*The Defense Mapping Agency*

DMA TR 8350.2
Second Edition
1 September 1991

## DMA Technical Report

# DEPARTMENT OF DEFENSE WORLD GEODETIC SYSTEM 1984

## ITS DEFINITION AND RELATIONSHIPS WITH LOCAL GEODETIC SYSTEMS



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This technical report presents the Department of Defense (DoD) World Geodetic System 1984 (WGS 84) developed as a replacement for WGS 72. The development of WGS 84 was initiated for the purpose of providing the more accurate geodetic and gravitational data required by DoD navigation and weapon systems. The new system represents the Defense Mapping Agency's modeling of the earth from a geometric, geodetic, and gravitational standpoint using data, techniques, and technology available through early 1984.

Additional Doppler and GPS survey information has since been used to update the datum transformation tables.

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DEFENSE MAPPING AGENCY TECHNICAL REPORT 8350.2

Department of Defense
World Geodetic System 1984

Its Definition and Relationships
with Local Geodetic Systems

## FOREWORD

1. This technical report presents the Department of Defense (DoD) World Geodetic System 1984 (WGS 84). The development of WGS 84 was initiated for the purpose of providing the more accurate and updated geodetic and gravitational data required by DoD weapon and navigation systems. The present WGS represents the Defense Mapping Agency (DMA) modeling of the earth from geometric, geodetic, and gravitational standpoints using data, techniques, and technology available through early 1984. However, the datum transformation relationships with geodetic datums/systems have been updated and revised based on information available through early 1991.

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JAMES K. SLUIS
Colonel, USAF
Chief of Staff

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# PREFACE

This technical report presents the Department of Defense (DoD) World Geodetic System 1984 (WGS 84). The major additions and modifications to the second edition include new transformation constants for geodetic datums and reference systems, deletion of multiple regression equations for small and isolated areas, and changes in symbols for the ellipsoidal and orthometric heights. In an effort to make this report a complete entity on its own, the most important and frequently used information from its supplements has been merged and included in the second edition. Thus, this modification has made it possible to eliminate the Supplement Part II (DMA TR 8350.2-B) and, henceforth, there will be only two supplements to this report.

Supplement Part I (DMA TR 8350.2-A) discusses WGS 84 and the methods, techniques, and data used in developing the parameters and products defining it. Considerable space is devoted in Part I to the discussion of the WGS 84 Reference Frame, Ellipsoid, Ellipsoidal Gravity Formula, Earth Gravitational Model, Geoid, and methods and procedures for obtaining WGS 84 coordinates. There is no change to this supplement.

Supplement Part III (DMA TR 8350.2-C) comprises the classified information for WGS 84. However, the associated Earth Gravitational Model coefficients above degree (n) and order (m) 18 and the corresponding geoid, previously classified, have now been declassified. This supplement, which is still classified, will be renumbered as Part II when reprinted in the future.

Also distributed with the technical report is a software program for datum transformation and coordinate conversions called MADTRAN-edition 2. The MADTRAN program (for **Ma**pping **D**atum **Tran**sformation) is provided on 5.25 inch floppy disc (double density) for IBM compatible personal computers. The program allows input from geodetic, Universal Transverse Mercator (UTM), or the Military Grid Reference System (MGRS) coordinates. Over 100 datums are available for transformation to or from WGS 84. Output is automatically presented as geodetic, UTM, and MGRS coordinates.

Users requiring any specific information, or any clarification, or data, should contact:

Director
Defense Mapping Agency
ATTN: PR, ST A-13
8613 Lee Highway
Fairfax, VA 22031-2137 (USA)

Similarly, requesters requiring the positioning of sites of interest directly in WGS 84 via satellite point positioning should contact the above address. Other WGS 84 related requests and/or questions may also be referred there.

Since WGS 84 is comprised of a consistent set of parameters, other DoD organizations should not make a substitution for any of the WGS 84 related parameters/equations in an attempt to improve the accuracy. Such a substitution may lead to less accurate WGS 84 products and may have adverse effects.

PREFACE (Cont'd)

Copies* of this technical report may be requested from:

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6001 MacArthur Boulevard
Bethesda, MD 20816-5001 (USA)

Phone: (301) 227-2534
1-800-826-0342

* Note: Non-DoD users can obtain copies of this report at cost. Call the above number for further information.

# TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

# 1. INTRODUCTION

The Defense Mapping Agency (DMA) produces numerous mapping, charting, geodetic, gravimetric, and digital products in support of the Department of Defense (DoD). It is advantageous to refer these products to a single geocentric coordinate system for many reasons other than ease of working with a large number and variety of systems. Such a system is needed due to accuracy and user interface considerations, the need for a product to support the widest possible range of applications (local, worldwide), the need to relate information from one product to data obtained from another source (e.g., map/chart positions to coordinates obtained from inertial navigation systems in real time), and the need to ensure a smooth transition in product use from one part of the world to another.

In accomplishing the preceding, such a geocentric system, termed a world geodetic system, provides the basic reference frame and geometric figure for the earth, models the earth gravimetrically, and provides the means for relating positions on various geodetic datums and systems to an Earth-Centered, Earth-Fixed (ECEF) coordinate system. In brief, a world geodetic system serves as the framework for DMA products and worldwide DoD operations.

Previously, three such systems, World Geodetic System 1960 (WGS 60), WGS 66, and WGS 72, each successively more accurate, have supported DoD activities. Although WGS 72 has aged gracefully and is still adequate for some DoD applications, it has several shortcomings which negate its continued use. For example, the WGS 72 Earth Gravitational Model (EGM) and Geoid are obsolete and local geodetic datum-to-WGS datum shifts of improved accuracy and greater geographic coverage are needed than are available from WGS 72. In addition, relatively minor orientation and scale errors also affect WGS 72. Other factors contributing to the desirability of replacing WGS 72 with an improved system are:

- Such an update and replacement occurs at a time when other geodetic system changes are either underway or contemplated; e.g., the up-dating, readjustment, and replacement of North American Datum 1927 (NAD 27) by NAD 83, the readjustment and analysis activities involving European Datum 1950 (ED 50), and the availability of the new Australian Geodetic Datum 1984 (AGD 84).

- An extensive increase in the data and types of data needed to develop an improved WGS.

- The availability of new theory and techniques to support a WGS improvement effort.

WGS 84 has been developed as a replacement for WGS 72 and represents DMA's modeling of the earth from a geometric, geodetic, and gravitational standpoint using data, techniques, and technology available through early 1984. It is an improvement over WGS 72 in several respects. New and more extensive data sets and improved computer software were used in the development. A more extensive file of Doppler-derived station coordinates was available, and for many more local geodetic datums; improved sets of ground-based Doppler and laser satellite tracking data and surface gravity were available; and geoid heights deduced from satellite radar altimetry (a new data type) were available for oceanic regions between 70 degrees north and south latitude (approximately).

The purpose of this publication is to provide a detailed report on WGS 84 and its updates/revisions which occurred since the first edition. An important feature of the current edition includes the use of additional Doppler and GPS survey information to update the datum transformation constants.

## 2. WGS 84 COORDINATE SYSTEM

### 2.1 General

The WGS 84 Coordinate System is a Conventional Terrestrial System (CTS), realized by modifying the Navy Navigation Satellite System (NNSS), or TRANSIT, Doppler Reference Frame (NSWC 9Z-2) in origin and scale, and rotating it to bring its reference meridian into coincidence with the Bureau International de l'Heure (BIH)-defined Zero Meridian.

From analyses discussed in [1], it was concluded that the NSWC 9Z-2 Coordinate System should be modified by:

- Shifting the NSWC 9Z-2 origin by 4.5 meters in the negative direction along the Z-axis.

- Rotating the NSWC 9Z-2 Reference Meridian (about the Z-axis) westward by 0.814 arc second to the BIH-defined Zero Meridian of 1984.0.

- Changing the NSWC 9Z-2 scale by $-0.6 \times 10^{-6}$.

The NSWC 9Z-2 Coordinate System, modified in this manner (Table 2.1), becomes (forms) the WGS 84 Coordinate System. The origin and longitude modifications are illustrated in Figures 2.1 and 2.2, respectively, as differences between NSWC 9Z-2 and WGS 84. Use of these modifications (Table 2.1) with the Molodensky Datum Transformation Formulas, after modifying the formulas slightly and setting $\Delta X = \Delta Y = 0$, provided the $\Delta\phi$, $\Delta\lambda$, $\Delta h$ formulas (Table 2.2) that produced the Doppler Station WGS 84 coordinates used to develop Local Geodetic Datum-to-WGS 84 Datum Transformations (Chapter 7).

Thus, analogous to the BIH-defined CTS, or BIH Terrestrial System (BTS), the origin of the WGS 84 Coordinate System is the center of mass of the earth; the WGS 84 Z-axis is in the direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by the BIH for epoch 1984.0 on the basis of the coordinates adopted for the BIH stations; the X-axis is the intersection of the WGS 84 reference meridian plane and the plane of the CTP's equator, the reference meridian being the Zero Meridian defined by the BIH for epoch 1984.0 on the basis of the coordinates adopted for the BIH stations; and, the Y-axis completes a right-handed, earth-fixed orthogonal coordinate system measured in the plane of the above equator, 90° east of the X-axis (Figure 2.3).

The WGS 84 Coordinate System origin and axes also serve as the geometric center and the X, Y, and Z axes of the WGS 84 Ellipsoid. (Thus, the WGS 84 Coordinate System Z-axis is the rotational axis of the WGS 84 Ellipsoid.)

The WGS 84 Coordinate System (reference frame) is the frame of a standard earth rotating at a constant rate around an average astronomic pole (the CTP). However, the universe is in motion, the earth is nonstandard, and events occur in an instantaneous world. Therefore, the WGS 84 Coordinate System (CTS) must be related mathematically to an Instantaneous Terrestrial System (ITS) and to a Conventional Inertial System (CIS).

## 2.2 Mathematical Relationship Between the CIS, ITS, and the WGS 84 Coordinate System

The mathematical relationship between the Conventional Inertial System, the Instantaneous Terrestrial System, and the WGS 84 Coordinate System, which is identical to the BIH-defined CTS in its definition [1], can be expressed as:

$$\text{CTS} = [A]\ [B]\ [C]\ [D]\ \text{CIS} \qquad (2\text{-}1)$$

In Equation (2-1), the rotation matrices for polar motion [A], sidereal time [B], astronomic nutation [C], and precession [D] provide the relationship between the CIS, defined by the *Fundamental Katlog* 5 (FK5) System referenced to Epoch J2000.0 [1], and the WGS 84 Coordinate System. Proceeding from right-to-left in Equation (2-1) through matrices D, C, and B establishes the relationship between the CIS and the ITS. Matrix A provides the relationship between the Celestial Ephemeris Pole (CEP), which approximates the instantaneous pole of the instantaneous earth, and the CTP, or average pole of the standard earth associated with the WGS 84 Coordinate System. Therefore, the application of Matrix A completes the mathematical connection between the WGS 84 Coordinate System, an ECEF Coordinate System, and the CIS, an Earth-Centered Inertial (ECI) Coordinate System. For detailed discussion on this subject, refer to [1].

Although tremendous progress has been made in the last decade in understanding and more precisely defining the ITS, the CTS, and the CIS, and the mathematical relationships between them [2], much work remains to be done. In particular, efforts to develop a precise mathematical connection between stellar (optical) and radio (Very Long Baseline Interferometry, or VLBI) systems and maintain the BIH-defined CIS and CTS with respect to a designated epoch, need to continue.

Table 2.1

Quantities Used in Converting
Doppler System Coordinates (NSWC 9Z-2) to WGS 84*

| Quantities | Explanation | |
|---|---|---|
| $\Delta Z = 4.5$ m | Shift in the Origin (Z-Axis Bias) | Equatorial Plane of Doppler Coordinate System is Offset North of BIH-Defined Coordinate System Equatorial Plane |
| $\Delta\lambda = 0.814''$ | Rotation in Longitude | Zero Meridian (X-Axis) of the Doppler Coordinate System is East of the BIH-Defined Zero Meridian (WGS 84 X-Axis) |
| $\Delta S = -0.6 \times 10^{-6}$ | Scale Change | Distances Derived in Doppler Coordinate System are Longer than Distances Determined via Very Long Baseline Interferometry |

* Also, see Table 2.2

Table 2.2

Formulas and Parameters
to Transform NSWC 9Z-2 Coordinates*
to WGS 84 Coordinates

| | |
|---|---|
| Formulas | $\Delta\phi'' = (4.5 \cos \phi) / (a \sin 1'') + (\Delta f \sin 2\phi) / (\sin 1'')$<br>$\Delta\lambda'' = 0.814$<br>$\Delta h = 4.5 \sin \phi + a\, \Delta f \sin^2\phi - \Delta a + \Delta r$ (Units = Meters) |
| Parameters | $\Delta f = -0.8120450 \times 10^{-7}$<br>$a = 6378145$ m<br>$\Delta a = -8.0$ m<br>$\Delta r = -3.8$ m |
| Instructions | To Obtain WGS 84 Coordinates, Add the $\Delta\phi$, $\Delta\lambda$, $\Delta h$ Changes, Calculated Using NSWC 9Z-2 Coordinates, to the NSWC 9Z-2 Coordinates ($\phi$, $\lambda$, and h, Respectively).<br>Latitude is Positive North and Longitude is Positive East (0° to 180°) |

* Navy Navigation Satellite Coordinate System

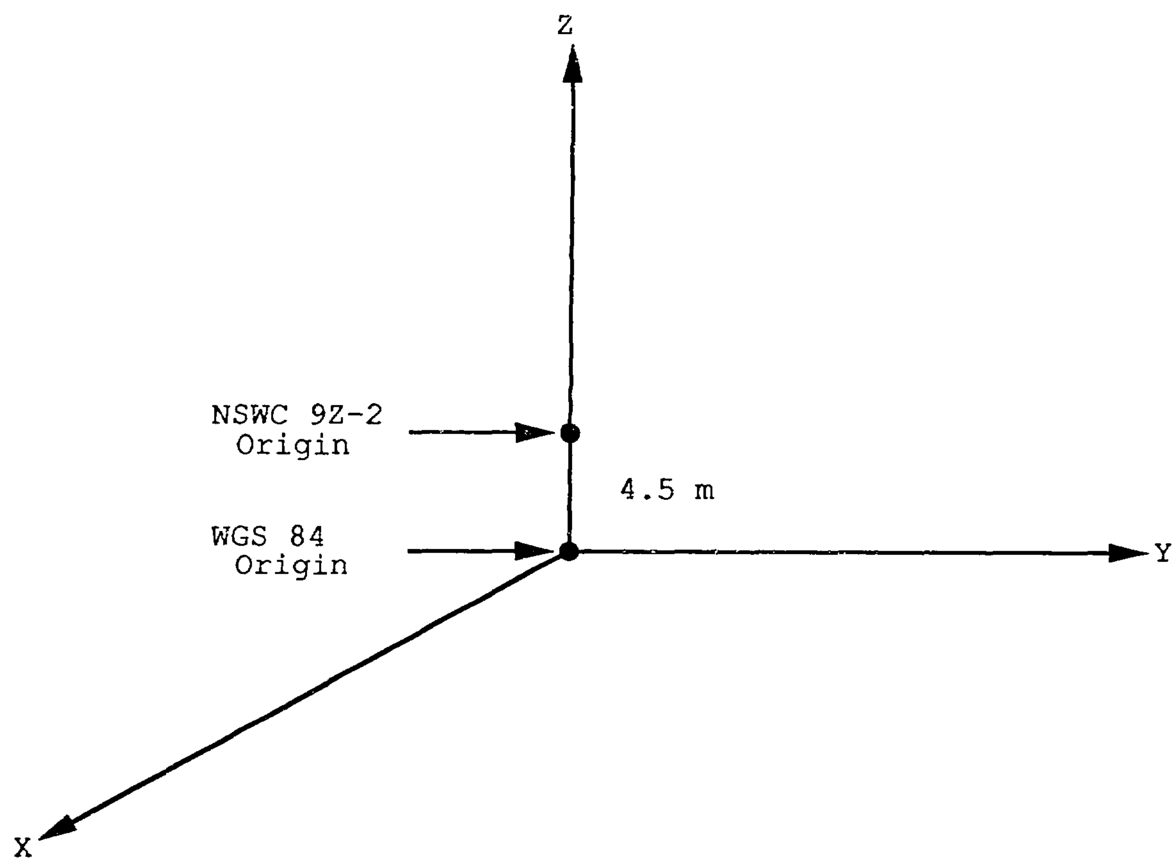


Figure 2.1. Difference Between NSWC 9Z-2 and WGS 84 Reference Frame Origins

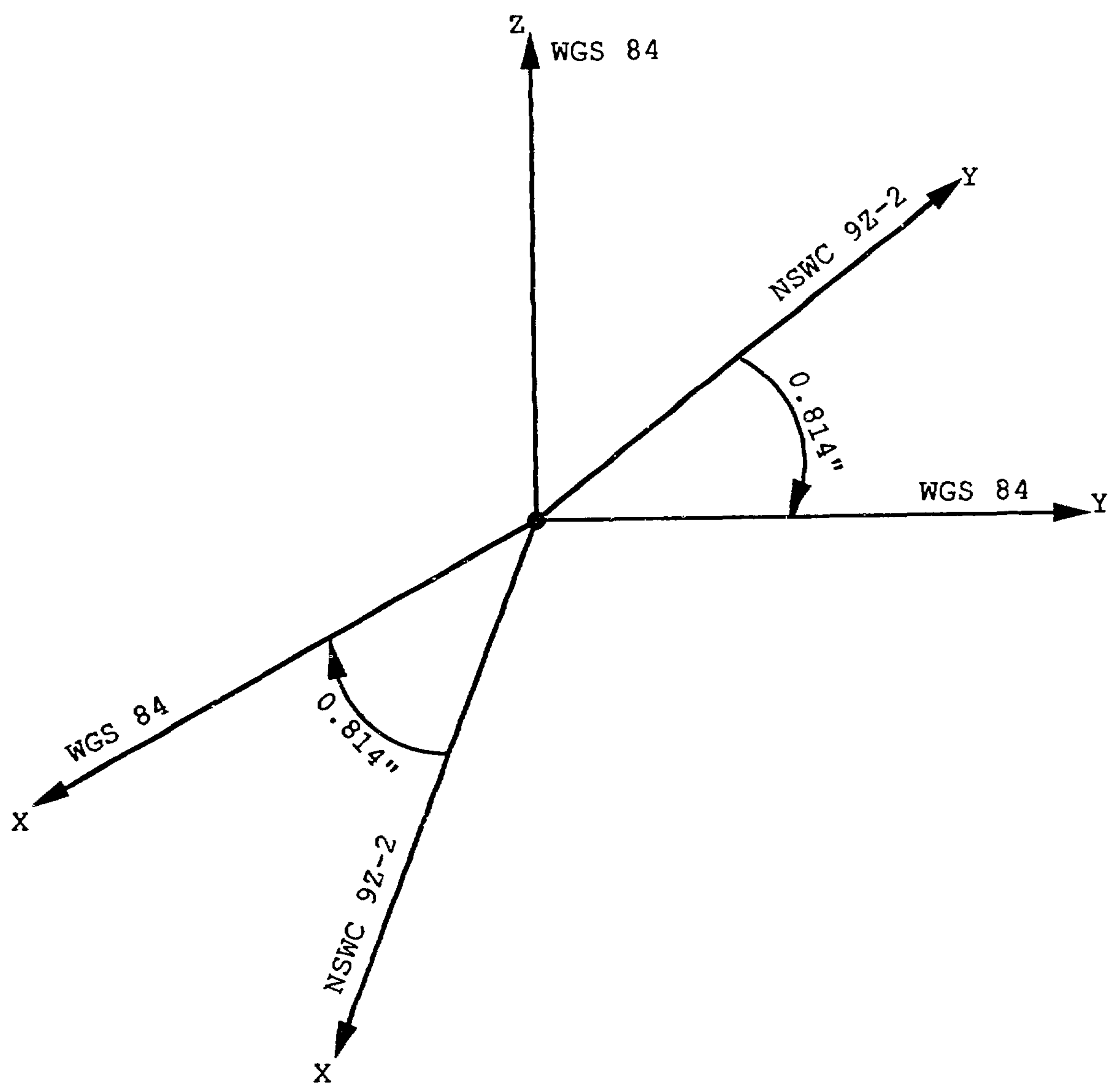


Figure 2.2. Difference Between NSWC 9Z-2 and WGS 84 Longitude References (X-Axes).

