoid heights deduced from SEASAT satellite radar altimeter data, NAVSTAR Global Positioning System (GPS) data, and "lumped coefficients". Seven satellites of different inclinations (i), BEACON C (i=41°), GEOS-1 (i=59°), Doppler Beacon 14 (i=63°), HILAT (High Latitude, i=82°), Navy Navigational Satellite 68 (i=90°), SEASAT (i=108°), and GEOS-3 (i=115°), provided Doppler data for the least squares solution. Laser satellite tracking data was provided by LAGEOS (Laser Geodynamics Satellite, i=110°) and the French Starlette Satellite (i=49.8^o). The point gravity anomaly data available in the Department of Defense (DoD) Gravity Library 1 January 1984 for use in developing the WGS 84 EGM consisted of 11,688,136 gravity values referenced to the International Gravity

Standardization Net 1971 (IGSN 71) [6] and the WGS 84 Ellipsoidal Gravity Formula. The influence of the observed gravity data was extended considerably by using it in combination with geological/geophysical parameters in certain land areas and with altimetric-derived geoid heights in selected oceanic areas to form equiangular 1^O x 1^O mean gravity anomalies. The remainder of the worldwide equiangular 1^O x 1^O field not formed in this way or from observed gravity data only was developed from satellite radar altimeter data alone (oceanic areas), and from a spherical harmonic expansion using a preliminary n=m=41 WGS 84 EGM. This worldwide set of 1^O x 1^O equiangular mean free-air gravity anomalies referenced to the WGS 84 Ellipsoidal Gravity Formula was then used to form the 4584-member set of 3° x 3° equal-area mean gravity anomalies used in the least squares EGM solution. The 2918-member set of oceanic 3° x 3° equal-area mean geoid heights was formed from an 18,056-member set of 1^O x 1^O equiangular SEASAT mean geoid heights referenced to the WGS 84 Ellipsoid. The limited NAVSTAR GPS data set consisted of four continuous weeks of simultaneous tracking data from five GPS satellites. After the n=m=41 portion of the WGS 84 EGM was available from the weighted least squares solution, the effect (contribution) of these coefficients was removed from the worldwide 1^O x 1^O equiangular mean gravity anomaly field leaving a worldwide residual 1^Ox1^O mean gravity anomaly field. This worldwide residual field was then used in a spherical harmonic analysis to obtain coefficients from n=42, m=0 through n=m=180. The coefficients through n=m=41 from the weighted least squares solution and the coefficients above n=m=41 from the spherical harmonic analysis comprise the n=m=180 WGS 84 EGM.

The WGS 84 EGM through n=m=180 is to be used when calculating WGS 84 Geoid Heights, WGS 84 gravity disturbance components (or deflection of the vertical components), and WGS 84 1^O x 1^O mean gravity anomalies via spherical harmonic expansions. Expansions to this degree and order (n=m=180), and higher, are needed to accurately model variations in the earth's gravitational field in or

near the earth's surface. While the WGS 84 (n=m=180) is needed for certain applications on the earth's surface and in near-earth space, it is not required and is impractical to apply for many applications. The WGS 84 EGM through n=m=41 is more appropriate for satellite orbit calculation and prediction purposes. The use of higher degree and order models for satellite orbit applications is not recommended at this time. The WGS 84 EGM through n=m=41 is available to qualified DoD requesters on magnetic tape in both conventional and normalized geopotential coefficient form. The WGS 84 EGM through n=m=180 is available to qualified DoD requesters on a separate magnetic tape in normalized geopotential coefficient form only.

5.0 THE WGS 84 GEOID

The principal functions of the WGS 84 Geoid are to serve as the reference surface for WGS 84-related height above mean sea level (h) values in those parts of the world where geodetic vertical datums are not available from tide gauge data, provide WGS 84 positional data in oceanic areas where WGS 84 geoid heights are equivalent to WGS 84 geodetic heights, and to provide a numerical measure of how well the WGS 84 Ellipsoid approximates the mean sea level surface of the earth (the root mean square geoid height, worldwide, equals ±30.5 meters). A spherical harmonic expansion involving the n=m=180 WGS 84 EGM defines the WGS 84 Geoid.

The WGS 84 Geoid is a considerable improvement over the WGS 72 Geoid. The root-mean-square (RMS) difference between a worldwide 1^O x 1^O grid of WGS 84 and WGS 72 geoid heights, each referenced to their respective ellipsoids, was ±4.6 meters. The largest positive and negative differences were 24.0 and -23.5 meters, respectively. The WGS 84 geoid heights have an error range of ±2 to ±6 meters (one sigma), their accuracy over approximately 70 percent of the earth ranging from ±2 to ±3 meters (one sigma). The WGS 84 geoid heights are available to qualified DoD requesters as a worldwide contour chart (contour interval = 5 meters), or as a magnetic tape containing a worldwide 30' x 30' grid of values and an

accompanying interpolation scheme. As a test of the interpolation scheme, out of 259,200 differences ("true" values minus interpolated values), only 32 exceeded one meter with the largest difference being 1.6 meters. The RMS difference was ±0.09 meter. Software for computing gridded or random point geoid heights is also available to qualified requesters.

6.0 LOCAL GEODETIC SYSTEM TO WGS 84 DATUM TRANSFORMATION

6.1 BASIC DATA

One of the principal purposes of a world geodetic system is to provide the means whereby local geodetic systems can be referenced to a single geocentric system. To accomplish this, local geodetic and WGS coordinates are both required at one or more sites within the local datum area so that local geodetic system-to-WGS datum shifts can be formed. Doppler stations positioned within the Navy Navigational Satellite System (NNSS) Coordinate System (NSWC 9Z-2), and with known local geodetic system coordinates, were the basic ingredient in the development of Local Geodetic System-to-WGS 84 datum shifts. The WGS 84 coordinates were obtained for these Doppler sites by modifying the NSWC 9Z-2 Coordinate System in origin and scale, and rotating it to bring its reference meridian into coincidence with the BIH-defined zero meridian. Over 1500 Doppler stations were used in the development of WGS 84. (By contrast, only 49 Doppler stations were available for use in the development of WGS 72.)

6.2 DATUM TRANSFORMATION FORMULAS

6.2.1 GENERAL

Methods (formulas) for converting local geodetic systems to WGS 84 include the Standard Molodensky Datum Transformation Formulas [7], the Abridged Molodensky Datum Transformation Formulas [8], and Datum Shift Multiple Regression Equations [9]. The Standard Molodensky Datum Transformation Formulas produce results at the ellipsoid surface more accurate in geodetic latitude by 0.6 meter than can be obtained with the more extensively used Abridged Molodensky Datum Transformation Formulas. (The Standard Molodensky

Datum Transformation Formulas also produce geodetic latitudes and longitudes more accurate by approximately one meter at approximately 40,000 feet altitude than can be obtained using the abridged formulas.) However, due to the triangulation extension errors that affect most local geodetic systems, use of either the Standard or Abridged Molodensky Datum Transformation Formulas produces results that are of sufficient accuracy only when <u>localized</u> rather than <u>mean</u> datum shifts $(\overline{\Delta X}, \overline{\Delta Y}, \overline{\Delta Z})$ are used. Efforts to have localized datum shifts available has led to the preparation of ΔX, ΔY, ΔZ datum shift contour charts. However, contour charts whether in datum shift or coordinate difference ($\Delta\phi, \Delta\lambda, \Delta H$) form are easily used only in an office environment. The combined need for the greater accuracy provided by localized datum shifts and ease in performing datum transformations in the field has led to the development of Datum Shift Multiple Regression Equations.

6.2.2 DATUM SHIFT MULTIPLE REGRESSION EQUATIONS

The development of Local Geodetic System-to-WGS 84 Datum Shift Multiple Regression Equations was initiated for two reasons--the need for better accuracy than could be achieved using the Molodensky Datum Transformation Formulas and mean datum shifts, and the need for a technique more amenable for real time use. The multiple regression equations approach essentially automates the WGS 84 minus local geodetic system coordinate difference contour charts ($\Delta\phi, \Delta\lambda, \Delta H$) making it relatively easy to obtain accurate WGS 84 geodetic coordinates via the relationships

$$\phi_{WGS\ 84} = \phi_{LOCAL} + \Delta\phi$$
$$\lambda_{WGS\ 84} = \lambda_{LOCAL} + \Delta\lambda$$
$$H_{WGS\ 84} = H_{LOCAL} + \Delta H$$