Origin = Earth's center of mass

Z-Axis = The direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by the Bureau International de l'Heure (BIH) on the basis of the coordinates adopted for the BIH stations.

X-Axis = Intersection of the WGS 84 Reference Meridian Plane and the plane of the CTP's Equator, the Reference Meridian being the Zero Meridian defined by the BIH on the basis of the coordinates adopted for the BIH stations.

Y-Axis = Completes a right-handed, Earth Centered, Earth Fixed (ECEF) orthogonal coordinate system, measured in the plane of the CTP Equator, $90^0$ East of the X-Axis.

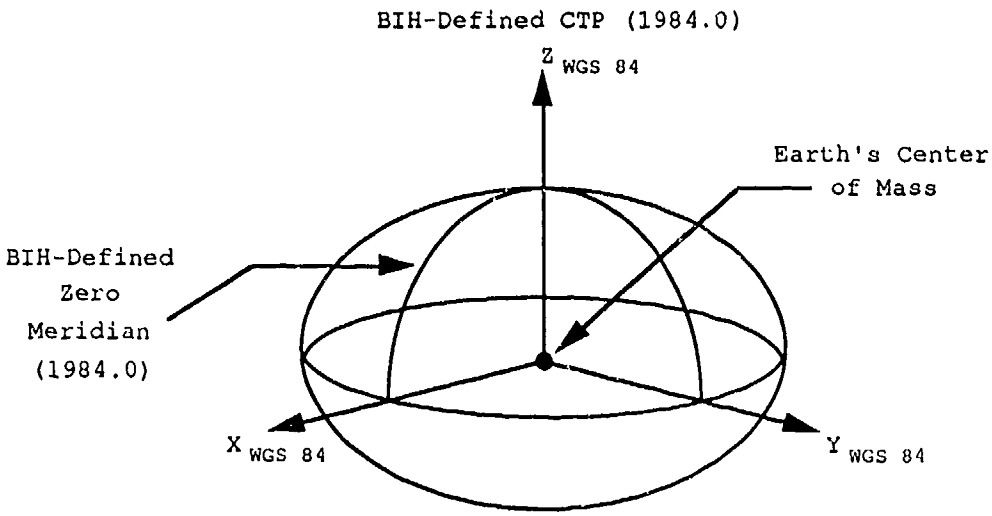


Figure 2.3. The WGS 84 Coordinate System* Definition

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* Analogous to the BIH Defined Conventional Terrestrial System (CTS), or BTS, 1984.0.

# 3. WGS 84 ELLIPSOID

## 3.1 General

In geodetic applications, three different surfaces or earth figures are normally involved. In addition to the earth's natural or physical surface, these include a geometric or mathematical reference surface, the ellipsoid, and an equipotential surface called the geoid (Chapter 6). In determining the WGS 84 Ellipsoid and associated parameters, the WGS 84 Development Committee, in keeping with DMA guidance, decided quite early to closely adhere to the thoughts and approach used by the International Union of Geodesy and Geophysics (IUGG) when the latter established and adopted Geodetic Reference System 1980 (GRS 80) [7]. Accordingly, a geocentric equipotential ellipsoid of revolution was taken as the form for the WGS 84 Ellipsoid. The parameters selected to define the WGS 84 Ellipsoid are the semimajor axis (a), the earth's gravitational constant (GM), the normalized second degree zonal gravitational coefficient ($\bar{C}_{20}$) and the angular velocity ($\omega$) of the earth (Table 3.1). These parameters are identical to those of the GRS 80 Ellipsoid with one minor exception. The coefficient form used for the second degree zonal is that of the WGS 84 Earth Gravitational Model rather than the notation $J_2$ used with GRS 80. Accuracy estimates (one sigma) are also included in Table 3.1 for the defining parameters.

## 3.2 Defining Parameters

### 3.2.1 Semimajor Axis (a)

The semimajor axis (a) was selected as one of the defining parameters of the WGS 84 Ellipsoid. Its adopted value and estimated accuracy (one sigma) are:

$$a = 6378137 \pm 2 \text{ meters.} \qquad (3\text{-}1)$$

This value, which is the same as that of the GRS 80 Ellipsoid, is two meters (m) larger than the value of 6378135 m adopted for the WGS 72 Ellipsoid [4]. As stated in [5], the GRS 80, and thus the WGS 84, a-value is based on estimates from the 1976-1979 time period, determined using laser, Doppler, radar altimeter, laser plus radar altimeter, and Doppler plus radar altimeter data/techniques. These efforts yielded values from 6378134.5 m to 6378140 m. The best estimate was considered to lie between 6378135 m and 6378140 m.

### 3.2.2 Earth's Gravitational Constant (GM)

#### 3.2.2.1 GM With Earth's Atmosphere Included (GM)

The value of the earth's gravitational constant, adopted as one of the four defining parameters of the WGS 84 Ellipsoid, and its one-sigma accuracy estimate are:

$$GM = (3986005 \pm 0.6) \times 10^8 m^3 s^{-2} \ . \qquad (3\text{-}2)$$

This value includes the mass of the atmosphere and is based on several types of space measurements. These measurement types and the associated estimates for GM are [3]:

Spacecraft radio tracking .............. $(3986005.0 \pm 0.5) \times 10^8 m^3 s^{-2}$
Lunar laser data analysis .............. $(3986004.6 \pm 0.3) \times 10^8 m^3 s^{-2}$
Satellite laser range measurements ...... $(3986004.4 \pm 0.2) \times 10^8 m^3 s^{-2}$

From these results, the representative value in Equation (3-2) for GM, consistent with the data used, was then adopted.

### 3.2.2.2 GM of the Earth's Atmosphere ($GM_A$)

For some applications, it is necessary to either have a GM value for the earth which does not include the mass of the earth's atmosphere, or have a GM value for the earth's atmosphere itself. For this, it is necessary to know both the mass of the earth's atmosphere, $M_A$, and the universal gravitational constant, G.

Using the value recommended for G [6] by the International Association of Geodesy (IAG), and the more recent value for $M_A$ [7], the product $GM_A$ to two significant digits yields the value currently recommended by the IAG for this constant [6]. This value, with an assigned accuracy estimate, was adopted for use with WGS 84:

$$GM_A = (3.5 \pm 0.1) \times 10^8 m^3 s^{-2} \qquad (3-3)$$

### 3.2.2.3 GM With Earth's Atmosphere Excluded (GM')

The earth's gravitational constant with the mass of the earth's atmosphere excluded (GM'), was obtained by subtracting $GM_A$, Equation (3-3), from GM, Equation (3-2)

$$GM' = (3986001.5 \pm 0.6) \times 10^8 m^3 s^{-2} \qquad (3-4)$$

The fact that the WGS 84 value for GM', Equation (3-4), is given to one more digit than the WGS 84 value for GM, Equation (3-2), does not imply that GM' is known more accurately than GM. The additional digit used with GM' only reflects a desire to maintain consistency between the various WGS 84 parameters and correction terms. In fact, GM' is known less well, due to the uncertainty introduced via $GM_A$. The lack of a more realistic accuracy value for $GM_A$ prevents acknowledgment of this in the above one-sigma accuracy estimate for GM'.

### 3.2.3 Normalized Second Degree Zonal Gravitational Coefficient $\overline{C}_{20}$

Another defining parameter of the WGS 84 Ellipsoid is the normalized second degree zonal gravitational coefficient, $\overline{C}_{20}$, which has the following value and assigned accuracy (one sigma):

$$\overline{C}_{20} = (-484.16685 \pm 0.00130) \times 10^{-6}. \qquad (3\text{-}5)$$

This $\overline{C}_{20}$ value was obtained from the adopted GRS 80 value for $J_2$ [3], $(J_2=J_{20})$,

$$J_2 = 108263 \times 10^{-8} \qquad (3\text{-}6)$$

by using the mathematical relationship

$$\overline{C}_{20} = -J_2/(5)^{1/2} \qquad (3\text{-}7)$$

and truncating the result to eight significant digits.

In keeping with the GRS 80 value for $J_2$, the $\overline{C}_{20}$ value for the WGS 84 Ellipsoid also does not include the permanent tidal deformation. This effect, usually represented by $\delta J_2$, is due to the attraction of the earth by the sun and moon. It has the magnitude [8]:

$$\delta J_2 = 9.3 \times 10^{-9} \qquad (3\text{-}8)$$

or, equivalently

$$\delta \overline{C}_{20} = -4.16 \times 10^{-9}. \qquad (3\text{-}9)$$

This quantity would be added to $\overline{C}_{20}$, Equation (3-5), if it were desired to have $\overline{C}_{20}$ include the permanent tidal deformation.

### 3.2.4 Angular Velocity of the Earth ($\omega$)

The value of $\omega$ used as one of the defining parameters of the WGS 84 (and GRS 80) Ellipsoid and its accuracy estimate (one sigma) are:

$$\omega = (7292115 \pm 0.1500) \times 10^{-11} \text{ radians/second} \quad (3\text{-}10)$$

This value, for a standard earth rotating with a constant angular velocity, is an IAG adopted value for the true angular velocity of the earth which fluctuates with time. However, for most geodetic applications which require angular velocity, these fluctuations do not have to be considered.

Although $\omega$ is suitable for use with a standard earth and the WGS 84 Ellipsoid, it is the International Astronomical Union (IAU), or the GRS 67, version of this value ($\omega'$)

$$\omega' = 7292115.1467 \times 10^{-11} \text{ radians/second} \quad (3\text{-}11)$$

that was used with the new definition of time [9].

For consistent satellite applications, the value of the earth's angular velocity ($\omega'$) from Equation (3-11), rather than $\omega$, should be used in the formula

$$\omega^* = \omega' + m \quad (3\text{-}12)$$

to obtain the angular velocity of the earth in a precessing reference frame ($\omega^*$). In the above equation [9] [10]:

m = precession rate in right ascension

$$m = (7.086 \times 10^{-12} + 4.3 \times 10^{-15} T_U) \text{ radians/second} \quad (3\text{-}13)$$

$T_U$ = Julian Centuries from Epoch J2000.0

$T_U = d_U/36525$

$d_U$ = Number of days of Universal Time (UT) from Julian Date (JD) 2451545.0 UT1, taking on values of ± 0.5, ± 1.5, ± 2.5,...

$d_U$ = JD - 2451545.

Therefore, the angular velocity of the earth in a precessing reference frame, for satellite applications, is given by:

$$\omega^* = (7292115.8553 \times 10^{-11} + 4.3 \times 10^{-15}\, T_U) \text{ radians/second} \qquad (3\text{-}14)$$

## 3.3 Derived Geometric and Physical Constants

### 3.3.1 General

Many parameters associated with the WGS 84 Ellipsoid, other than the four defining parameters (Table 3.1), are needed for geodetic and gravimetric applications. Using the four defining parameters, it is possible to derive these associated constants. The more commonly used geometric and physical constants associated with the WGS 84 Ellipsoid are listed in Tables 3.2 and 3.3. The formulas used in the calculation of these constants are primarily from [3] and [11].

The defining parameters are considered to be exact. On the other hand, the other constants are derived. Users are reminded that the derived constants must retain the listed significant digits if consistency between the magnitudes of the various parameters is to be maintained. These constants should always be calculated to, and used with, the number of digits required to maintain the consistency needed for each specific application.

### 3.3.2 Relevant Miscellaneous Constants/Conversion Factors

In addition to the four defining parameters of the WGS 84 Ellipsoid (Table 3.1), necessary for describing (representing) the ellipsoid geometrically and gravimetrically, and the derived sets of commonly used geometric and physical constants associated with the WGS 84 Ellipsoid (Tables 3.2 and 3.3), two other important constants are an integral part of the definition of WGS 84. These constants are the velocity of light (c) and the dynamical ellipticity (H).

The currently accepted value for the velocity of light in a vacuum (c) is [12]:

$$c = (299792458 \pm 1.2)\ \mathrm{m\ s^{-1}}\ . \qquad (3\text{-}15)$$

This value is officially recognized by both the IAG [6] and IAU [10], and has been adopted for use with WGS 84.

The dynamical ellipticity (H) is necessary for determining the earth's principal moments of inertia, A, B, and C. In the literature, H is variously referred to as dynamical ellipticity, mechanical ellipticity, or the precessional constant. It is a factor in the theoretical value of the rate of precession of the equinoxes, which is well known from observation. In a recent IAG report on fundamental geodetic constants [8], the following value for the reciprocal of H was given in the discussion of moments of inertia:

$$1/H = 305.4413 \pm 0.0005. \qquad (3\text{-}16)$$

For consistency, this value has been adopted for use with WGS 84.

Values of the velocity of light in a vacuum and the dynamical ellipticity adopted for use with WGS 84 are listed in Table 3.4 along with other WGS 84 associated constants used in special applications. Factors for effecting a conversion between meters, feet, and/or nautical and statute miles are also given in the table.

## 3.4 Comments

The four defining parameters ( a, $\bar{C}_{20}$, $\omega$, GM ) of the WGS 84 Ellipsoid were used to calculate the more commonly used geometric and physical constants associated with the WGS 84 Ellipsoid. As a result of the use of $\bar{C}_{20}$ in the form described, the derived WGS 84 Ellipsoid parameters are slightly different from their GRS 80 Ellipsoid counterparts. Although these minute parameter differences and the conversion of the GRS 80 $J_2$-value to $\bar{C}_{20}$ are insignificant from a practical standpoint, it has been more appropriate to refer to the ellipsoid used with WGS 84 as the WGS 84 Ellipsoid.

In contrast, since NAD 83 does not have an associated EGM, the $J_2$ to $\bar{C}_{20}$ conversion does not arise and the ellipsoid used with NAD 83 by the National Geodetic Survey (NGS) is, in name and in both defined and derived parameters, the GRS 80 Ellipsoid. Although it is important to know that these small undesirable inconsistencies exist between the WGS 84 and GRS 80 Ellipsoids, from a practical application standpoint they are insignificant. This is especially true with respect to the defining parameters. Therefore, as long as the preceding is recognized, it can be stated that WGS 84 and NAD 83 are based on the same ellipsoid.

Table 3.1

WGS 84 Ellipsoid
- Four Defining Parameters -

| Parameters | Notation | Magnitude | Accuracy ($1\sigma$) |
|---|---|---|---|
| Semimajor Axis | a | 6378137 m | $\pm 2$ m |
| Normalized Second Degree Zonal Harmonic Coefficient of the Gravitational Potential | $\bar{C}_{20}$ | $-484.16685 \times 10^{-6}$ | $\pm 1.30 \times 10^{-9}$ |
| Angular Velocity of the Earth | $\omega$ | $7292115 \times 10^{-11}$ rad $s^{-1}$ | $\pm 0.1500 \times 10^{-11}$ rad $s^{-1}$ |
| The Earth's Gravitational Constant (Mass of Earth's Atmosphere Included) | GM | $3986005 \times 10^{8}$ $m^3$ $s^{-2}$ | $\pm 0.6 \times 10^{8}$ $m^3$ $s^{-2}$ |
| Parameter Values for Special Applications | | | |
| The Earth's Gravitational Constant (Mass of Earth's Atmosphere Not Included) | GM' | $3986001.5 \times 10^{8}$ $m^3$ $s^{-2}$ | $\pm 0.6 \times 10^{8}$ $m^3$ $s^{-2}$ |
| Angular Velocity of the Earth (In a Precessing Reference Frame) | $\omega^*$ | $(7292115.8553 \times 10^{-11} + 4.3 \times 10^{-15}\, T_U)$ rad $s^{-1}$ | $\pm 0.1500 \times 10^{-11}$ rad $s^{-2}$ |

$T_U$ = Julian Centuries From Epoch J2000.0

Table 3.2

WGS 84 Ellipsoid
- Derived Geometric Constants -

| Constant | Notation | Value |
|---|---|---|
| Flattening (Ellipticity) | $f$ | 1/298.257223563 (0.00335281066474) |
| Semiminor Axis | $b$ | 6356752.3142 m |
| First Eccentricity | $e$ | 0.0818191908426 |
| First Eccentricity Squared | $e^2$ | 0.00669437999013 |
| Second Eccentricity | $e'$ | 0.0820944379496 |
| Second Eccentricity Squared | $e'^2$ | 0.00673949674227 |
| Linear Eccentricity | $E$ | 521854.0084 m |
| Polar Radius of Curvature | $c$ | 6399593.6258 m |
| Axis Ratio | $b/a$ | 0.996647189335 |
| Mean Radius of Semiaxes | $R_1$ | 6371008.7714 m |
| Radius of Sphere With Equal Area | $R_2$ | 6371007.1809 m |
| Radius of Sphere With Equal Volume | $R_3$ | 6371000.7900 m |

Table 3.3

WGS 84 Ellipsoid
- Derived Physical Constants -

| Constants | Notation | Value |
|---|---|---|
| Theoretical (Normal) Gravity Potential of the Ellipsoid | $U_0$ | 62636860.8497 $m^2\ s^{-2}$ |
| Theoretical (Normal) Gravity at the Equator (on the Ellipsoid) | $\gamma_e$ | 9.7803267714 $m\ s^{-2}$ |
| Theoretical (Normal) Gravity at the Poles (on the Ellipsoid) | $\gamma_p$ | 9.8321863685 $m\ s^{-2}$ |
| Mean Value of Theoretical (Normal) Gravity | $\overline{\gamma}$ | 9.7976446561 $m\ s^{-2}$ |
| Theoretical (Normal) Gravity Formula Constant | k | 0.00193185138639 |
| Mass of Earth (Includes the Atmosphere) | M | $5.9733328 \times 10^{24}$ kg |
| $m = \omega^2 a^2 b/GM$ | m | 0.00344978600313 |