Prior to beginning the development process, individual $\Delta\phi$, $\Delta\lambda$, ΔH coordinate differences (WGS 84 minus local geodetic) are formed at each Doppler station within the datum area. The multiple regression procedure is then initiated to develop separate equations to fit the $\Delta\phi$, $\Delta\lambda$, and ΔH coordinate differences. The first step of the procedure produces a constant term and a variable term. The variable

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term will either be a function of ϕ or λ, or both. The procedure then sequentially adds one variable at a time to the equation--the variable that provides the greatest improvement in fitting the coordinate difference. After a variable is added, all variables previously incorporated into the equation are tested and, if one is no longer significant, it is removed. Each addition or removal of a variable is called a "step". This stepwise addition and removal of variables ensures that only significant variables are retained in the final equation. The stepwise regression procedure continues until the precision desired for the equation is obtained. For most local geodetic systems, the Doppler station coverage is sufficient only for developing multiple regression equations that are reliable within the area "covered" by the stations, not from datum boundary-to-datum boundary. However, by introducing auxiliary points into the development process, multiple regression equations were developed that are reliable throughout the datum area. To obtain the auxiliary points, a 1° x 1° grid of $\Delta\phi$, $\Delta\lambda$, ΔH coordinate differences were formed by interpolating such values from the five closest Doppler stations. From this 1° x 1° grid of values, auxiliary points (each having interpolated $\Delta\phi$, $\Delta\lambda$, ΔH values) were then selected to fill areas of sparse Doppler station coverage and to provide coverage slightly external to the datum boundary. The validity of the resulting datum shift multiple regression equations was checked by using them to generate $\Delta\phi$, $\Delta\lambda$, ΔH contour charts which were compared visually with similar graphics developed from the original data ($\Delta\phi$, $\Delta\lambda$, ΔH values).

6.2.3 DMA-DEVELOPED LOCAL GEOID HEIGHTS

The determination of Local Geodetic-to-WGS 84 datum shifts ($\Delta X, \Delta Y, \Delta Z$) is contingent upon having local geodetic and WGS 84 coordinates available for each Doppler station involved in the datum transformation process. The local geodetic system coordinates (ϕ, λ, H) of a Doppler station are used to compute the site's local geodetic system X,Y,Z values. For many local geodetic systems, local geoid heights (N) are either not available or are unreliable.

As a result, the local geodetic heights of Doppler stations determined using such data are of poor quality. (The relevant formula is $H_{Local} = N_{Local} + h$ where h is the elevation of the station above mean sea level.) This, in turn, leads to poor definitions for:

- The differences (ΔH) between the local and WGS 84 geodetic heights of Doppler stations
- The local geodetic system X, Y, Z coordinates of Doppler stations.

(Also, any degradation inherent in the latter adversely affects the quality of Local Geodetic System-to-WGS 84 datum shifts developed in ΔX, ΔY, ΔZ form.) This undesirable situation (due either to the lack of local geoid heights or their poor quality) is widespread, affecting with only a few exceptions all the local geodetic systems for which Local Geodetic System-to-WGS 84 datum shifts are desired. For example, although North American Datum 1927 (NAD 27) astro-geodetic geoid heights are available for much of North America, they are not of high accuracy due to the sparse and uneven distribution of, and the errors in, the basic astrogeodetic deflection of the vertical (DOV) components used in their development. The 1978 Version of the European Datum 1950 Geoid [10], although of more recent construction than the NAD 27 Astrogeodetic Geoid, is felt to have somewhat the same problems especially in coastal areas and near the limits of the datum boundary.

In developing WGS 84, datum shifts were needed for referencing approximately 80 local geodetic systems to WGS 84. Local geoid heights, regardless of accuracy, were available for only 16 of the 80 datums. Faced with the need for local geoid heights for approximately 80 datums, and the uncertainties known to exist (or strongly suspected) in practically all of the 16 local geoids that were available, DMA decided to develop a local geoid for each local geodetic system for which Local Geodetic System-to-WGS 84 datum shifts were needed. This resolved the problem of how to cope with missing and poor quality local geoids and at the same time offered the advantage of having all local geoids based on the same develop-

ment technique and type of data. These local geoids were prepared by re-referencing the WGS 84 Geoid from the WGS 84 Ellipsoid to the reference ellipsoid and orientation associated with each of the local geodetic systems.

The DMA-developed local geoid heights were used in forming the local geodetic heights of the Doppler stations, and, therefore, are inherently contained in the Local Geodetic-to-WGS 84 datum shifts. This applies whether the Local Geodetic-to-WGS 84 transformation takes the form of Multiple Regression Equations, ($\Delta\phi$, $\Delta\lambda$, ΔH) contour charts, or Molodensky Datum Transformation Formulas which utilize ΔX, ΔY, ΔZ datum shifts. (The latter may be mean or regional values or quantities estimated from ΔX, ΔY, ΔZ contour charts.) However, the local geodetic height is needed as input data by only one of the datum transformation techniques (providing $\Delta\phi$, $\Delta\lambda$, ΔH values), the Standard Molodensky Datum Transformation Formulas. Although an approximate local geodetic height is suitable for that purpose, use of a local geodetic height incorporating the DMA-developed local geoid height is needed to obtain an accurate WGS 84 geodetic height for the site in question. Local geodetic system geoid heights can be estimated from DMA-prepared contour charts, a geoid height multiple regression equation, or interpolated from gridded values ($>5'x5'$), available from DMA upon request.

6.2.4 PROCEDURE FOR OBTAINING WGS 84 COORDINATES

It is desirable to have only one set of WGS 84 coordinates for any given site to prevent errors, confusion, and delays. This is particularly important when more than one organization is involved in a project that requires the exchange (or use) of coordinates for the same site or results influenced by them. However, this desirable state is difficult to achieve (maintain) since several different approaches are available for determining WGS 84 coordinates. These approaches are based on the geodetic data available, or data situation existing, at the site to be positioned on WGS 84. These data situations and the associated WGS 84 positioning approaches or procedures that are available are listed in Table 3 in

order of preference. Each positioning approach provides a slightly different set of WGS 84 coordinates for a site. The first approach is the most accurate and preferred approach and is expected to be used when positioning new sites or re-positioning important sites on WGS 84. The second most accurate approach will see little if any further use since the NSWC 9Z-2 Coordinate System will no longer be used (the NNSS will be on WGS 84). The third approach will be the technique most used to obtain WGS 84 coordinates for sites of interest. Eight different Local Geodetic System-to-WGS-84 Datum Transformation techniques of varying accuracy and ease of use are listed in 'Table 4. These techniques (options) are quickly reduced in number by noting those that do not remove the degrading effect of local network distortions on WGS 84 coordinates (Options 7 and 8) and omitting the abridged formulas (Options 2 and 6) in favor of the standard formulas. Options 1 and 4 are omitted since they are visual estimation methods primarily suitable for periodic office use, and Option 5 is eliminated due to the difficulty involved in adapting it for real time or field use. (This difficulty arises because of the need to account in the software for the boundaries associated with each regional datum shift.) Thus, the multiple regression equation approach has been selected as the best overall technique for accomplishing Local Geodetic System-to-WGS 84 datum transformations.

6.2.5 ACCURACY OF WGS 84 COORDINATES

6.2.5.1 DOPPLER STATIONS

The accuracy of WGS 84 coordinates determined by Doppler satellite point positioning utilizing NNSS satellites and their respective ephemerides is ± 2 meters (one sigma) in each component, whether in rectangular (X,Y,Z) or geodetic coordinate (ϕ,λ,H) form. Future WGS 84 Doppler station coordinates obtained directly in WGS 84 from a satellite point positioning solution utilizing the NNSS in its WGS 84 coordinate system are expected to be slightly more accurate than those obtained in the WGS 84 development process using the NSWC 9Z-2 to WGS 84 coordinate conversion. Should future