Table 3.4
Relevant Miscellaneous Constants
and Conversion Factors

| Constant | Symbol | Numerical Value |
|---|---|---|
| Velocity of Light (in a Vacuum) | c | 299792458 m $s^{-1}$ |
| Dynamical Ellipticity | H | 1/305.4413 |
| Earth's Angular Velocity [for Satellite Applications; see Equation (3-14)] | $\omega^*$ | $(7292115.8553 \times 10^{-11} + 4.3 \times 10^{-15} T_U)$ rad $s^{-1}$ |
| Universal Constant of Gravitation | G | $6.673 \times 10^{-11} m^3 s^{-2} kg^{-1}$ |
| GM of the Earth's Atmosphere | $GM_A$ | $3.5 \times 10^8 m^3 s^{-2}$ |
| Earth's Gravitational Constant (Excluding the Mass of the Earth's Atmosphere) | GM' | $3986001.5 \times 10^8 m^3 s^{-2}$ |
| Earth's Principal Moments of Inertia (Dynamic Solution) | A<br>B<br>C | $8.0091029 \times 10^{37}$ kg $m^2$<br>$8.0092559 \times 10^{37}$ kg $m^2$<br>$8.0354872 \times 10^{37}$ kg $m^2$ |

Conversion Factors

| | |
|---|---|
| 1 Meter | = 3.28083333333 US Survey Feet |
| 1 Meter | = 3.28083989501 International Feet |
| 1 International Foot | = 0.3048 Meter (Exact) |
| 1 US Survey Foot | = 1200/3937 Meter (Exact) |
| 1 US Survey Foot | = 0.30480060960 Meter |
| 1 International Nautical Mile | = 1852 Meters (Exact)<br>= 6076.10333333 US Survey Feet<br>= 6076.11548556 International Feet |
| 1 International Statute Mile | = 1609.344 Meters (Exact)<br>= 5280 International Feet (Exact) |

$T_U$ = Julian Centuries from Epoch J2000.0

# 4. WGS 84 ELLIPSOIDAL GRAVITY FORMULA

## 4.1 General

In Section 3.1, the WGS 84 Ellipsoid is identified as being a geocentric equipotential ellipsoid of revolution. An equipotential ellipsoid is simply an ellipsoid defined to be an equipotential surface, i.e., a surface on which all values of the gravity potential are equal. Given an ellipsoid of revolution, it can be made an equipotential surface of a certain potential function, the theoretical (normal) gravity potential (U). This theoretical gravity potential can be uniquely determined, independent of the density distribution within the ellipsoid, by using any system of four independent constants as the defining parameters of the ellipsoid. As noted earlier for the WGS 84 Ellipsoid (Chapter 3), these are the semimajor axis (a), the normalized second degree zonal gravitational coefficient ($\bar{C}_{20}$), the earth's angular velocity ($\omega$), and the earth's gravitational constant (GM).

Theoretical gravity ($\gamma$), the gradient of U, is given on (at) the surface of the ellipsoid by the closed formula of Somigliana [13]:

$$\gamma = (a\ \gamma_e \cos^2\phi + b\ \gamma_p \sin^2\phi)) / (a^2\cos^2\phi + b^2\sin^2\phi)^{1/2} \qquad (4\text{-}1)$$

where

a, b = semimajor and semiminor axes of the ellipsoid, respectively

$\gamma_e, \gamma_p$ = theoretical gravity at the equator and poles, respectively

$\phi$ = geodetic latitude.

Thus, the equipotential ellipsoid serves not only as the reference surface or geometric figure of the earth, but leads to a closed formula for theoretical gravity at the ellipsoidal surface.

### 4.2 Analytical and Numerical Forms

The closed gravity formula of Somigliana in the form [3]

$$\gamma = \gamma_e \, (1 + k \sin^2\phi)/(1 - e^2\sin^2\phi)^{1/2} \qquad (4\text{-}2)$$

has been selected as the official WGS 84 Ellipsoidal Gravity Formula. In Equation (4-2):

$$k = (b\, \gamma_p / a\, \gamma_e) - 1 \qquad (4\text{-}3)$$

$e^2$ = square of the first eccentricity of the ellipsoid.

Equation (4-2) was selected for use with WGS 84 in preference to Equation (4-1) since it is more convenient for numerical computations and explicitly contains only $\gamma_e$ as the first factor in the equation.

The analytical and numerical forms of the WGS 84 Ellipsoidal Gravity Formula are provided in Table 4.1.

Table 4.1

WGS 84
Ellipsoidal Gravity Formula

| Provides Gravity Values at (on) the Surface of the WGS 84 Ellipsoid |
|---|
| **Notation**<br><br>$\gamma$ = Acceleration of a unit test mass due to theoretical gravity.<br><br>$\gamma_e$ = Acceleration at the equator (on the WGS 84 Ellipsoid) of a unit test mass due to theoretical gravity.<br><br>k = Constant = $(b\ \gamma_p/a\ \gamma_e) - 1$<br><br>a = Semimajor axis (WGS 84 Ellipsoid)<br>b = Semiminor axis (WGS 84 Ellipsoid)<br>$\gamma_p$ = Theoretical gravity at the poles (on the WGS 84 Ellipsoid)<br><br>$\phi$ = Geodetic latitude<br><br>$e^2$ = First eccentricity squared (WGS 84 Ellipsoid). |
| **Analytical Form**<br><br>$\gamma = \gamma_e\ (1 + k \sin^2\phi)/(1 - e^2\sin^2\phi)^{1/2}$ |
| **Numerical Form**<br><br>$\gamma = 978032.67714\ (1 + 0.00193185138639 \sin^2\phi)\ /$<br>$(1 - 0.00669437999013 \sin^2\phi)^{1/2} \times 10^{-5}$ m/second$^2$ (mgal) |
| An acceleration due to gravity of $1 \times 10^{-5}$ m/second$^2$ = 1 mgal |

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# 5. WGS 84 GRAVITY MODELING

## 5.1 Earth Gravitational Model (EGM)

The form of the WGS 84 EGM is a spherical harmonic expansion (Table 5.1) of the gravitational potential (V). The WGS 84 EGM, complete through degree (n) and order (m) 180, is comprised of 32755 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, surface gravity data, oceanic geoid heights deduced from satellite radar altimeter data, Navstar Global Positioning System (GPS) data, and "lumped coefficients". The effect (contribution) of coefficients through n=m=41 was removed from a worldwide 1°x1° mean gravity anomaly field leaving a worldwide residual 1°x1° mean gravity anomaly field. The WGS 84 EGM coefficients from n=42, m=0 through n=m=180 were then determined independently via harmonic analysis using the residual field. The coefficients through n=m=41 from the weighted least squares solution and the coefficients above n=m=41 from the independent 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°x1° mean gravity anomalies via spherical harmonic expansions. Expansions to this degree and order (n=m=180) are needed to accurately model variations in the earth's gravitational field on or near the earth's surface.

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 such applications is not recommended at this time. However, if required for a special application, DMA and other DoD users will need to conduct orbital analyses and ascertain the EGM truncation level that is "best" suited for the satellite project involved.

The WGS 84 EGM through n=m=180 is available on magnetic tape in normalized form. The WGS 84 EGM through n=m=41 is available on a separate magnetic tape in both normalized and conventional form. However, the WGS 84 EGM coefficients through n=m=18 are provided in Table 5.2 in normalized form.

Accuracy values are not available for all of the WGS 84 EGM coefficients. However, an error covariance matrix is available for those coefficients through n=m=41 determined from the weighted least squares solution. Gravity anomaly degree variances are given in Table 5.3 for the WGS 84 EGM (n=m=180). Requesters having a need for the full WGS 84 EGM and/or its error data should forward their correspondence to the address listed in the PREFACE.

## 5.2 Gravity Potential (W)

Using the WGS 84 EGM model (Table 5.1), the earth's total gravity potential (W) is then defined as

$$W = V + \Phi \qquad (5\text{-}1)$$

where $\Phi$ is the centrifugal potential due to the earth's rotation. If $\omega$ is the angular velocity [Equation (3-10)], then

$$\Phi = \frac{1}{2}\,\omega^2 (X^2 + Y^2) \qquad (5\text{-}2)$$

where X and Y are the geocentric coordinates of the rotating mass in the WGS 84 reference frame (See Figure 2.3).

Table 5.1

Form of the WGS 84
Earth Gravitational Model

$$V = \frac{GM}{r}\left[1 + \sum_{n=2}^{n_{max}} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n \overline{P}_{nm}(\sin\phi')\,(\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda)\right]$$

| Parameter | Definition |
|---|---|
| $V$ | = Gravitational potential function ($m^2s^{-2}$) |
| $GM$ | = Earth's gravitational constant |
| $r$ | = Radius vector from the earth's center of mass |
| $a$ | = Semimajor axis of the WGS 84 Ellipsoid |
| $n,m$ | = Degree and order, respectively |
| $\phi'$ | = Geocentric latitude** |
| $\lambda$ | = Geocentric longitude = geodetic longitude** |
| $\overline{C}_{nm}, \overline{S}_{nm}$ | = Normalized gravitational coefficients* |
| $\overline{P}_{nm}(\sin\phi')$ | = Normalized associated Legendre function |
| | $= \left[\frac{(n-m)!\ (2n+1)k}{(n+m)!}\right]^{1/2} P_{nm}(\sin\phi')$ |
| $P_{nm}(\sin\phi')$ | = Associated Legendre function |

* See next page.

** Latitude is positive north and longitude is positive east ($0^0$ to $180^0$)

Table 5.1 (Cont'd)

Form of the WGS 84
Earth Gravitational Model

| Parameter | Definition |
| --- | --- |
| $P_{nm}(\sin\phi')$ | $= (\cos\phi')^m \dfrac{d^m}{d(\sin\phi')^m} [P_n(\sin\phi')]$ |
| $P_n\ (\sin\phi')$ | = Legendre polynomial |
| $P_n\ (\sin\phi')$ | $= \dfrac{1}{2^n n!} \dfrac{d^n}{d(\sin\phi')^n} (\sin^2\phi' - 1)^n$ |

*Note:

$$\begin{matrix}\overline{C}_{nm} \\ \\ \overline{S}_{nm}\end{matrix} = \left[ \frac{(n+m)!}{(n-m)!\ (2n+1)k} \right]^{1/2} \begin{matrix}C_{nm} \\ \\ S_{nm}\end{matrix}$$

where

$C_{nm}$, $S_{nm}$ = Conventional gravitational coefficients

For $m=0$, $k=1$;

$m \geq 1$, $k=2$.

Table 5.2

WGS 84
Earth Gravitational Model
(Truncated at n=m=18)*

| Degree and Order | | Normalized Gravitational Coefficients | | Degree and Order | | Normalized Gravitational Coefficients | |
|---|---|---|---|---|---|---|---|
| n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ | n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ |
| 2 | 0 | -0.48416685E-03 | | 6 | 3 | 0.53370577E-07 | 0.61334720E-08 |
| 2 | 1 | -------------- | -------------- | 6 | 4 | -0.88694856E-07 | -0.47260945E-06 |
| 2 | 2 | 0.24395796E-05 | -0.13979548E-05 | 6 | 5 | -0.26818820E-06 | -0.53491073E-06 |
| 3 | 0 | 0.95706390E-06 | | 6 | 6 | 0.10237832E-07 | -0.23741002E-06 |
| 3 | 1 | 0.20318729E-05 | 0.25085759E-06 | 7 | 0 | 0.85819217E-07 | |
| 3 | 2 | 0.90666113E-06 | -0.62102428E-06 | 7 | 1 | 0.27905196E-06 | 0.94231346E-07 |
| 3 | 3 | 0.71770352E-06 | 0.14152388E-05 | 7 | 2 | 0.32873832E-06 | 0.88835092E-07 |
| 4 | 0 | 0.53699587E-06 | | 7 | 3 | 0.24940240E-06 | -0.21223369E-06 |
| 4 | 1 | -0.53548044E-06 | -0.47420394E-06 | 7 | 4 | -0.27123034E-06 | -0.12696607E-06 |
| 4 | 2 | 0.34797519E-06 | 0.65579158E-06 | 7 | 5 | 0.10246290E-08 | 0.17321672E-07 |
| 4 | 3 | 0.99172321E-06 | -0.19912491E-06 | 7 | 6 | -0.35843745E-06 | 0.15202633E-06 |
| 4 | 4 | -0.18686124E-06 | 0.30953114E-06 | 7 | 7 | -0.20991457E-08 | 0.22805664E-07 |
| 5 | 0 | 0.71092048E-07 | | 8 | 0 | 0.42979835E-07 | |
| 5 | 1 | -0.64185265E-07 | -0.92492959E-07 | 8 | 1 | 0.18889342E-07 | 0.47856967E-07 |
| 5 | 2 | 0.65184984E-06 | -0.32007416E-06 | 8 | 2 | 0.73553952E-07 | 0.47867693E-07 |
| 5 | 3 | -0.44903639E-06 | -0.21328272E-06 | 8 | 3 | -0.12132459E-07 | -0.83461853E-07 |
| 5 | 4 | -0.29719055E-06 | 0.53213480E-07 | 8 | 4 | -0.24208264E-06 | 0.71603924E-07 |
| 5 | 5 | 0.17523221E-06 | -0.67059456E-06 | 8 | 5 | -0.24966587E-07 | 0.87751047E-07 |
| 6 | 0 | -0.15064821E-06 | | 8 | 6 | -0.65093424E-07 | 0.30904202E-06 |
| 6 | 1 | -0.74180259E-07 | 0.32780040E-07 | 8 | 7 | 0.66323292E-07 | 0.74661766E-07 |
| 6 | 2 | 0.51824409E-07 | -0.35866634E-06 | 8 | 8 | -0.12372281E-06 | 0.12210258E-06 |

E-03 = X $10^{-3}$; E-05 = X $10^{-5}$; Etc.

* See Section 5.1

Table 5.2 (Cont'd)

WGS 84
Earth Gravitational Model
(Truncated at n=m=18)*

| Degree and Order | | Normalized Gravitational Coefficients | | Degree and Order | | Normalized Gravitational Coefficients | |
|---|---|---|---|---|---|---|---|
| n | m | $\overline{C}_{nm}$ | $\overline{S}_{nm}$ | n | m | $\overline{C}_{nm}$ | $\overline{S}_{nm}$ |
| 9 | 0 | 0.33173231E-07 | | 11 | 2 | 0.21716225E-07 | -0.10224810E-06 |
| 9 | 1 | 0.14747969E-06 | 0.23894354E-07 | 11 | 3 | -0.30023695E-07 | -0.13422019E-06 |
| 9 | 2 | 0.22052093E-07 | -0.26876665E-07 | 11 | 4 | -0.30407161E-07 | -0.69823333E-07 |
| 9 | 3 | -0.16256047E-06 | -0.85928431E-07 | 11 | 5 | 0.35104609E-07 | 0.49175170E-07 |
| 9 | 4 | -0.17193827E-07 | 0.26077030E-07 | 11 | 6 | -0.37911105E-08 | 0.36848522E-07 |
| 9 | 5 | -0.16902791E-07 | -0.50337365E-07 | 11 | 7 | 0.25774039E-08 | -0.88658395E-07 |
| 9 | 6 | 0.65717910E-07 | 0.22275858E-06 | 11 | 8 | -0.71396627E-08 | 0.23243077E-07 |
| 9 | 7 | -0.11648016E-06 | -0.97298769E-07 | 11 | 9 | -0.30246313E-07 | 0.41776400E-07 |
| 9 | 8 | 0.18896045E-06 | -0.31026222E-08 | 11 | 10 | -0.53424279E-07 | -0.18716766E-07 |
| 9 | 9 | -0.48275744E-07 | 0.96381072E-07 | 11 | 11 | 0.47514858E-07 | -0.70415796E-07 |
| 10 | 0 | 0.50931575E-07 | | 12 | 0 | 0.34073235E-07 | |
| 10 | 1 | 0.88706517E-07 | -0.12536457E-06 | 12 | 1 | -0.60609926E-07 | -0.38189082E-07 |
| 10 | 2 | -0.82375203E-07 | -0.38280049E-07 | 12 | 2 | 0.74200188E-08 | 0.24640620E-07 |
| 10 | 3 | -0.13137371E-07 | -0.15553732E-06 | 12 | 3 | 0.42149817E-07 | 0.32189594E-07 |
| 10 | 4 | -0.87424319E-07 | -0.79215732E-07 | 12 | 4 | -0.64346831E-07 | -0.25364931E-08 |
| 10 | 5 | -0.53980821E-07 | -0.46294947E-07 | 12 | 5 | 0.33126200E-07 | -0.40658586E-09 |
| 10 | 6 | -0.42371448E-07 | -0.79680607E-07 | 12 | 6 | 0.86981502E-08 | 0.36711094E-07 |
| 10 | 7 | 0.83736045E-08 | -0.25636582E-08 | 12 | 7 | -0.16598048E-07 | 0.34475954E-07 |
| 10 | 8 | 0.41239589E-07 | -0.92269095E-07 | 12 | 8 | -0.26843700E-07 | 0.17838309E-07 |
| 10 | 9 | 0.12539514E-06 | -0.37687117E-07 | 12 | 9 | 0.42293015E-07 | 0.27107811E-07 |
| 10 | 10 | 0.10124370E-06 | -0.24874984E-07 | 12 | 10 | -0.44237357E-08 | 0.30823394E-07 |
| 11 | 0 | -0.58114696E-07 | | 12 | 11 | 0.96462514E-08 | -0.60711291E-08 |
| 11 | 1 | 0.95375839E-08 | -0.22094828E-07 | 12 | 12 | -0.30878714E-08 | -0.10932316E-07 |

E-03 = X $10^{-3}$; E-05 = X $10^{-5}$; Etc.

* See Section 5.1

Table 5.2 (Cont'd)

WGS 84
Earth Gravitational Model
(Truncated at n=m=18)*

| n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ | n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ |
|---|---|---|---|---|---|---|---|
| 13 | 0 | 0.48159534E-07 | | 14 | 7 | 0.39355808E-07 | -0.52187212E-08 |
| 13 | 1 | -0.47921675E-07 | 0.34957177E-07 | 14 | 8 | -0.31866053E-07 | -0.16609601E-07 |
| 13 | 2 | 0.48705121E-07 | -0.63933232E-07 | 14 | 9 | 0.30182993E-07 | 0.23942248E-07 |
| 13 | 3 | -0.17219549E-07 | 0.82465794E-07 | 14 | 10 | 0.36008306E-07 | -0.43924872E-09 |
| 13 | 4 | -0.92616056E-08 | -0.98249479E-09 | 14 | 11 | 0.16006347E-07 | -0.40475033E-07 |
| 13 | 5 | 0.58545255E-07 | 0.66075856E-07 | 14 | 12 | 0.79810549E-08 | -0.31068551E-07 |
| 13 | 6 | -0.28548757E-07 | -0.13018250E-07 | 14 | 13 | 0.33446421E-07 | 0.44622344E-07 |
| 13 | 7 | 0.10048687E-07 | -0.12672050E-07 | 14 | 14 | -0.52174166E-07 | -0.48789452E-08 |
| 13 | 8 | -0.12236037E-07 | -0.11680475E-07 | 15 | 0 | -0.55534001E-08 | |
| 13 | 9 | 0.25798630E-07 | 0.46771958E-07 | 15 | 1 | 0.77027909E-08 | 0.12667983E-07 |
| 13 | 10 | 0.42112066E-07 | -0.35203559E-07 | 15 | 2 | -0.13310361E-07 | -0.25570239E-07 |
| 13 | 11 | -0.44423472E-07 | -0.63137559E-08 | 15 | 3 | 0.53469109E-07 | 0.21540830E-07 |
| 13 | 12 | -0.31610688E-07 | 0.86378230E-07 | 15 | 4 | -0.35485140E-07 | -0.38325971E-08 |
| 13 | 13 | -0.61019573E-07 | 0.63712423E-07 | 15 | 5 | 0.80670670E-08 | 0.95367405E-08 |
| 14 | 0 | -0.25559279E-07 | | 15 | 6 | 0.28835774E-07 | -0.29584853E-07 |
| 14 | 1 | -0.10581256E-07 | 0.22739082E-07 | 15 | 7 | 0.55297561E-07 | 0.12688881E-07 |
| 14 | 2 | -0.32588467E-07 | -0.45984585E-08 | 15 | 8 | -0.26866012E-07 | 0.28508669E-07 |
| 14 | 3 | 0.33411750E-07 | 0.72271094E-08 | 15 | 9 | 0.15229368E-07 | 0.40242957E-07 |
| 14 | 4 | 0.34163340E-08 | -0.23062568E-07 | 15 | 10 | 0.78226264E-08 | 0.16482104E-07 |
| 14 | 5 | 0.21777499E-07 | -0.44340974E-08 | 15 | 11 | -0.45323941E-08 | 0.16379211E-07 |
| 14 | 6 | -0.23022045E-07 | 0.79137357E-08 | 15 | 12 | -0.34310516E-07 | 0.13248557E-07 |

E-03 = X $10^{-3}$; E-05 = X $10^{-5}$; Etc.

* See Section 5.1

Table 5.2 (Cont'd)

WGS 84
Earth Gravitational Model
(Truncated at n=m=18)*

| Degree and Order n | m | Normalized Gravitational Coefficients $\bar{C}_{nm}$ | $\bar{S}_{nm}$ | Degree and Order n | m | Normalized Gravitational Coefficients $\bar{C}_{nm}$ | $\bar{S}_{nm}$ |
|---|---|---|---|---|---|---|---|
| 15 | 13 | -0.27865470E-07 | -0.51124016E-08 | 17 | 0 | 0.27418160E-07 | |
| 15 | 14 | 0.58007239E-08 | -0.24830947E-07 | 17 | 1 | -0.17492372E-07 | -0.29004434E-07 |
| 15 | 15 | -0.18756974E-07 | -0.53745848E-08 | 17 | 2 | -0.24972136E-07 | 0.52345300E-08 |
| 16 | 0 | 0.96352958E-08 | | 17 | 3 | 0.75958226E-08 | 0.13161951E-07 |
| 16 | 1 | 0.16657011E-07 | 0.32088971E-07 | 17 | 4 | -0.35567936E-08 | 0.29108859E-07 |
| 16 | 2 | -0.22051986E-07 | 0.26286204E-07 | 17 | 5 | -0.16440517E-07 | 0.15666155E-07 |
| 16 | 3 | -0.29514849E-07 | -0.95827659E-08 | 17 | 6 | -0.29053420E-08 | -0.41239945E-07 |
| 16 | 4 | 0.37621131E-07 | 0.55477548E-07 | 17 | 7 | 0.30327591E-07 | -0.54652615E-08 |
| 16 | 5 | -0.10479239E-07 | -0.27382338E-08 | 17 | 8 | 0.26828952E-07 | -0.69634040E-08 |
| 16 | 6 | 0.97407454E-08 | -0.43087957E-07 | 17 | 9 | -0.74685923E-09 | -0.31300568E-07 |
| 16 | 7 | -0.12168169E-07 | -0.56636996E-08 | 17 | 10 | -0.10536220E-08 | 0.18628074E-07 |
| 16 | 8 | -0.25034024E-07 | 0.22895737E-08 | 17 | 11 | -0.13049234E-07 | 0.13662390E-07 |
| 16 | 9 | -0.17908785E-07 | -0.29938908E-07 | 17 | 12 | 0.32820228E-07 | 0.17654374E-07 |
| 16 | 10 | -0.10129689E-07 | 0.12404473E-07 | 17 | 13 | 0.17049873E-07 | 0.19279770E-07 |
| 16 | 11 | 0.19053980E-07 | -0.17354590E-08 | 17 | 14 | -0.14027974E-07 | 0.11214602E-07 |
| 16 | 12 | 0.18888013E-07 | 0.46949615E-08 | 17 | 15 | 0.56624501E-08 | 0.56527252E-08 |
| 16 | 13 | 0.15158142E-07 | -0.17410596E-09 | 17 | 16 | -0.32153542E-07 | 0.33341657E-08 |
| 16 | 14 | -0.19416172E-07 | -0.38724225E-07 | 17 | 17 | -0.37961677E-07 | -0.17192537E-07 |
| 16 | 15 | -0.14400649E-07 | -0.33151819E-07 | 18 | 0 | 0.10196218E-07 | |
| 16 | 16 | -0.40920912E-07 | 0.23449430E-08 | 18 | 1 | 0.85717760E-08 | -0.32887288E-07 |

E-03 = X $10^{-3}$; E-05 = X $10^{-5}$; Etc.

* See Section 5.1

Table 5.2 (Cont'd)

WGS 84
Earth Gravitational Model
(Truncated at n=m=18)*

| Degree and Order | | Normalized Gravitational Coefficients | | Degree and Order | | Normalized Gravitational Coefficients | |
|---|---|---|---|---|---|---|---|
| n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ | n | m | $\bar{C}_{nm}$ | $\bar{S}_{nm}$ |
| 18 | 2 | 0.11021506E-07 | 0.96877203E-08 | 18 | 11 | -0.92784417E-08 | 0.11278314E-08 |
| 18 | 3 | -0.78128408E-08 | -0.16263649E-07 | 18 | 12 | -0.29997564E-07 | -0.13762992E-07 |
| 18 | 4 | 0.50107239E-07 | -0.35094534E-08 | 18 | 13 | -0.61616779E-08 | -0.34022737E-07 |
| 18 | 5 | -0.35408518E-08 | 0.26790491E-07 | 18 | 14 | -0.77166667E-08 | -0.13392253E-07 |
| 18 | 6 | 0.12489735E-07 | -0.12526195E-07 | 18 | 15 | -0.38973604E-07 | -0.20668220E-07 |
| 18 | 7 | 0.14813821E-07 | -0.18829836E-08 | 18 | 16 | 0.10273437E-07 | 0.69198054E-08 |
| 18 | 8 | 0.35285229E-07 | 0.13368789E-08 | 18 | 17 | 0.33491685E-08 | 0.54056479E-08 |
| 18 | 9 | -0.24544444E-07 | 0.25745394E-07 | 18 | 18 | 0.11121796E-08 | -0.94806182E-08 |
| 18 | 10 | 0.84106552E-09 | -0.44929528E-08 | | | | |

E-03 = X $10^{-3}$; E-05 = X $10^{-5}$; Etc.

* See Section 5.1

Table 5.3

WGS 84 EGM
Gravity Anomaly Degree Variances ($c_n$)*

| Degree | Degree Variances | Degree | Degree Variances | Degree | Degree Variances |
|---|---|---|---|---|---|
| 2 | 7.6 | 41 | 2.8 | 80 | 2.3 |
| 3 | 33.9 | 42 | 2.7 | 81 | 2.6 |
| 4 | 19.2 | 43 | 2.4 | 82 | 2.8 |
| 5 | 21.0 | 44 | 2.8 | 83 | 2.7 |
| 6 | 19.4 | 45 | 2.7 | 84 | 2.4 |
| 7 | 19.3 | 46 | 2.7 | 85 | 2.2 |
| 8 | 10.9 | 47 | 3.1 | 86 | 2.7 |
| 9 | 11.5 | 48 | 2.5 | 87 | 2.4 |
| 10 | 9.7 | 49 | 2.5 | 88 | 2.2 |
| 11 | 6.4 | 50 | 2.8 | 89 | 2.0 |
| 12 | 2.6 | 51 | 2.8 | 90 | 2.0 |
| 13 | 7.4 | 52 | 2.6 | 91 | 2.3 |
| 14 | 3.2 | 53 | 3.1 | 92 | 2.0 |
| 15 | 3.4 | 54 | 2.8 | 93 | 2.2 |
| 16 | 3.9 | 55 | 3.0 | 94 | 2.0 |
| 17 | 3.6 | 56 | 3.0 | 95 | 1.8 |
| 18 | 3.6 | 57 | 3.0 | 96 | 2.0 |
| 19 | 3.3 | 58 | 2.6 | 97 | 1.9 |
| 20 | 3.1 | 59 | 3.0 | 98 | 2.1 |
| 21 | 3.2 | 60 | 2.6 | 99 | 1.7 |
| 22 | 3.6 | 61 | 2.5 | 100 | 1.8 |
| 23 | 2.7 | 62 | 2.9 | 101 | 1.7 |
| 24 | 2.6 | 63 | 2.5 | 102 | 2.1 |
| 25 | 2.9 | 64 | 2.7 | 103 | 2.3 |
| 26 | 2.4 | 65 | 2.1 | 104 | 1.8 |
| 27 | 1.9 | 66 | 2.6 | 105 | 1.8 |
| 28 | 2.4 | 67 | 2.5 | 106 | 1.7 |
| 29 | 2.4 | 68 | 2.6 | 107 | 1.8 |
| 30 | 2.8 | 69 | 2.9 | 108 | 1.9 |
| 31 | 2.9 | 70 | 2.3 | 109 | 2.0 |
| 32 | 4.1 | 71 | 2.3 | 110 | 2.0 |
| 33 | 3.4 | 72 | 2.7 | 111 | 1.7 |
| 34 | 5.0 | 73 | 2.4 | 112 | 1.6 |
| 35 | 4.4 | 74 | 2.6 | 113 | 1.8 |
| 36 | 3.6 | 75 | 2.2 | 114 | 1.6 |
| 37 | 3.4 | 76 | 2.3 | 115 | 1.9 |
| 38 | 2.8 | 77 | 2.3 | 116 | 1.7 |
| 39 | 3.5 | 78 | 2.4 | 117 | 1.7 |
| 40 | 3.6 | 79 | 2.2 | 118 | 1.6 |

Units = $(1 \times 10^{-5}\ \text{m/second}^2)^2$ or $\text{mgal}^2$

* See next page.

Table 5.3 (Cont'd)

WGS 84 EGM
Gravity Anomaly Degree Variances ($c_n$)*

| Degree | Degree Variances | Degree | Degree Variances | Degree | Degree Variances |
|---|---|---|---|---|---|
| 119 | 1.6 | 140 | 1.3 | 161 | 0.9 |
| 120 | 1.6 | 141 | 1.1 | 162 | 0.8 |
| 121 | 1.5 | 142 | 1.0 | 163 | 0.9 |
| 122 | 1.3 | 143 | 1.1 | 164 | 1.0 |
| 123 | 1.6 | 144 | 1.1 | 165 | 0.9 |
| 124 | 1.6 | 145 | 1.0 | 166 | 0.8 |
| 125 | 1.5 | 146 | 1.0 | 167 | 0.9 |
| 126 | 1.3 | 147 | 1.0 | 168 | 0.8 |
| 127 | 1.5 | 148 | 1.2 | 169 | 0.8 |
| 128 | 1.2 | 149 | 1.0 | 170 | 0.8 |
| 129 | 1.4 | 150 | 1.0 | 171 | 0.9 |
| 130 | 1.3 | 151 | 1.0 | 172 | 0.7 |
| 131 | 1.3 | 152 | 1.0 | 173 | 0.8 |
| 132 | 1.4 | 153 | 1.0 | 174 | 0.8 |
| 133 | 1.4 | 154 | 1.0 | 175 | 0.8 |
| 134 | 1.2 | 155 | 0.9 | 176 | 0.8 |
| 135 | 1.2 | 156 | 1.0 | 177 | 0.6 |
| 136 | 1.2 | 157 | 0.8 | 178 | 0.7 |
| 137 | 1.3 | 158 | 0.8 | 179 | 0.8 |
| 138 | 1.3 | 159 | 0.8 | 180 | 0.8 |
| 139 | 1.2 | 160 | 0.9 | | |

Units = $(1 \times 10^{-5}$ m/second$^2)^2$ or mgal$^2$

*Formula for computing gravity anomaly degree variances ($c_n$)

$$c_n = \bar{\gamma}^2 (n-1)^2 \sum_{m=0}^{n} (\bar{C}^2_{nm} + \bar{S}^2_{nm})$$

$c_n$ = Gravity anomaly degree variance in mgal$^2$ for degree n

$\bar{\gamma}$ = Average value of theoretical gravity

$\bar{\gamma}$ = 979764.46561 mgal (based on WGS 84 Ellipsoidal Gravity Formula)

$\bar{C}_{nm}$, $\bar{S}_{nm}$ = Normalized gravitational coefficients of degree n and order m

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## 6. WGS 84 GEOID

### 6.1 General

In geodetic applications, three different surfaces or earth figures are normally involved. In addition to the earth's natural or actual surface, the other two include a geometric or mathematical figure taken to be an equipotential ellipsoid of revolution (Chapter 3), and a physical figure defined as an equipotential surface in the earth's gravity field, or the geoid.

The equation

$$W(X,Y,Z) = \text{constant} \tag{6-1}$$

defines a family of equipotential surfaces (GEOPS) of the earth's gravity field. The geoid is that particular equipotential GEOP for which the constant in Equation (6-1) is equal to $W_0$ (or the ellipsoidal potential $U_0$) defined in Table 3.3.

For some practical applications, the geoid, defined as above, is approximated by the mean sea level (msl) over the oceans (or its hypothetical extension under the land masses). It may be necessary to clarify that the msl is not an equipotential surface and in its simplest definition would comprise a mean of sea level surfaces approximated and observed over 18.67 years.

In a mathematical sense, the geoid is also defined (or realized) as so many meters above (+N) or below (-N) the ellipsoid, the geometric figure.

In the definition of the geoid, a great practical importance exists: the geoid can serve as the approximation for the vertical datum reference surface for mean sea level heights (H)*. In areas where

* Note the other usage of this symbol in Equation (3-16) and Table 3.4.

general elevation data is not available from conventional leveling, the "approximate" determination of the H-values can be achieved using the equation

$$h \simeq N + H \tag{6-2}$$

$$H \simeq h - N \tag{6-3}$$

where:

$h$ = geodetic height = height relative to the ellipsoid

$N$ = geoid height

$H$ = orthometric height relative to the geoid (or, approximately, mean sea level height)

Equation (6-3) illustrates the use of geoid heights in the determination of H-values from geodetic heights derived using satellite positions (e.g., TRANSIT or Navstar Global Positioning System) located on the earth's physical surface or aboard a vehicle operating near the earth's surface.

## 6.2 Formulas and Representations/Analysis

### 6.2.1 Formulas

The WGS 84 Geoid Heights were calculated using a spherical harmonic expansion and the WGS 84 EGM coefficients through n=m=180. The formula for calculating WGS 84 Geoid Heights has the form:

$$N = \frac{GM}{r\gamma}\left[\sum_{n=2}^{n_{max}} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n (\overline{C}_{nm}\cos m\lambda + \overline{S}_{nm}\sin m\lambda)\,\overline{P}_{nm}(\sin\phi')\right] \tag{6-4}$$

where N is the geoid height in meters, $\gamma$ is theoretical gravity calculated using the WGS 84 Ellipsoidal Gravity Formula (Table 4.1), and all other quantities are defined as for the WGS 84 EGM with one exception. In Equation (6-4), the even degree zonal coefficients of subscripts 2 through 10 are coefficient differences between the WGS 84 EGM minus normalized gravity. (See Sections 6.2.1 and 6.2.2 in [1]).

### 6.2.2 Representations/Analysis

The geoid can be depicted as a contour chart which shows the deviations of the geoid from the ellipsoid selected as the mathematical figure of the earth. Figure 6.1 is a worldwide WGS 84 Geoid Height Contour Chart developed from a worldwide 1°x1° grid of geoid heights calculated by using WGS 84 numerical data and the WGS 84 EGM coefficients through n=m=18 in Equation (6-4).

Table 6.1 contains a worldwide 10°x10° grid of WGS 84 Geoid Heights calculated using WGS 84 EGM coefficients through n=m=180.

A worldwide 1°x1° grid of WGS 84 Geoid Heights was computed and compared with a similar grid of WGS 72 Geoid Heights referenced to the WGS 72 Ellipsoid. The root-mean-square (RMS) difference was ±4.6 meters, with the largest positive and negative differences being 24 and -23.5 meters, respectively. Of the 64,800 geoid height differences, 21.36 percent (13,841 differences) were larger then 5 meters.

The RMS WGS 84 Geoid Height, taken worldwide on the basis of a 1°x1° grid, is 30.5 meters. This RMS value indicates how well the WGS 84 Ellipsoid, taken as the mathematical figure of the earth, fits the earth's geoidal surface.

The WGS 84 Geoid Heights have an error range of ±2 to ±6 meters (one sigma), and are known to accuracies of ±2 to ±3 meters over approximately 55 percent of the earth. Approximately 93 percent of the earth has WGS 84 Geoid Heights of accuracy better than ±4 meters.

## 6.3 Availability of WGS 84 Geoid Height Data

The WGS 84 Geoid Heights, the related data, and products, which can be provided to requesters (see PREFACE), are:

- A worldwide WGS 84 Geoid Height Contour Chart with 5 meters contour interval. If needed, contour charts of other physical sizes, geographic areas, contour intervals and scales can be provided.

- A magnetic tape containing the worldwide 1°x1° or 30'x30' grid of WGS 84 Geoid Heights.

- A Bi-Linear Interpolation program (Table 6.2) for interpolation of WGS 84 Geoid Heights at random points. Users are advised to check interpolation error(s) pertaining to application(s).

- A Computer Program for computation of WGS 84 Geoid Heights at a specified grid interval or at random points with associated documentation and appropriate test cases.