results so warrant, new NNSS-derived WGS 84 Doppler station coordinates will be assigned an accuracy value better than the currently stated ± 2 meters. The accuracy value of ± 2 meters is an absolute accuracy value since it incorporates not only the "observational" or Doppler solution error, but the errors associated with placing the origin of the WGS 84 (Doppler) coordinate system at the earth's center of mass and determining the correct scale for the WGS 84 (Doppler) coordinate system. It does not include the uncertainty associated with bringing into coincidence the WGS 84 (Doppler) and the BIH-defined zero meridians. This was not necessary since the location of the WGS 84 (Doppler) longitude reference or zero meridian is arbitrary. This ± 2 meters accuracy value should not be confused with the approximately ± 1 meter (one sigma) precision with which each coordinate can be determined from a Doppler solution (the "observational" error) or the approximately ± 1 meter (one sigma) accuracy with which each coordinate can be obtained from a solution repeated independently at the same site.

6.2.5.2 NON-DOPPLER STATIONS

The WGS 84 coordinates of a non-Doppler local geodetic network station will be less accurate than the WGS 84 coordinates of a Doppler station. This is due to the distortions present in local geodetic networks, the lack of a sufficient number of properly placed Doppler stations colocated with local geodetic network stations for use in forming the Local Geodetic System-to-WGS 84 datum shifts, and the uncertainty introduced by the Local Geodetic System-to-WGS 84 Datum Transformation Formulas themselves. This accuracy information will appear in the soon-to-be-published DMA WGS 84 Technical Reports. The accuracy of NAVSTAR GPS-derived WGS 84 coordinates is treated elsewhere [11].

7.0 STATUS OF WGS 84 IMPLEMENTATION (APRIL 1986)

Completion and distribution of the DMA technical reports treating the development, definition, and components of WGS 84 are behind schedule, as is the implementation. This is primarily due to the amount and complexity of information involved, the large number

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and diversity of mapping, charting, and geodetic (MC&G) organiza-
tions and product/data users affected by WGS 84, and the desire to
ensure use of the same longitude reference for WGS 84 and the
still-in-work North American Datum 1983 (NAD 83). Currently, DMA
plans to initiate production of WGS-related MC&G products on WGS 84
during Calendar Year 1986 and distribute the WGS 84 Technical
Reports. Users of DMA-generated MC&G products/data should become
familiar with WGS 84, its effect on their activities and inter-
organizational involvements, and prepare for its implementation. In
recognition of software improvement/replacement cycles and WGS
72-to-WGS '84 conversion costs, DMA will (if necessary) pro-
duce/maintain a product on both WGS 72 and WGS 84 until the
conversion to WGS 84 can be effected in a logical cost-effective
manner.

8.0   CONCLUSIONS/SUMMARY

World Geodetic System 1984 is more accurate than WGS 72 and
replaces the latter as the geocentric system officially authorized
for DoD use. The reference frame for WGS 84 is more accurately
defined than that of its predecessor, local geodetic-to-WGS 84 datum
shifts of improved accuracy are available, and for many more datums
(approximately 80 for WGS 84 versus 28 for WGS 72). In addition,
the WGS 84 EGM and geoid are considerably more accurate than their
WGS 72 counterparts, and the scale and orientation of WGS 84 are
superior (to WGS 72). These improvements translate into more
accurate maps and charts (of scale 1:50,000 and larger), geodetic
coordinates, geoid heights, heights above mean sea level, and
distances; including an improved capability for satellite orbit
determination and prediction, and the placement of many more local
geodetic systems on a world geodetic system. The latter is parti-
cularly important for those local geodetic systems affected by large
distortions. Placement of such local datums on WGS 84, using the
variable datum shifts made possible by a well dispersed set of
Doppler sites, effectively removes these distortions. Thus, it is
beneficial for nations to participate in cooperative Doppler

observation programs where additional accuracy can be obtained through the use of precise rather than broadcast satellite ephemerides.

The value of WGS 84 will become increasingly evident in the late 1980s when NAVSTAR GPS will be fully operational. Since the reference system for NAVSTAR GPS will be WGS 84, the means exist for automatically obtaining high quality geocentric coordinates from NAVSTAR GPS user equipment. For those using NAVSTAR GPS, but still utilizing local geodetic systems and products, the availability of the more accurate WGS 84-to-local geodetic system datum shifts makes it possible to obtain GPS-derived local geodetic coordinates of improved accuracy. Again, the value of having all mapping, charting, and geodetic (MC&G) products and navigational activities referenced to WGS 84 is noted. But if local geodetic systems are in use, requiring a WGS 84-to-local geodetic system transformation, then the value of having variable datum shifts (made possible by a well dispersed set of Doppler sites throughout the region) is apparent.