Table 6.1

WGS 84 Geoid Heights
(n=m=180, 10°x10° Grid, Units = Meters)

| Latitude (Degrees) | 0° | 10° | 20° | 30° | 40° | 50° | 60° | 70° | 80° | 90° | 100° | 110° | 120° | 130° | 140° | 150° | 160° | 170° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90° | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| 80° | 33 | 34 | 28 | 23 | 17 | 13 | 9 | 4 | 4 | 1 | -2 | -2 | 0 | 2 | 3 | 2 | 1 | 1 |
| 70° | 51 | 43 | 29 | 20 | 12 | 5 | -2 | -10 | -14 | -12 | -10 | -14 | -12 | -6 | -2 | 3 | 6 | 4 |
| 60° | 47 | 41 | 21 | 18 | 14 | 7 | -3 | -22 | -29 | -32 | -32 | -26 | -15 | -2 | 13 | 17 | 19 | 6 |
| 50° | 47 | 48 | 42 | 28 | 12 | -10 | -19 | -33 | -43 | -42 | -43 | -29 | -2 | 17 | 23 | 22 | 6 | 2 |
| 40° | 52 | 48 | 35 | 40 | 33 | -9 | -28 | -39 | -48 | -59 | -50 | -28 | 3 | 23 | 37 | 18 | -1 | -11 |
| 30° | 36 | 28 | 29 | 17 | 12 | -20 | -15 | -40 | -33 | -34 | -34 | -28 | 7 | 29 | 43 | 20 | 4 | -6 |
| 20° | 31 | 26 | 15 | 6 | 1 | -29 | -44 | -61 | -67 | -59 | -36 | -11 | 21 | 39 | 49 | 39 | 22 | 10 |
| 10° | 22 | 23 | 2 | -3 | -7 | -36 | -59 | -90 | -95 | -63 | -24 | 12 | 53 | 60 | 58 | 46 | 36 | 26 |
| 0° | 18 | 12 | -13 | -9 | -28 | -49 | -62 | -89 | -102 | -63 | -9 | 33 | 58 | 73 | 74 | 63 | 50 | 32 |
| -10° | 12 | 13 | -2 | -14 | -25 | -32 | -38 | -60 | -75 | -63 | -26 | 0 | 35 | 52 | 68 | 76 | 64 | 52 |
| -20° | 17 | 23 | 21 | 8 | -9 | -10 | -11 | 20 | -40 | -47 | -45 | -25 | 5 | 23 | 45 | 58 | 57 | 63 |
| -30° | 22 | 27 | 34 | 29 | 14 | 15 | 15 | 7 | -9 | -25 | -37 | -39 | -23 | -14 | 15 | 33 | 34 | 45 |
| -40° | 18 | 26 | 31 | 33 | 39 | 41 | 30 | 24 | 13 | -2 | -20 | -32 | -33 | -27 | -14 | -2 | 5 | 20 |
| -50° | 25 | 26 | 34 | 39 | 45 | 45 | 38 | 39 | 28 | 13 | -1 | -15 | -22 | -22 | -18 | -15 | -14 | -10 |
| -60° | 16 | 19 | 25 | 30 | 35 | 35 | 33 | 30 | 27 | 10 | -2 | -14 | -23 | -30 | -33 | -29 | -35 | -43 |
| -70° | 16 | 16 | 17 | 21 | 20 | 26 | 26 | 22 | 16 | 10 | -1 | -16 | -29 | -36 | -46 | -55 | -54 | -59 |
| -80° | -4 | -1 | 1 | 4 | 4 | 6 | 5 | 4 | 2 | -6 | -15 | -24 | -33 | -40 | -48 | -50 | -53 | -52 |
| -90° | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 |

Longitude (Degrees)

Table 6.1 (Cont'd)

WGS 84 Geoid Heights
(n=m=180, 10°x10° Grid, Units = Meters)

| Latitude (Degrees) | 180° | 190° | 200° | 210° | 220° | 230° | 240° | 250° | 260° | 270° | 280° | 290° | 300° | 310° | 320° | 330° | 340° | 350° |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90° | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| 80° | 3 | 1 | -2 | -3 | -3 | -3 | -1 | 3 | 1 | 5 | 9 | 11 | 19 | 27 | 31 | 34 | 33 | 34 |
| 70° | 2 | 2 | 1 | -1 | -3 | -7 | -14 | -24 | -27 | -25 | -19 | 3 | 24 | 37 | 47 | 60 | 61 | 58 |
| 60° | 2 | 9 | 17 | 10 | 13 | 1 | -14 | -30 | -39 | -46 | -42 | -21 | 6 | 29 | 49 | 65 | 60 | 57 |
| 50° | -8 | 8 | 8 | 1 | -11 | -19 | -16 | -18 | -22 | -35 | -40 | -26 | -12 | 24 | 45 | 63 | 62 | 59 |
| 40° | -12 | -10 | -13 | -20 | -31 | -34 | -21 | -16 | -26 | -34 | -33 | -35 | -26 | 2 | 33 | 59 | 52 | 51 |
| 30° | -7 | -5 | -8 | -15 | -28 | -40 | -42 | -29 | -22 | -26 | -32 | -51 | -40 | -17 | 17 | 31 | 34 | 44 |
| 20° | 5 | 10 | 7 | -7 | -23 | -39 | -47 | -34 | -9 | -10 | -20 | -45 | -48 | -32 | -9 | 17 | 25 | 31 |
| 10° | 13 | 12 | 11 | 2 | -11 | -28 | -38 | -29 | -10 | 3 | 1 | -11 | -41 | -42 | -16 | 3 | 17 | 33 |
| 0° | 22 | 16 | 17 | 13 | 1 | -12 | -23 | -20 | -14 | -3 | 14 | 10 | -15 | -27 | -18 | 3 | 12 | 20 |
| -10° | 36 | 22 | 11 | 6 | -1 | -8 | -10 | -8 | -11 | -9 | 1 | 32 | 4 | -18 | -13 | -9 | 4 | 14 |
| -20° | 51 | 27 | 10 | 0 | -9 | -11 | -5 | -2 | -3 | -1 | 9 | 35 | 20 | -5 | -6 | -5 | 0 | 13 |
| -30° | 46 | 22 | 5 | -2 | -8 | -13 | -10 | -7 | -4 | 1 | 9 | 32 | 16 | 4 | -8 | 4 | 12 | 15 |
| -40° | 21 | 6 | 1 | -7 | -12 | -12 | -12 | -10 | -7 | -1 | 8 | 23 | 15 | -2 | -6 | 6 | 21 | 24 |
| -50° | -15 | -18 | -18 | -16 | -17 | -15 | -10 | -10 | -8 | -2 | 6 | 14 | 13 | 3 | 3 | 10 | 20 | 27 |
| -60° | -45 | -43 | -37 | -32 | -30 | -26 | -23 | -22 | -16 | -10 | -2 | 10 | 20 | 20 | 21 | 24 | 22 | 17 |
| -70° | -61 | -60 | -61 | -55 | -49 | -44 | -38 | -31 | -25 | -16 | -6 | | 4 | 5 | 4 | 2 | 6 | 12 |
| -80° | -53 | -54 | -55 | -52 | -48 | -42 | -38 | -38 | -29 | -26 | -26 | -24 | -23 | -21 | -19 | -16 | -12 | -8 |
| -90° | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 | -30 |

Longitude (Degrees)

Table 6.2

Interpolation of WGS 84 Geoid Heights

| Bi-Linear Interpolation Method (Formula) |
|---|
| $N_p(\phi,\lambda) = a_0 + a_1X + a_2Y + a_3XY$ |
| = Geoid height (N) to be interpolated at Point $P(\phi,\lambda)$ |
| $a_0 = N_1$ |
| $a_1 = N_2 - N_1$ |
| $a_2 = N_4 - N_1$ |
| $a_3 = N_1 + N_3 - N_2 - N_4$ |
| $X = (\lambda - \lambda_1)/(\lambda_2 - \lambda_1)$ |
| $Y = (\phi - \phi_1)/(\phi_2 - \phi_1)$ |
| $\phi$ = Geodetic latitude of Point P |
| $\lambda$ = Geodetic longitude of Point P |
| $N_1, N_2, N_3, N_4$ = Known geoid heights at grid points used in the interpolation process |
| [See Associated Coordinate System, Figure 6.2] |

Note: Use of consistent units is necessary.

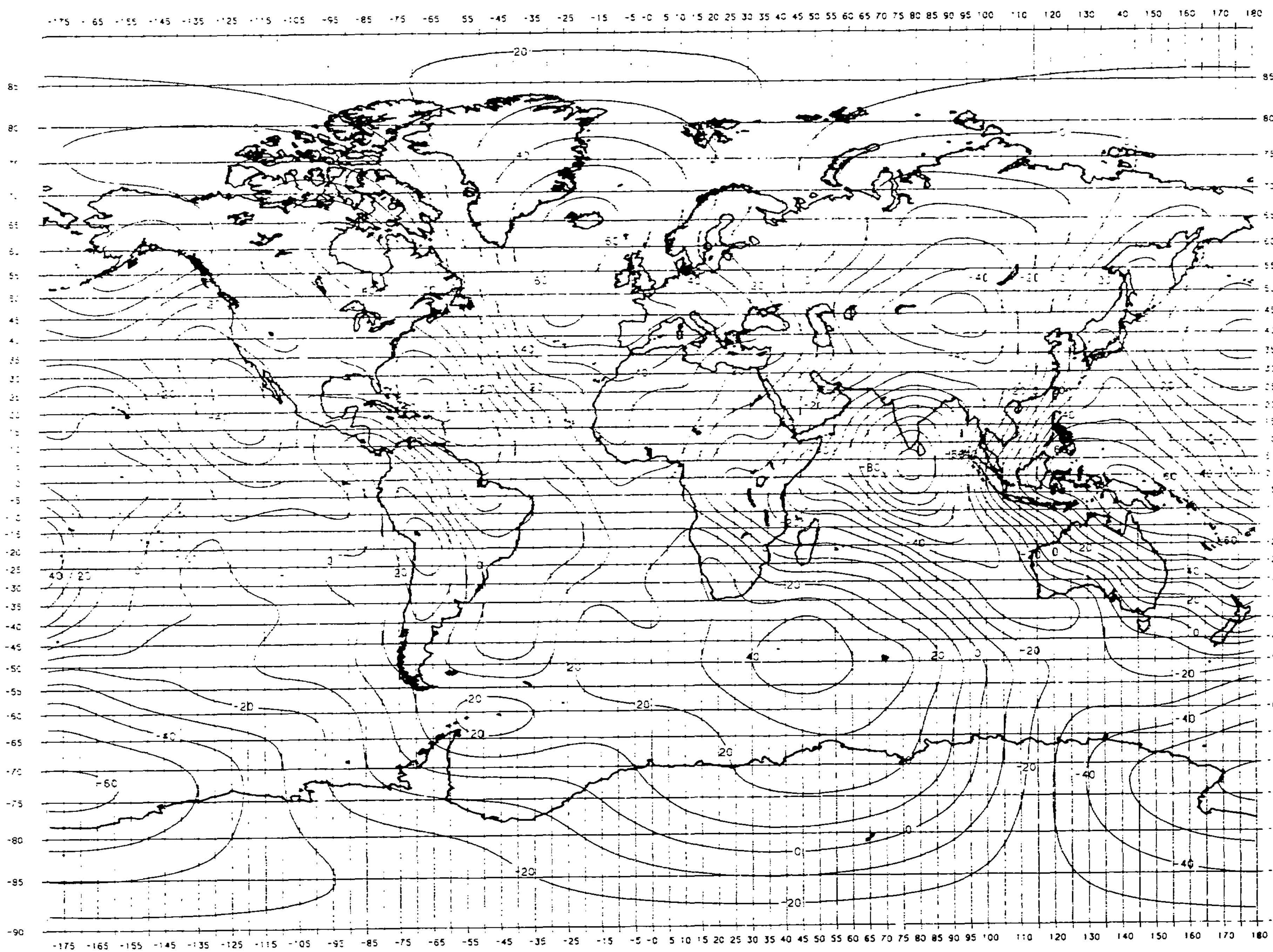

Figure 6.1. WGS 84 Geoid (n = m = 18 Truncation) Referenced to WGS 84 Ellipsoid (Units = Meters)

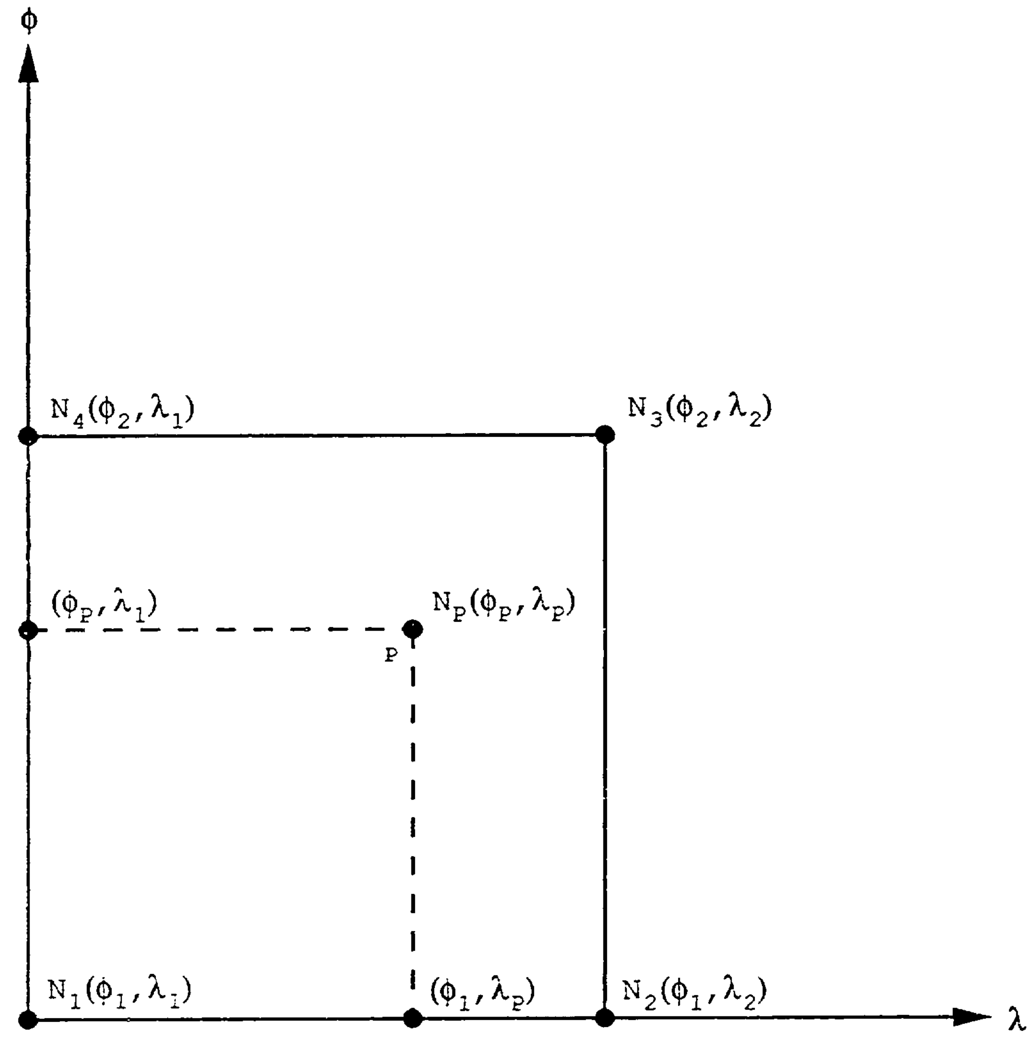


Figure 6.2. Coordinate System Associated With Geoid Height Bi-Linear Interpolation Scheme

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# 7. WGS 84 RELATIONSHIPS WITH OTHER GEODETIC SYSTEMS

## 7.1 General

One of the principal purposes of a world geodetic system is to provide the means whereby local geodetic datums can be referenced to a single geocentric system. The number of local geodetic datums, or local horizontal datums, requiring such referencing is extensive. Counting island and/or astronomic-based datums, the number exceeds several hundred. To accomplish the conversion, local geodetic datum and WGS coordinates are both required at one or more sites within the local datum area so that local geodetic datum-to-WGS datum shifts can be formed. Satellite stations positioned within WGS 84, and with known local geodetic datum coordinates, were the basic ingredients in the development of local geodetic datum-to-WGS 84 datum shifts.

The most accurate approach for obtaining WGS 84 coordinates is to acquire satellite tracking data at the site of interest and position it directly in WGS 84 using the Satellite Point Positioning technique [1]. However, it is unrealistic to presume that use of this technique will always be possible. In such cases, the transformation from WGS 72 to WGS 84 or from local geodetic datums to WGS 84 should be used (sections 7.2 and 7.3).

## 7.2 WGS 72-to-WGS 84 Transformation

Situations arise where only WGS 72 coordinates are available for a site. In such instances, the WGS 72-to-WGS 84 Transformation listed in Table 7.1 can be used with the following equations to obtain WGS 84 coordinates for the sites:

$$\phi_{WGS\ 84} = \phi_{WGS\ 72} + \Delta\phi$$

$$\lambda_{WGS\ 84} = \lambda_{WGS\ 72} + \Delta\lambda \qquad (7\text{-}1)$$

$$h_{WGS\ 84} = h_{WGS\ 72} + \Delta h$$

As indicated from Table 7.1, when proceeding directly from WGS 72 coordinates to obtain WGS 84 values, the WGS 84 coordinates will differ from the WGS 72 coordinates due to a shift in the coordinate system origin, a change in the longitude reference, a scale change (treated through $\Delta r$), and changes in the size and shape of the ellipsoid. In addition, it is important to be aware that $\Delta\phi$, $\Delta\lambda$, $\Delta h$ values calculated using Table 7.1 do not reflect the effect of differences between the WGS 72 and WGS 84 EGMs and Geoids. The following cases are important to note:

a. Table 7.1 equations are to be used for direct transformation of Doppler-derived WGS 72 coordinates. These transformed coordinates should agree to within approximately $\pm 2$ meters with the directly surveyed WGS 84 coordinates using TRANSIT or GPS point positioning.

b. Table 7.1 should not be used for satellite local geodetic stations whose WGS 72 coordinates were determined using datum shifts from [4]. The preferred approach is to transform such WGS 72 coordinates, using datum shifts from [4], back to their respective local datums, and then transform the local datum coordinates to WGS 84 using Appendices B and C.

Table 7.1 should be used only when no other approach is applicable.

## 7.3 Local Geodetic Datum-to-WGS 84 Datum Transformations

### 7.3.1 General

Most WGS 84 coordinates needed for applications and DoD operations in Mapping, Charting, and Geodesy (MC&G) will be obtained from a Local Geodetic Datum-to-WGS 84 Datum Transformation. This transformation can be performed either in curvilinear (geodetic) coordinates:

$$\begin{aligned} \phi_{WGS\ 84} &= \phi_{Local} + \Delta\phi \\ \lambda_{WGS\ 84} &= \lambda_{Local} + \Delta\lambda \\ h_{WGS\ 84} &= h_{Local} + \Delta h \end{aligned} \tag{7-2}$$

or, in rectangular coordinates [14]:

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{WGS\ 84} = \begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{Local} + \begin{vmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{vmatrix} + \begin{vmatrix} \Delta S & \omega & -\psi \\ -\omega & \Delta S & \varepsilon \\ \psi & -\varepsilon & \Delta S \end{vmatrix} \begin{vmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{vmatrix}_{Local} \tag{7-3}$$

where $\Delta S$ and $(\varepsilon, \psi, \omega)$ represent changes in local geodetic datum scale and reference frame orientation, respectively, and $(X_0, Y_0, Z_0)$ are the coordinates of the "initial" (defining) point of the local geodetic datum.

There are several datum transformation formulas for accomplishing the preceding. The most common techniques are, in the curvilinear case, the Standard Molodensky, and in the rectangular case, the 3-, 4-, or 7-parameter transformations depending on the availability (and/or reliability) of the transformation parameters. It may be noted that the 3-parameter rectangular case is embedded mathematically in the Molodensky Formulas to eliminate the conversion from geodetic to rectangular coordinates.

In addition, the curvilinear and rectangular coordinate datum transformations can be accomplished using a Multiple Regression Equation (MRE) technique which accounts for the non-linear distortion in the local geodetic datum [15]. The above methods are discussed separately in [1]. Only the Standard Molodensky Formula and MRE technique are discussed here.

### 7.3.2 The Standard Molodensky Datum Transformation Formulas

The Standard Molodensky Datum Transformation Formulas [4][16], along with definitions of the terms, are listed in Table 7.2. As the Molodensky Formulas do not provide satisfactory results near the poles, the following three-step transformation is recommended:

$$
\begin{tikzcd}
(\phi, \lambda, h)_{\text{Local}} \arrow[r] & (X, Y, Z)_{\text{Local}} \arrow[d, "(\Delta X, \Delta Y, \Delta Z)"] \\
(\phi, \lambda, h)_{\text{WGS 84}} & (X, Y, Z)_{\text{WGS 84}} \arrow[l]
\end{tikzcd}
$$

Appendix A lists the reference ellipsoid names and parameters (semimajor axis and flattening) for local datums currently tied to WGS 84 and used for generating datum transformations.

Appendix B contains transformation parameters for the geodetic datums/systems which have been generated from satellite ties to the respective geodetic control. Due to the errors and distortion that affect most local geodetic datums, use of mean datum shifts ($\Delta X$, $\Delta Y$, $\Delta Z$) in the Standard Molodensky Datum Transformation Formulas may produce results with poor quality of "fit". Improved fit between the local datum and WGS 84 may result only with better and more dense ties with local or regional control points.

Datum transformation shifts derived from non-satellite information are available in Appendix C.

DMA-developed local geodetic datum geoid heights were used in forming the Local Geodetic Datum-to-WGS 84 Datum Shifts [17]. An example of such a geoid for NAD 27 is included in contour chart form (Figure 7.1) for the Contiguous United States (CONUS).

### 7.3.3 Datum Transformation Multiple Regression Equations

The development of Local Geodetic Datum-to-WGS 84 Datum Transformation Multiple Regression Equations [15] was initiated to obtain better fits over continental size land areas than could be achieved using the Standard Molodensky Formula with datum shifts ($\Delta X$, $\Delta Y$, $\Delta Z$).

For $\Delta\phi$, the general form of the Multiple Regression Equation is (also see [1]):

$$\Delta\phi = A_0 + A_1U + A_2V + A_3U^2 + A_4UV + A_5V^2 + \ldots + A_{99}U^9V^9 \qquad (7\text{-}4)$$

where

$A_0$ = constant

$A_1, A_2, \ldots$ = coefficients determined in the development

$U = k\ (\phi - \phi_m)$ = normalized geodetic latitude of the computation point

$V = k\ (\lambda - \lambda_m)$ = normalized geodetic longitude of the computation point

k = scale factor, and degree-to-radian conversion

$\phi, \lambda$ = local geodetic latitude and local geodetic longitude (in degrees), respectively, of the computation point

$\phi_m, \lambda_m$ = mid-latitude and mid-longitude values, respectively, of the local geodetic datum area (in degrees).

Similiar equations are obtained for $\Delta\lambda$ and $\Delta h$ by replacing $\Delta\phi$ in the left portion of Equation (7-4) by $\Delta\lambda$ and $\Delta h$, respectively.

Local Geodetic Datum-to-WGS 84 Datum Transformation Multiple Regression Equations for seven major continental size datums, covering contiguous continental size land areas with large distortion, are provided in Appendix D. The main advantage of MRE's lies in modeling of distortion for better fit in geodetic applications.

Table 7.1

Formulas and Parameters
to Transform WGS 72 Coordinates
to WGS 84 Coordinates

| | |
|---|---|
| Formulas | $\Delta\phi'' = (4.5 \cos \phi) / (a \sin 1'') + (\Delta f \sin 2\phi) / (\sin 1'')$<br>$\Delta\lambda'' = 0.554$<br>$\Delta h = 4.5 \sin \phi + a\ \Delta f \sin^2\phi - \Delta a + \Delta r$ (Units = Meters) |
| Parameters | $\Delta f = 0.3121057 \times 10^{-7}$<br>$a = 6378135$ m<br>$\Delta a = 2.0$ m<br>$\Delta r = 1.4$ m |
| Instructions | To Obtain WGS 84 Coordinates, Add the $\Delta\phi$, $\Delta\lambda$, $\Delta h$ Changes Calculated Using WGS 72 Coordinates to the WGS 72 Coordinates ($\phi$, $\lambda$, and h, Respectively).<br>Latitude is Positive North and Longitude is Positive East (0° to 180°). |

Table 7.2

Standard Molodensky Datum Transformation Formulas*
- Local Geodetic Datum to WGS 84 -

1. The Standard Molodensky Formulas

$$\Delta\phi'' = \{- \Delta X \sin\phi \cos\lambda - \Delta Y \sin\phi \sin\lambda + \Delta Z \cos\phi + \Delta a \, (R_N e^2 \sin\phi \cos\phi)/a + \Delta f \, [R_M (a/b) + R_N (b/a)] \sin\phi \cos\phi\} \cdot [(R_M + h) \sin 1'']^{-1}$$

$$\Delta\lambda'' = [- \Delta X \sin\lambda + \Delta Y \cos\lambda] \cdot [(R_N + h) \cos\phi \sin 1'']^{-1}$$

$$\Delta h = \Delta X \cos\phi \cos\lambda + \Delta Y \cos\phi \sin\lambda + \Delta Z \sin\phi - \Delta a \, (a/R_N) + \Delta f \, (b/a) \, R_N \sin^2\phi$$

2. Definition of Terms in the Molodensky Formulas

$\phi$, $\lambda$, h = geodetic coordinates (old ellipsoid)

$\phi$ = geodetic latitude. The angle between the plane of the geodetic equator and the ellipsoidal normal at a point (measured positive north from the geodetic equator, negative south).

$\lambda$ = geodetic longitude. The angle between the plane of the Zero Meridian and the plane of the geodetic meridian of the point (measured in the plane of the geodetic equator, positive from 0° to 180° E, and negative from 0° to 180° W).

h = geodetic height (ellipsoidal height). The distance of a point from the ellipsoid measured from the surface of the ellipsoid along the ellipsoidal normal to the point.

$h \simeq N + H$

N = ellipsoid to geoid separation. The distance of the geoid above (+N) or below (-N) the ellipsoid.

H = distance of a point from the geoid (or, approximately, elevation of the point above/below mean sea level); positive above mean sea level, negative below mean sea level.

* Not to be used between $89^0$ Latitude and the pole (see Section 7.3.2).

Table 7.2 (Cont'd)

Standard Molodensky Datum Transformation Formulas
- Local Geodetic Datum to WGS 84 -

$\Delta\phi$, $\Delta\lambda$, $\Delta h$ = corrections to transform local geodetic datum coordinates to WGS 84 $\phi$, $\lambda$, h values. The units of $\Delta\phi$ and $\Delta\lambda$ are arc seconds ("); the units of $\Delta h$ are meters (m).

| |
|---|
| **NOTE: AS "h's" ARE NOT AVAILABLE FOR LOCAL GEODETIC DATUMS, THE $\Delta h$ CORRECTION WILL NOT BE APPLICABLE WHEN TRANSFORMING <u>TO</u> WGS84.** |

$\Delta X$, $\Delta Y$, $\Delta Z$ = shifts between centers of the local geodetic datum and WGS 84 Ellipsoids; corrections to transform local geodetic system-related rectangular coordinates (X, Y, Z) to WGS 84-related X, Y, Z values.

a = semimajor axis of the local geodetic datum ellipsoid.

b = semiminor axis of the local geodetic datum ellipsoid.

$b/a = 1 - f$

f = flattening of the local geodetic datum ellipsoid.

$\Delta a$, $\Delta f$ = differences between the semimajor axis and flattening of the local geodetic datum ellipsoid and the WGS 84 Ellipsoid, respectively (WGS 84 minus Local).

e = first eccentricity.

$e^2 = 2f - f^2$

$R_N$ = radius of curvature in the prime vertical.

$R_N = a/(1-e^2\sin^2\phi)^{1/2}$

$R_M$ = radius of curvature in the meridian.

$R_M = a(1-e^2)/(1-e^2\sin^2\phi)^{3/2}$

<u>NOTE</u>: All $\Delta$-quantities are formed by subtracting local geodetic datum ellipsoid values <u>from</u> WGS 84 Ellipsoid values.

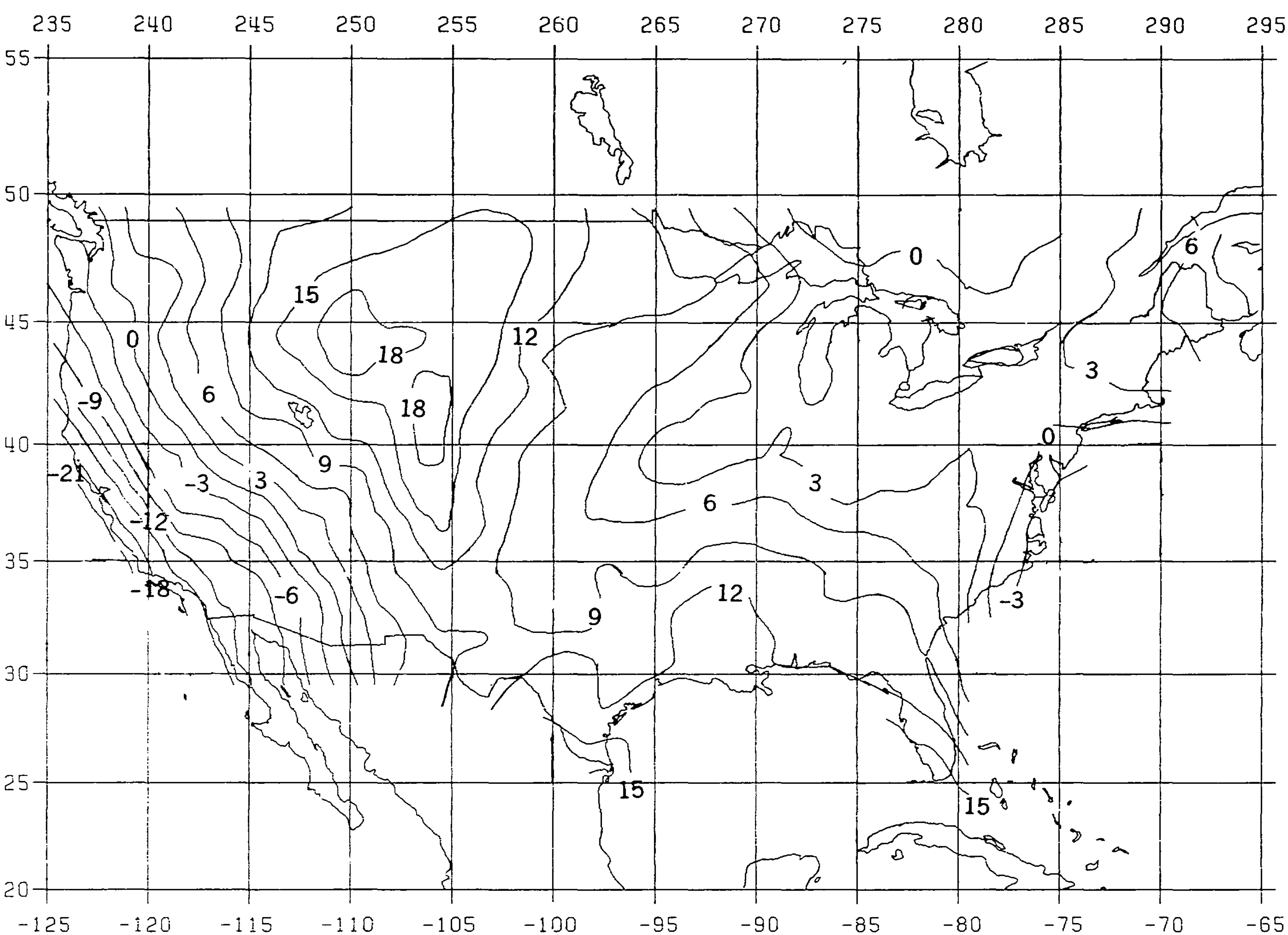

Figure 7.1. DMA- Developed NAD 27 Geoid (CONUS; Referenced to Clarke 1866 Ellipsoid; Units = Meters)

## 8. ACCURACY OF WGS 84 COORDINATES

The accuracy of the WGS 84 coordinates of a site is significantly influenced by the method used to determine the coordinates. Depending on the data available, the WGS 84 coordinates of a site can be determined:

- Directly in WGS 84 via a satellite point positioning solution using ground-based Doppler or GPS satellite tracking data and broadcast or precise satellite ephemerides.

- By a WGS 72-to-WGS 84 Coordinate Transformation.

- By a Local Geodetic Datum-to-WGS 84 Datum Transformation.

However, the situation is even more complicated since there are several techniques for accomplishing a Local Geodetic Datum-to-WGS 84 Datum Transformation. In addition, the accuracy of the WGS 84 coordinates of a site is different depending on whether it is a satellite station or a non-satellite geodetic network station, or whether the WGS 84 coordinates were determined by a receiver operated in a dynamic or static mode.

The accuracy (one sigma) of WGS 84 coordinates directly determined in WGS 84 by Doppler or GPS Satellite Point Positioning, their respective precise ephemerides and ground-based satellite tracking data acquired in the static mode, is in geodetic latitude, geodetic longitude, and geodetic height:

$$\sigma_\phi = \sigma_\lambda = \pm 1 \text{ m} \qquad (8\text{-}1)$$

$$\sigma_h = \pm 1 \text{ to } \pm 2 \text{ m.} \qquad (8\text{-}2)$$

The Doppler stations used in the development of WGS 84 were surveyed prior to 1 January 1987 in the NSWC 9Z-2 system. As such, the indirectly obtained WGS 84 coordinates (through corrections of biases given in Chapter 2) for these Doppler stations have been established at lower accuracies compared to Doppler stations directly surveyed in the WGS 84 reference frame. Thus, the absolute accuracy (one sigma) of these Doppler station WGS 84 coordinates was assumed to be:

$$\sigma_\phi = \sigma_\lambda = \pm 2 \text{ m} \tag{8-3}$$

$$\sigma_h = \pm 2 \text{ to } \pm 3 \text{ m.} \tag{8-4}$$

The WGS 84 coordinates for 1591 Doppler stations, surveyed up to 31 December 1986 and used as an integral part of the WGS 84 development, and additional stations, surveyed after 1 January 1987, have been used to develop Local Geodetic Datum-to-WGS 84 Datum Transformations (Chapter 7).

The WGS 84 coordinate accuracies in the two paragraphs immediately above are absolute accuracies in that they incorporate not only the "observational" or solution error, but the errors associated with placing the origin of the WGS 84 Coordinate System at the earth's center of mass and determining the correct scale for the WGS 84 Coordinate System. The error estimates do not include the uncertainty associated with the attempt to bring the WGS 84 zero meridian into coincidence with the BIH-defined Zero Meridian for the epoch 1984.0. This is not necessary since the location of the WGS 84 longitude reference or zero meridian is arbitrary. These absolute accuracy values should not be confused with the sub-meter precision:

- Of a Doppler or GPS coordinate solution (the "observational" error).

- Of a Doppler or GPS coordinate solution which has been repeated independently at the same site.

The WGS 84 coordinates of a non-satellite derived local geodetic network station will be less accurate than the WGS 84 coordinates of a Doppler or GPS station. This is due to the distortions and surveying errors present in local geodetic datum networks, the lack (in general) of a sufficient number of properly placed Doppler or GPS stations colocated with local geodetic datum stations for use in forming the Local Geodetic Datum-to-WGS 84 Datum Shifts, and the uncertainty introduced by the datum transformation.

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## 9. CONCLUSIONS/SUMMARY

World Geodetic System 1984 is based on the use of data, techniques, and technology available in early 1984. As a result, WGS 84 is more accurate than WGS 72 and replaces the latter as the geocentric system officially authorized for DoD use.

The origin and orientation of the WGS 84 Reference Frame are more accurately defined than they were for WGS 72. In addition, Doppler and GPS-derived Local Geodetic Datum-to-WGS 84 Datum Shifts are more accurate than analogous WGS 72 values, and are available for many more datums for WGS 84 as compared to WGS 72. Further, the WGS 84 EGM and geoid are considerably more accurate than their WGS 72 counterparts, and minor scale errors inherent in WGS 72 are reduced in WGS 84. These improvements translate into:

- More accurate maps and charts of scale 1:50,000 and larger.

- More accurate geodetic coordinates, geoid heights, heights above the geoid (approximately mean sea level), and distances.

- An improved capability for satellite orbit determination and prediction.

- The capability to place many more local geodetic datums on a world geodetic system, and do it more accurately.

The latter is particularly important for those local geodetic datums 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 or GPS sites, effectively removes these distortions.

The value of WGS 84 will become increasingly evident in the early 1990s when Navstar GPS will be fully operational. Since the reference system for Navstar GPS is WGS 84, high quality geocentric coordinates can be provided automatically by Navstar GPS User Equipment. For those using Navstar GPS but still utilizing local geodetic datums and products, the availability of the more accurate WGS 84-to-Local Geodetic Datum Shifts will lead to an improved recovery of local coordinates. Again, the value of having all MC&G products and navigational activities referenced to WGS 84 is noted. But if local geodetic datums are in use, requiring a WGS 84-to-Local Geodetic Datum Transformation, then the value of having improved datum shifts (made possible by a well dispersed set of Doppler or GPS sites throughout the region) is apparent.

Efforts have been initiated to enhance/refine WGS 84 to satisfy anticipated future requirements for MC&G products and data of increased accuracy.