From an international standpoint, the trend toward the use of a world geodetic system is unmistakable. The International Hydrographic Organization (IHO) needs such a system as does the United Nations, e.g., for the resolution of disputes involving the national boundaries of Exclusive Economic Zones (EEZs). This trend is furthered by the adoption of an earth-centered system by Canada, Mexico, and the United States for North American Datum 1983 (NAD 83) and the efforts underway for the replacement of European Datum 1950 (ED 50) with a geocentric system. Isolated and/or additional positions can easily be incorporated into an earth-centered system and such a system is automatically suitable for supporting space-related activities and is more closely related to the navigation and positioning activities of NAVSTAR GPS users.

Initial stages of the conversion of WGS 72-referenced mapping, charting, geodetic, gravimetric, and digital products to WGS 84 are underway. Questions regarding product conversion schedules, user

interface problems, etc., should be referred to Hq DMA, Attn: DH, United States Naval Observatory, Building 56, Washington, DC 20305-3000; Autovon 294-1219, Commercial 202-653-1219.

NOTE: The WGS 84 longitude-related information that appears in this paper may change slightly, 0.1 to 0.3 arc second, when on-going efforts to ensure that WGS 84 and the in-work NAD 83 utilize the same longitude reference are completed.

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TABLE 1
DEFINING PARAMETERS
OF
THE WGS 84 ELLIPSOID

PARAMETERS	NOTATION	VALUE
SEMIMAJOR AXIS	a	6378137 m
SECOND DEGREE ZONAL HARMONIC COEFFICIENT OF THE GEOPOTENTIAL	$\bar{C}_{2,0}$	$-484.16685 \times 10^{-6}$
ANGULAR VELOCITY OF THE EARTH	ω	7292115×10^{-11} rad s^{-1}
THE EARTH'S GRAVITATIONAL CONSTANT (MASS OF EARTH'S ATMOSPHERE INCLUDED)	GM	3986005×10^{8} m^{3} s^{-2}

TABLE 2

DIFFERENCES BETWEEN WGS 72 AND WGS 84 ELLIPSOID PARAMETERS

ELLIPSOID PARAMETERS	NOTATION	WGS 72	WGS 84	DIFFERENCE*
SEMIMAJOR AXIS	a **	6378135 m	6378137 m	2 m
FLATTENING	f	1/298.26	1/298.257223563	0.3121057×10^{-7}
ANGULAR VELOCITY	ω **	$7292115.147 \times 10^{-11}$ rad s^{-1}	7292115×10^{-11} rad s^{-1}	-0.147×10^{-11} rad s^{-1}
SECOND DEGREE ZONAL	$\bar{C}_{2,0}$ **	-484.1605×10^{-6}	$-484.16685 \times 10^{-6}$	-0.00635×10^{-6}
GRAVITATIONAL CONSTANT (MASS OF EARTH'S ATMOSPHERE INCLUDED)	GM **	3986008×10^{8} m^{3}s^{-2}	3986005×10^{8} m^{3}s^{-2}	-3×10^{8} m^{3}s^{-2}
GRAVITATIONAL CONSTANT (WITHOUT MASS OF EARTH'S ATMOSPHERE)	GM'	3986005×10^{8} m^{3}s^{-2}	3986001.5×10^{8} m^{3}s^{-2}	-3.5×10^{8} m^{3}s^{-2}
ANGULAR VELOCITY (UNTRUNCATED)	ω' ***	---	$7292115.1467 \times 10^{-11}$ rad s^{-1}	---