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# APPENDIX A

## LIST OF REFERENCE ELLIPSOID NAMES AND PARAMETERS (USED FOR GENERATING DATUM TRANSFORMATIONS)

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## REFERENCE ELLIPSOIDS
## FOR
## LOCAL GEODETIC DATUMS

### 1. GENERAL

This appendix lists the reference ellipsoids and their constants (a,f) associated with the local geodetic datums which are tied to WGS 84 through datum transformation constants and/or MRE's (Appendices B, C, and D).

### 2. CONSTANT CHARACTERSTICS

In Appendix A.1, the list of ellipsoids includes a new feature. Some of the reference ellipsoids have more than one semi-major axis (a) associated with them. These different values of axis (a) vary from one region or country to another or from one year to another within the same region or country.

A typical example of such an ellipsoid is Everest whose semi-major axis (a) was originally defined in yards. Here, changes in the yard to meter conversion ratio over the years have resulted in five different values for the constant (a), as identified in Appendix A.1.

To facilitate correct referencing, a standardized two letter code is also included to identify the different ellipsoids and/or their "versions" pertaining to the different values of the semi-major axis (a).

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## Appendix A.1

### Reference Ellipsoid Names and Constants Used for Datum Transformations*

| Reference Ellipsoid Name | ID Code | a (Meters) | $f^{-1}$ |
|---|---|---|---|
| Airy 1830 | AA | 6377563.396 | 299.3249646 |
| Australian National | AN | 6378160 | 298.25 |
| Bessel 1841 | | | |
| Ethiopia, Indonesia, Japan, and Korea | BR | 6377397.155 | 299.1528128 |
| Namibia | BN | 6377483.865 | 299.1528128 |
| Clarke 1866 | CC | 6378206.4 | 294.9786982 |
| Clarke 1880** | CD | 6378249.145 | 293.465 |
| Everest | | | |
| Brunei and E. Malaysia (Sabah and Sarawak) | EB | 6377298.556 | 300.8017 |
| India 1830 | EA | 6377276.345 | 300.8017 |
| India 1956*** | EC | 6377301.243 | 300.8017 |
| W. Malaysia and Singapore 1948 | EE | 6377304.063 | 300.8017 |
| W. Malaysia 1969*** | ED | 6377295.664 | 300.8017 |
| Geodetic Reference System 1980 | RF | 6378137 | 298.257222101 |
| Helmert 1906 | HE | 6378200 | 298.3 |
| Hough 1960 | HO | 6378270 | 297 |
| International 1924 | IN | 6378388 | 297 |
| Krassovsky 1940 | KA | 6378245 | 298.3 |
| Modified Airy | AM | 6377340.189 | 299.3249646 |
| Modified Fischer 1960 | FA | 6378155 | 298.3 |
| South American 1969 | SA | 6378160 | 298.25 |
| WGS 1972 | WD | 6378135 | 298.26 |
| WGS 1984 | WE | 6378137 | 298.257223563 |

* Refer to Appendices B,C, and D.

** As accepted by DMA.

*** Through adoption of a new yard to meter conversion factor in the referenced country.

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# APPENDIX B

# DATUM TRANSFORMATIONS DERIVED USING SATELLITE TIES TO GEODETIC DATUMS/SYSTEMS

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## DATUM TRANSFORMATION CONSTANTS
## - GEODETIC DATUMS/SYSTEMS TO WGS 84 -
## (THROUGH SATELLITE TIES)

### 1. GENERAL

This appendix provides the details about the reference ellipsoids (Appendix A) which are used as defining parameters for the geodetic datums and systems.

There are 99 local geodetic datums which are currently related to WGS 84 through satellite ties.

### 2. LOCAL DATUM ELLIPSOIDS

Appendix B.1 lists, alphabetically, the local geodetic datums and the Soviet Geodetic system 1985 (SGS 85) with their associated ellipsoids. Two letter ellipsoidal codes (Appendix A) have also been included to clearly indicate which "version" of the ellipsoid was used in determining the transformation constants.

### 3. TRANSFORMATION CONSTANTS

Appendices B.2 through B.7 list the constants for local datums for continental areas. The continents and the local geodetic datums are arranged alphabetically.

Appendices B.8 through B.10 list the constants for local datums which fall within the ocean areas. The ocean areas and the geodetic datums are also arranged alphabetically.

### 4. ERROR ESTIMATES

The $1\sigma$ error estimates for the datum transformation constants ($\Delta X, \Delta Y, \Delta Z$), obtained from the computed solutions, are also tabulated. These estimates do not include the errors of the common control station coordinates which were used to compute the shift constants.

For datums having <u>four or less</u> common control stations, the $1\sigma$ errors for shift constants are non-computed estimates.

The current set of error estimates have been revaluated and revised after careful consideration of the datum transformation solutions and the related geodetic information; the intent has been to assign estimates as realistic as possible.

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## Appendix B.1

### Geodetic Datums/Reference Systems Related to World Geodetic System 1984 (Through Satellite Ties)

| Local Geodetic Datum | Associated* Reference Ellipsoid | Code |
|---|---|---|
| Adindan | Clarke 1880 | CD |
| Afgooye | Krassovsky 1940 | KA |
| Ain el Abd 1970 | International 1924 | IN |
| Anna 1 Astro 1965 | Australian National | AN |
| Antigua Island Astro 1943 | Clarke 1880 | CD |
| Arc 1950 | Clarke 1880 | CD |
| Arc 1960 | Clarke 1880 | CD |
| Ascension Island 1958 | International 1924 | IN |
| Astro Beacon "E" 1945 | International 1924 | IN |
| Astro DOS 71/4 | International 1924 | IN |
| Astro Tern Island (FRIG) 1961 | International 1924 | IN |
| Astronomical Station 1952 | International 1924 | IN |
| Australian Geodetic 1966 | Australian National | AN |
| Australian Geodetic 1984 | Australian National | AN |
| Ayabelle Lighthouse | Clarke 1880 | CD |
| Bellevue (IGN) | International 1924 | IN |
| Bermuda 1957 | Clarke 1866 | CC |
| Bissau | International 1924 | IN |
| Bogota Observatory | International 1924 | IN |
| Campo Inchauspe | International 1924 | IN |
| Canton Astro 1966 | International 1924 | IN |
| Cape | Clarke 1880 | CD |
| Cape Canaveral | Clarke 1866 | CC |
| Carthage | Clarke 1880 | CD |
| Chatham Island Astro 1971 | International 1924 | IN |
| Chua Astro | International 1924 | IN |
| Corrego Alegre | International 1924 | IN |
| Dabola | Clarke 1880 | CD |
| Djakarta (Batavia) | Bessel 1841 | BR |
| DOS 1968 | International 1924 | IN |

* See Appendix A.1 for associated constants a,f.

Appendix B.1 (Cont'd)

Geodetic Datums/Reference Systems
Related to World Geodetic System 1984
(Through Satellite Ties)

| Local Geodetic Datum | Associated* Reference Ellipsoid | Code |
|---|---|---|
| Easter Island 1967 | International 1924 | IN |
| European 1950 | International 1924 | IN |
| European 1979 | International 1924 | IN |
| Fort Thomas 1955 | Clarke 1880 | CD |
| Gan 1970 | International 1924 | IN |
| Geodetic Datum 1949 | International 1924 | IN |
| Graciosa Base SW 1948 | International 1924 | IN |
| Guam 1963 | Clarke 1866 | CC |
| GUX 1 Astro | International 1924 | IN |
| Hjorsey 1955 | International 1924 | IN |
| Hong Kong 1963 | International 1924 | IN |
| Hu-Tzu-Shan | International 1924 | IN |
| Indian | Everest | EA/EC** |
| Indian 1954 | Everest | EA |
| Indian 1975 | Everest | EA |
| Ireland 1965 | Modified Airy | AM |
| ISTS 061 Astro 1968 | International 1924 | IN |
| ISTS 073 Astro 1969 | International 1924 | IN |
| Johnston Island 1961 | International 1924 | IN |
| Kandawala | Everest | EA |
| Kerguelen Island 1949 | International 1924 | IN |
| Kertau 1948 | Everest | EE |
| Kusaie Astro 1951 | International 1924 | IN |
| L. C. 5 Astro 1961 | Clarke 1866 | CC |
| Leigon | Clarke 1880 | CD |
| Liberia 1964 | Clarke 1880 | CD |
| Luzon | Clarke 1866 | CC |
| Mahe 1971 | Clarke 1880 | CD |
| Massawa | Bessel 1841 | BR |
| Merchich | Clarke 1880 | CD |

* See Appendix A.1 for associated constants a,f.

** Due to different semi-major axes. See Appendix A.1.

Appendix B.1 (Cont'd)

Geodetic Datums/Reference Systems
Related to World Geodetic System 1984
(Through Satellite Ties)

| Local Geodetic Datum | Associated* Reference Ellipsoid | Code |
|---|---|---|
| Midway Astro 1961 | International 1924 | IN |
| Minna | Clarke 1880 | CD |
| Montserrat Island Astro 1958 | Clarke 1880 | CD |
| M'Poraloko | Clarke 1880 | CD |
| Nahrwan | Clarke 1880 | CD |
| Naparima, BWI | International 1924 | IN |
| North American 1927 | Clarke 1866 | CC |
| North American 1983 | GRS 80*** | RF |
| Observatorio Meteorologico 1939 | International 1924 | IN |
| Old Egyptian 1907 | Helmert 1906 | HE |
| Old Hawaiian | Clarke 1866 | CC |
| Oman | Clarke 1880 | CD |
| Ordnance Survey of Great Britain 1936 | Airy 1830 | AA |
| Pico de las Nieves | International 1924 | IN |
| Pitcairn Astro 1967 | International 1924 | IN |
| Point 58 | Clarke 1880 | CD |
| Pointe Noire 1948 | Clarke 1880 | CD |
| Porto Santo 1936 | International 1924 | IN |
| Provisional South American 1956 | International 1924 | IN |
| Provisional South Chilean 1963**** | International 1924 | IN |
| Puerto Rico | Clarke 1866 | CC |
| Qatar National | International 1924 | IN |
| Qornoq | International 1924 | IN |
| Reunion | International 1924 | IN |
| Rome 1940 | International 1924 | IN |
| Santo (DOS) 1965 | International 1924 | IN |
| Sao Braz | International 1924 | IN |
| Sapper Hill 1943 | International 1924 | IN |
| Schwarzeck | Bessel 1841 | BN |
| Selvagem Grande 1938 | International 1924 | IN |

* See Appendix A.1 for associated constants a,f.

*** Geodetic Reference System 1980

****Also known as Hito XVIII 1963

Appendix B.1 (Cont'd)

Geodetic Datums/Reference Systems
Related to World Geodetic System 1984
(Through Satellite Ties)

| Local Geodetic Datum | Associated* Reference Ellipsoid | Code |
|---|---|---|
| South American 1969 | South American 1969 | SA |
| South Asia | Modified Fischer 1960 | FA |
| Timbalai 1948 | Everest | EB |
| Tokyo | Bessel 1841 | BR |
| Tristan Astro 1968 | International 1924 | IN |
| Viti Levu 1916 | Clarke 1880 | CD |
| Wake-Eniwetok 1960 | Hough 1960 | HO |
| Wake Island Astro 1952 | International 1924 | IN |
| Zanderij | International 1924 | IN |

* See Appendix A.1 for associated constants a,f.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ADINDAN** | ADI | Clarke 1880 | -112.145 | -0.54750714 | | | | |
| Mean Solution (Ethiopia and Sudan) | ADI-M | | | | 22 | -166 ±5 | -15 ±5 | 204 ±3 |
| Burkina Faso | ADI-E | | | | 1 | -118 ±25 | -14 ±25 | 218 ±25 |
| Cameroon | ADI-F | | | | 1 | -134 ±25 | -2 ±25 | 210 ±25 |
| Ethiopia | ADI-A | | | | 8 | -165 ±3 | -11 ±3 | 206 ±3 |
| Mali | ADI-C | | | | 1 | -123 ±25 | -20 ±25 | 220 ±25 |
| Senegal | ADI-D | | | | 2 | -128 ±25 | -18 ±25 | 224 ±25 |
| Sudan | ADI-B | | | | 14 | -161 ±3 | -14 ±5 | 205 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **AFGOOYE** Somalia | AFG | Krassovsky | -108 | 0.00480795 | 1 | -43 ±25 | -163 ±25 | 45 ±25 |
| **ARC 1950** Mean Solution (Botswana, Lesotho, Malawi, Swaziland, Zaire, Zambia and Zimbabwe) | ARF ARF-M | Clarke 1880 | -112.145 | -0.54750714 | 41 | -143 ±20 | -90 ±33 | -294 ±20 |
| Botswana | ARF-A | | | | 9 | -138 ±3 | -105 ±5 | -289 ±3 |
| Burundi | ARF-B | | | | 3 | -153 ±20 | -5 ±20 | -292 ±20 |
| Lesotho | ARF-B | | | | 5 | -125 ±3 | -108 ±3 | -295 ±8 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ARC 1950** (Cont'd) | ARF | Clarke 1880 | -112.145 | -0.54750714 | | | | |
| Malawi | ARF-C | | | | 6 | -161 ±9 | -73 ±24 | -317 ±8 |
| Swaziland | ARF-D | | | | 4 | -134 ±15 | -105 ±15 | -295 ±15 |
| Zaire | ARF-E | | | | 2 | -169 ±25 | -19 ±25 | -278 ±25 |
| Zambia | ARF-F | | | | 5 | -147 ±21 | -74 ±21 | -283 ±27 |
| Zimbabwe | ARF-G | | | | 10 | -142 ±5 | -96 ±8 | -293 ±11 |
| **ARC 1960** Mean Solution (Kenya and Tanzania) | ARS | Clarke 1880 | -112.145 | -0.54750714 | 25 | -160 ±20 | -6 ±20 | -302 ±20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **AYABELLE LIGHTHOUSE** Djibouti | PHA | Clarke 1880 | -112.145 | -0.54750714 | 1 | -79 ±25 | -129 ±25 | 145 ±25 |
| **BISSAU** Guinea-Bissau | BID | International 1924 | -251 | -0.14192702 | 2 | -173 ±25 | 253 ±25 | 27 ±25 |
| **CAPE** South Africa | CAP | Clarke 1880 | -112.145 | -0.54750714 | 5 | -136 ±3 | -108 ±6 | -292 ±6 |
| **CARTHAGE** Tunisia | CGE | Clarke 1880 | -112.145 | -0.54750714 | 5 | -263 ±6 | 6 ±9 | 431 ±8 |
| **DABOLA** Guinea | DAL | Clarke 1880 | -112.145 | -0.54750714 | 4 | -83 ±15 | 37 ±15 | 124 ±15 |
| **EUROPEAN 1950** Egypt | EUR EUR-F | International 1924 | -251 | -0.14192702 | 14 | -130 ±6 | -117 ±8 | -151 ±8 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **LEIGON** Ghana | LEH | Clarke 1880 | -112.145 | -0.54750714 | 8 | -130 ±2 | 29 ±3 | 364 ±2 |
| **LIBERIA 1964** Liberia | LIB | Clarke 1880 | -112.145 | -0.54750714 | 4 | -90 ±15 | 40 ±15 | 88 ±15 |
| **MASSAWA** Eritrea (Ethiopia) | MAS | Bessel 1841 | 739.845 | 0.10037483 | 1 | 639 ±25 | 405 ±25 | 60 ±25 |
| **MERCHICH** Morocco | MER | Clarke 1880 | -112.145 | -0.54750714 | 9 | 31 ±5 | 146 ±3 | 47 ±3 |
| **MINNA** | MIN | Clarke 1880 | -112.145 | -0.54750714 | | | | |
| Cameroon | MIN-A | | | | 2 | -81 ±25 | -84 ±25 | 115 ±25 |
| Nigeria | MIN-B | | | | 6 | -92 ±3 | -93 ±6 | 122 ±5 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.2
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AFRICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **M'PORALOKO** Gabon | MPO | Clarke 1880 | -112.145 | -0.54750714 | 1 | -74 $\pm$25 | -130 $\pm$25 | 42 $\pm$25 |
| **OLD EGYPTIAN 1907** Egypt | OEG | Helmert 1906 | -63 | 0.00480795 | 14 | -130 $\pm$3 | 110 $\pm$6 | -13 $\pm$8 |
| **POINT 58** Mean Solution (Burkina Faso and Niger) | PTB | Clarke 1880 | -112.145 | -0.54750714 | 2 | -106 $\pm$25 | -129 $\pm$25 | 165 $\pm$25 |
| **POINTE NOIRE 1948** Congo | PTN | Clarke 1880 | -112.145 | -0.54750714 | 1 | -148 $\pm$25 | 51 $\pm$25 | -291 $\pm$25 |
| **SCHWARZECK** Namibia | SCK | Bessel 1841 | 653.135# | 0.10037483 | 3 | 616 $\pm$20 | 97 $\pm$20 | -251 $\pm$20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# This $\Delta a$ value reflects an a-value of 63[illegible]483.865 meters for the Bessel 1841 Ellipsoid in Namibia.

Appendix B.3
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ASIA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **AIN EL ABD 1970** | AIN | International 1924 | -251 | -0.14192702 | | | | |
| Bahrain Island | AIN-A | | | | 2 | -150 ±25 | -250 ±25 | -1 ±25 |
| Saudi Arabia | AIN-B | | | | 9# | -143 ±10 | -236 ±10 | 7 ±10 |
| **DJAKARTA (BATAVIA)** | BAT | Bessel 1841 | 739.845 | 0.10037483 | | | | |
| Sumatra (Indonesia) | | | | | 5 | -377 ±3 | 681 ±3 | -50 ±3 |
| **EUROPEAN 1950** | EUR | International 1924 | -251 | -0.14192702 | | | | |
| Iran | EUR-H | | | | 27 | -117 ±9 | -132 ±12 | -164 ±11 |
| **HONG KONG 1963** | HKD | International 1924 | -251 | -0.14192702 | | | | |
| Hong Kong | | | | | 2 | -156 ±25 | -271 ±25 | -189 ±25 |
| **HU-TZU-SHAN** | HTN | International 1924 | -251 | -0.14192702 | | | | |
| Taiwan | | | | | 4 | -637 ±15 | -549 ±15 | -203 ±15 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# Using GPS stations.