*WGS 84 MINUS WGS 72
**DEFINING PARAMETERS
***SEE TEXT, SECTION 3

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TABLE 3

APPROACHES FOR DETERMINING WGS 84 COORDINATES

FOR

SITES OF INTEREST

DATA SITUATION AT SITES TO BE POSITIONED ON WGS 84	WGS 84 POSITIONING APPROACH
1. GROUND-BASED SATELLITE RECEIVERS HAVE "TRACKED" NNSS SATELLITES AND ACQUIRED DOPPLER DATA AT THE SITE. (LOCAL GEODETIC SYSTEM COORDINATES MAY OR MAY NOT BE AVAILABLE FOR THE SITE, AND ARE NOT REQUIRED.)	USE THE DOPPLER DATA AVAILABLE FOR THE SITE AND SOLVE FOR THE SITE'S COORDINATES DIRECTLY IN WGS 84. [THE NNSS (SATELLITE EPHEMERIDES, TRANET STATION COORDINATES, ETC.) WILL HAVE BEEN PLACED ON WGS 84.]
2. NSWC 9Z-2 COORDINATES AVAILABLE FOR THE SITE. (DOPPLER DATA AND APPROPRIATE SATELLITE EPHEMERIDES NO LONGER AVAILABLE.)	USE THE NSWC 9Z-2 TO WGS 84 CONVERSION.
3. LOCAL GEODETIC SYSTEM COORDINATES ARE AVAILABLE FOR THE SITE, AND PERHAPS WGS 72 COORDINATES. (NO DOPPLER DATA AND APPROPRIATE SATELLITE EPHEMERIDES, OR NSWC 9Z-2 COORDINATES, AVAILABLE FOR THE SITE.)	USE LOCAL GEODETIC TO WGS 84 DATUM TRANSFORMATION FORMULAS, IGNORING ANY WGS 72 COORDINATES AVAILABLE.
4. ONLY WGS 72 COORDINATES AVAILABLE FOR THE SITE. (NO DOPPLER DATA AND APPROPRIATE SATELLITE EPHEMERIDES, OR NSWC 9Z-2, OR LOCAL GEODETIC SYSTEM COORDINATES AVAILABLE FOR THE SITE.)	USE THE WGS 72-TO-WGS 84 CONVERSION. HOWEVER, RE-POSITIONING OF THE SITE VIA THE FIRST APPROACH (ABOVE) IS PREFERRED.

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TABLE 4

TECHNIQUES AVAILABLE FOR TRANSFORMING
LOCAL GEODETIC COORDINATES (ϕ, λ, H) TO WGS 84 COORDINATES (ϕ, λ, H)

OPTIONS	TECHNIQUES
1	STANDARD MOLODENSKY DATUM TRANSFORMATION FORMULAS AND ΔX, ΔY, ΔZ DATUM SHIFTS INTERPOLATED FROM ΔX, ΔY, ΔZ CONTOUR CHARTS.
2	ABRIDGED MOLODENSKY DATUM TRANSFORMATION FORMULAS AND ΔX, ΔY, ΔZ DATUM SHIFTS INTERPOLATED FROM ΔX, ΔY, ΔZ CONTOUR CHARTS.
3	MULTIPLE REGRESSION DATUM TRANSFORMATION EQUATIONS*.
4	INTERPOLATE $\Delta\phi$, $\Delta\lambda$, ΔH VALUES FROM $\Delta\phi$, $\Delta\lambda$, ΔH CONTOUR CHARTS.
5	STANDARD MOLODENSKY DATUM TRANSFORMATION FORMULAS WITH REGIONAL ΔX, ΔY, ΔZ DATUM SHIFTS.
6	ABRIDGED MOLODENSKY DATUM TRANSFORMATION FORMULAS WITH REGIONAL ΔX, ΔY, ΔZ DATUM SHIFTS.
7	STANDARD MOLODENSKY DATUM TRANSFORMATION FORMULAS WITH MEAN ΔX, ΔY, ΔZ DATUM SHIFTS.
8	ABRIDGED MOLODENSKY DATUM TRANSFORMATION FORMULAS WITH MEAN ΔX, ΔY, ΔZ DATUM SHIFTS.

*THIS TECHNIQUE FOR CALCULATING $\Delta\phi$, $\Delta\lambda$, ΔH REQUIRES NO GRAPHICS OR INTERPOLATION ACTIVITIES WHILE
STILL PROVIDING GOOD ACCURACY; IDEALLY SUITED FOR REAL TIME OR FIELD USE.

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