Appendix B.3
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ASIA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | Δa (m) | Δf x $10^4$ | | ΔX (m) | ΔY (m) | ΔZ (m) |
| **INDIAN** | IND | Everest | | | | | | |
| Bangladesh | IND-B | (1830) | 860.655# | 0.28361368 | 6 | 282 ±10 | 726 ±8 | 254 ±12 |
| India and Nepal | IND-I | (1956) | 835.757# | 0.28361368 | 7 | 295 ±12 | 736 ±10 | 257 ±15 |
| **INDIAN 1954** Thailand and Vietnam | INF INF-A | Everest (1830) | 860.655# | 0.28361368 | 14 | 218 ±20 | 816 ±20 | 297 ±20 |
| **INDIAN 1975** Thailand | INH INH-A | Everest (1830) | 860.655# | 0.28361368 | 6 | 209 ±12 | 818 ±10 | 290 ±12 |
| **KANDAWALA** Sri Lanka | KAN | Everest (1830) | 860.655# | 0.28361368 | 3 | -97 ±20 | 787 ±20 | 86 ±20 |
| **KERTAU 1948** West Malaysia and Singapore | KEA | Everest (1948) | 832.937# | 0.28361368 | 6 | -11 ±10 | 851 ±8 | 5 ±6 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# See Appendix A.1

Appendix B.3
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ASIA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NAHRWAN** | NAH | Clarke 1880 | -112.145 | -0.54750714 | | | | |
| Masirah Island (Oman) | NAH-A | | | | 2 | -247 $\pm$25 | -148 $\pm$25 | 369 $\pm$25 |
| United Arab Emirates | NAH-B | | | | 2 | -249 $\pm$25 | -156 $\pm$25 | 381 $\pm$25 |
| Saudi Arabia | NAH-C | | | | 3 | -243 $\pm$20 | -192 $\pm$20 | 477 $\pm$20 |
| **OMAN** Oman | FAH | Clarke 1880 | -112.145 | -0.54750714 | 7 | -346 $\pm$3 | -1 $\pm$3 | 224 $\pm$9 |
| **QATAR NATIONAL** Qatar | QAT | International 1924 | -251 | -0.14192702 | 3 | -128 $\pm$20 | -283 $\pm$20 | 22 $\pm$20 |
| **SOUTH ASIA** Singapore | SOA | Modified Fischer 1960 | -18 | 0.00480795 | 1 | 7 $\pm$25 | -10 $\pm$25 | -26 $\pm$25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.3
Post WGS84 Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ASIA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **TIMBALAI 1948** Brunei and East Malaysia (Sarawak and Sabah) | TIL | Everest | 838.444# | 0.28361368 | 8 | -679 $\pm$10 | 669 $\pm$10 | -48 $\pm$12 |
| **TOKYO** Mean Solution (Japan, Korea, and Okinawa) | TOY TOY-M | Bessel 1841 | 739.845 | 0.10037483 | 31 | -148 $\pm$20 | 507 $\pm$5 | 685 $\pm$20 |
| Japan | TOY-A | | | | 16 | -148 $\pm$8 | 507 $\pm$5 | 585 $\pm$8 |
| Korea | TOY-B | | | | 12 | -146 $\pm$8 | 507 $\pm$5 | 687 $\pm$8 |
| Okinawa | TOY-C | | | | 3 | -158 $\pm$20 | 507 $\pm$5 | 676 $\pm$20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# See Appendix A.1

Appendix B.4
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **AUSTRALIA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **AUSTRALIAN GEODETIC 1966** | AUA | Australian National | -23 | -0.00081204 | | | | |
| Australia and Tasmania | | | | | 105 | $-133 \pm 3$ | $-48 \pm 3$ | $148 \pm 3$ |
| **AUSTRALIAN GEODETIC 1984** | AUG | Australian National | -23 | -0.00081204 | | | | |
| Australia and Tasmania | | | | | 90 | $-134 \pm 2$ | $-48 \pm 2$ | $149 \pm 2$ |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

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Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **EUROPEAN 1950** Mean Solution [Austria, Belgium, Denmark, Finland, France, FRG (Federal Republic of Germany)#, Gibraltar, Greece, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, and Switzerland] | EUR EUR-M | International 1924 | -251 | -0.14192702 | 85 | -87 ±3 | -98 ±8 | -121 ±5 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# Prior to October, 1990.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **EUROPEAN 1950** (Cont'd) | EUR | International 1924 | -251 | -0.14192702 | | | | |
| Western Europe [Limited to Austria, Denmark, France, FRG (Federal Republic of Germany) #, Netherlands, and Switzerland] | EUR-A | | | | 52 | -87 ±3 | -96 ±3 | -120 ±3 |
| Cyprus | EUR-E | | | | 4 | -104 ±15 | -101 ±15 | -140 ±15 |
| Egypt | EUR-F | | | | 14 | -130 ±6 | -117 ±8 | -151 ±8 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# Prior to October, 1990.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **EUROPEAN 1950** (Cont'd) | EUR | International 1924 | -251 | -0.14192702 | | | | |
| England, Channel Islands, Scotland, and Shetland Islands## | EUR-G | | | | 40 | -86 ±3 | -96 ±3 | -120 ±3 |
| England, Ireland, Scotland, and Shetland Islands## | EUR-K | | | | 47 | -86 ±3 | -96 ±3 | -120 ±3 |
| Greece | EUR-B | | | | 2 | -84 ±25 | -95 ±25 | -130 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\## European Datum 1950 coordinates developed from Ordnance Survey of Great Britain (OSGB) Scientific Network 1980 (SN 80) coordinates.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | Δa (m) | Δf x 10⁴ | | ΔX (m) | ΔY (m) | ΔZ (m) |
| **EUROPEAN 1950** (Cont'd) | EUR | International 1924 | -251 | -0.14192702 | | | | |
| Iran | EUR-H | | | | 27 | -117 ±9 | -132 ±12 | -164 ±11 |
| Italy | | | | | | | | |
| Sardinia | EUR-I | | | | 2 | -97 ±25 | -103 ±25 | -120 ±25 |
| Sicily | EUR-J | | | | 3 | -97 ±20 | -88 ±20 | -135 ±20 |
| Malta | EUR-L | | | | 1 | -107 ±25 | -88 ±25 | -149 ±25 |
| Norway and Finland | EUR-C | | | | 20 | -87 ±3 | -95 ±5 | -120 ±3 |
| Portugal and Spain | EUR-D | | | | 18 | -84 ±5 | -107 ±6 | -120 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **EUROPEAN 1979** Mean Solution (Austria, Finland, Netherlands, Norway, Spain, Sweden, and Switzerland) | EUS | International 1924 | -251 | -0.14192702 | 22 | -86 ±3 | -98 ±3 | -119 ±3 |
| **HJORSEY 1955** Iceland | HJO | International 1924 | -251 | -0.14192702 | 6 | -73 ±3 | 46 ±3 | -86 ±6 |
| **IRELAND 1965** Ireland | IRL | Modified Airy | 796.811 | 0.11960023 | 7 | 506 ±3 | -122 ±3 | 611 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ORDNANCE SURVEY OF GREAT BRITAIN 1936** | OGB | Airy | 573.604 | 0.11960023 | | | | |
| Mean Solution (England, Isle of Man, Scotland, Shetland Islands, and Wales) | OGB-M | | | | 38 | 375 $\pm$10 | -111 $\pm$10 | 431 $\pm$15 |
| England | OGB-A | | | | 21 | 371 $\pm$5 | -112 $\pm$5 | 434 $\pm$6 |
| England, Isle of Man, and Wales | OGB-B | | | | 25 | 371 $\pm$10 | -111 $\pm$10 | 434 $\pm$15 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.5
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **EUROPE**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ORDNANCE SURVEY OF GREAT BRITAIN 1936** (Cont'd) | OGB | Airy | 573.604 | 0.11960023 | | | | |
| Scotland and Shetland Islands | OGB-C | | | | 13 | 384 $\pm$10 | -111 $\pm$10 | 425 $\pm$10 |
| Wales | OGB-D | | | | 3 | 370 $\pm$20 | -108 $\pm$20 | 434 $\pm$20 |
| **ROME 1940** Sardinia | MOD | International 1924 | -251 | -0.14192702 | 1 | -225 $\pm$25 | -65 $\pm$25 | 9 $\pm$25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

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Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **CAPE CANAVERAL** Mean Solution (Florida and Bahamas) | CAC | Clarke 1866 | -69.4 | -0.37264639 | 19 | -2 ±3 | 151 ±3 | 181 ±3 |
| **NORTH AMERICAN 1927** | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Mean Solution (CONUS) | NAS-C | | | | 405 | -8 ±5 | 160 ±5 | 176 ±6 |
| Western United States (Arizona, Arkansas, California, Colorado, Idaho, Iowa, Kansas, Montana, Nebraska, | NAS-B | | | | 276 | -8 ±5 | 159 ±3 | 175 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming) | NAS-B | | | | | | | |
| Eastern United States (Alabama, Connecticut, Delaware, District of Columbia, | NAS-A | | | | 129 | -9 ±5 | 161 ±5 | 179 ±8 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, New Hampshire, | NAS-A | | | | | | | |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, West Virginia, and Wisconsin) | NAS-A | | | | | | | |
| Alaska | NAS-D | | | | 47 | -5 ±5 | 135 ±9 | 172 ±5 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Bahamas (Excluding San Salvador Island) | NAS-Q | | | | 11 | -4 ±5 | 154 ±3 | 178 ±5 |
| San Salvador Island | NAS-R | | | | 1 | 1 ±25 | 140 ±25 | 165 ±25 |
| Canada Mean Solution (Including Newfoundland) | NAS-E | | | | 112 | -10 ±15 | 158 ±11 | 187 ±6 |
| Alberta and British Columbia | NAS-F | | | | 25 | -7 ±8 | 162 ±8 | 188 ±6 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Eastern Canada (Newfoundland, New Brunswick, Nova Scotia, and Quebec) | NAS-G | | | | 37 | -22 ±6 | 160 ±6 | 190 ±3 |
| Manitoba and Ontario | NAS-H | | | | 25 | -9 ±9 | 157 ±5 | 184 ±5 |
| Northwest Territories and Saskatchewan | NAS-I | | | | 17 | 4 ±5 | 159 ±5 | 188 ±3 |
| Yukon | NAS-J | | | | 8 | -7 ±5 | 139 ±8 | 181 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Canal Zone | NAS-O | | | | 3 | 0 ±20 | 125 ±20 | 201 ±20 |
| Caribbean (Antigua Island, Barbados, Barbuda, Caicos Islands, Cuba, Dominican Republic, Grand Cayman, Jamaica, and Turks Islands) | NAS-P | | | | 15 | -3 ±3 | 142 ±9 | 183 ±12 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN 1927** (Cont'd) | NAS | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua) | NAS-N | | | | 19 | 0 $\pm$8 | 125 $\pm$3 | 194 $\pm$5 |
| Cuba | NAS-T | | | | 1 | -9 $\pm$25 | 152 $\pm$25 | 178 $\pm$25 |
| Greenland (Hayes Peninsula) | NAS-U | | | | 2 | 11 $\pm$25 | 114 $\pm$25 | 195 $\pm$25 |
| Mexico | NAS-L | | | | 22 | -12 $\pm$8 | 130 $\pm$6 | 190 $\pm$6 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.6
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **NORTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **NORTH AMERICAN** 1983 | NAR | GRS 80 | 0 | -0.00000016 | | | | |
| Alaska | NAR-A | | | | 42 | $0 \pm 2$ | $0 \pm 2$ | $0 \pm 2$ |
| Canada | NAR-B | | | | 96 | $0 \pm 2$ | $0 \pm 2$ | $0 \pm 2$ |
| CONUS | NAR-C | | | | 216 | $0 \pm 2$ | $0 \pm 2$ | $0 \pm 2$ |
| Mexico and Central America | NAR-D | | | | 25 | $0 \pm 2$ | $0 \pm 2$ | $0 \pm 2$ |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

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Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **BOGOTA OBSERVATORY** Colombia | BOO | International 1924 | -251 | -0.14192702 | 7 | 307 ±6 | 304 ±5 | -318 ±6 |
| **CAMPO INCHAUSPE** Argentina | CAI | International 1924 | -251 | -0.14192702 | 20 | -148 ±5 | 136 ±5 | 90 ±5 |
| **CHUA ASTRO** Paraguay | CHU | International 1924 | -251 | -0.14192702 | 6 | -134 ±6 | 229 ±9 | -29 ±5 |
| **CORREGO ALEGRE** Brazil | COA | International 1924 | -251 | -0.14192702 | 17 | -206 ±5 | 172 ±3 | -6 ±5 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **PROVISIONAL SOUTH AMERICAN 1956** | PRP | International 1924 | -251 | -0.14192702 | | | | |
| Mean Solution (Bolivia, Chile, Colombia, Ecuador, Guyana, Peru, and Venezuela) | PRP-M | | | | 63 | -288 ±17 | 175 ±27 | -376 ±27 |
| Bolivia | PRP-A | | | | 5 | -270 ±5 | 188 ±11 | -388 ±14 |
| Chile | | | | | | | | |
| Northern Chile (near 19°S) | PRP-B | | | | 1 | -270 ±25 | 183 ±25 | -390 ±25 |
| Southern Chile (near 43°S) | PRP-C | | | | 3 | -305 ±20 | 243 ±20 | -442 ±20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **PROVISIONAL SOUTH AMERICAN 1956** (Cont'd) | PRP | International 1924 | -251 | -0.14192702 | | | | |
| Colombia | PRP-D | | | | 4 | -282 ±15 | 169 ±15 | -371 ±15 |
| Ecuador | PRP-E | | | | 11 | -278 ±3 | 171 ±5 | -367 ±3 |
| Guyana | PRP-F | | | | 9 | -298 ±6 | 159 ±14 | -369 ±5 |
| Peru | PRP-G | | | | 6 | -279 ±6 | 175 ±8 | -379 ±12 |
| Venezuela | PRP-H | | | | 24 | -295 ±9 | 173 ±14 | -371 ±15 |
| **PROVISIONAL SOUTH CHILEAN 1963#** | HIT | International 1924 | -251 | -0.14192702 | | | | |
| Southern Chile (near 53°S) | | | | | 2 | 16 ±25 | 196 ±25 | 93 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

\# Also known as Hito XVIII 1963.

Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | Δa (m) | Δf x $10^4$ | | ΔX (m) | ΔY (m) | ΔZ (m) |
| **SOUTH AMERICAN 1969** | SAN | South American 1969 | -23 | -0.00081204 | | | | |
| Mean Solution (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Trinidad and Tobago, and Venezuela) | SAN-M | | | | 84 | -57 ±15 | 1 ±6 | -41 ±9 |
| Argentina | SAN-A | | | | 10 | -62 ±5 | -1 ±5 | -37 ±5 |
| Bolivia | SAN-B | | | | 4 | -61 ±15 | 2 ±15 | -48 ±15 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **SOUTH AMERICAN 1969** (Cont'd) | SAN | South American 1969 | -23 | -0.00081204 | | | | |
| Brazil | SAN-C | | | | 22 | -60 ±3 | -2 ±5 | -41 ±5 |
| Chile | SAN-D | | | | 9 | -75 ±15 | -1 ±8 | -44 ±11 |
| Colombia | SAN-E | | | | 7 | -44 ±6 | 6 ±6 | -36 ±5 |
| Ecuador (Excluding Galapagos Islands) | SAN-F | | | | 11 | -48 ±3 | 3 ±3 | -44 ±3 |
| Baltra, Galapagos Islands | SAN-J | | | | 1 | -47 ±25 | 26 ±25 | -42 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.7
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **SOUTH AMERICA**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | Δa (m) | Δf x $10^4$ | | ΔX (m) | ΔY (m) | ΔZ (m) |
| **SOUTH AMERICAN 1969** (Cont'd) | SAN | South American 1969 | -23 | -0.00081204 | | | | |
| Guyana | SAN-G | | | | 5 | -53 ±9 | 3 ±5 | -47 ±5 |
| Paraguay | SAN-H | | | | 4 | -61 ±15 | 2 ±15 | -33 ±15 |
| Peru | SAN-I | | | | 6 | -58 ±5 | 0 ±5 | -44 ±5 |
| Trinidad and Tobago | SAN-K | | | | 1 | -45 ±25 | 12 ±25 | -33 ±25 |
| Venezuela | SAN-L | | | | 5 | -45 ±3 | 8 ±6 | -33 ±3 |
| **ZANDERIJ** Suriname | ZAN | International 1924 | -251 | -0.14192702 | 5 | -265 ±5 | 120 ±5 | -358 ±8 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ANTIGUA ISLAND ASTRO 1943** Antigua, Leeward Islands | AIA | Clarke 1880 | -112.145 | -0.54750714 | 1 | -270 $\pm$25 | 13 $\pm$25 | 62 $\pm$25 |
| **ASCENSION ISLAND 1958** Ascension Island | ASC | International 1924 | -251 | -0.14192702 | 2 | -205 $\pm$25 | 107 $\pm$25 | 53 $\pm$25 |
| **ASTRO DOS 71/4** St. Helena Island | SHB | International 1924 | -251 | -0.14192702 | 1 | -320 $\pm$25 | 550 $\pm$25 | -494 $\pm$25 |
| **BERMUDA 1957** Bermuda Islands | BER | Clarke 1866 | -69.4 | -0.37264639 | 3 | -73 $\pm$20 | 213 $\pm$20 | 296 $\pm$20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **CAPE CANAVERAL** Mean Solution (Bahamas and Florida) | CAC | Clarke 1866 | -69.4 | -0.37264[illegible] | 19 | -2 ±3 | [illegible] ±3 | 181 ±3 |
| **FORT THOMAS 1955** Nevis, St. Kitts, Leeward Islands | FOT | Clarke 1880 | -112.145 | -0.54750714 | 2 | -7 ±25 | 215 ±25 | 225 ±25 |
| **GRACIOSA BASE SW 1948** Faial, Graciosa, Pico, Sao Jorge, and Terceira Islands (Azores) | GRA | International 1924 | -251 | -0.14192702 | 5 | -104 ±3 | 167 ±3 | -38 ±3 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **HJORSEY 1955** Iceland | HJO | International 1924 | -251 | -0.14192702 | 6 | -73 $\pm$3 | 46 $\pm$3 | -86 $\pm$6 |
| **ISTS 061 ASTRO 1968** South Georgia Islands | ISG | International 1924 | -251 | -0.14192702 | 1 | -794 $\pm$25 | 119 $\pm$25 | -298 $\pm$25 |
| **L.C. 5 ASTRO 1961** Cayman Brac Island | LCF | Clarke 1866 | -69.4 | -0.37264639 | 1 | 42 $\pm$25 | 124 $\pm$25 | 147 $\pm$25 |
| **MONTSERRAT ISLAND ASTRO 1958** Montserrat, Leeward Islands | ASM | Clarke 1880 | -112.145 | -0.54750714 | 1 | 174 $\pm$25 | 359 $\pm$25 | 365 $\pm$25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | Δa (m) | $\Delta f \times 10^4$ | | ΔX (m) | ΔY (m) | ΔZ (m) |
| **NAPARIMA, BWI** Trinidad and Tobago | NAP | International 1924 | -251 | -0.14192702 | 4 | -10 ±15 | 375 ±15 | 165 ±15 |
| **OBSERVATORIO METEOROLOGICO 1939** Corvo and Flores Islands (Azores) | FLO | International 1924 | -251 | -0.14192702 | 3 | -425 ±20 | -169 ±20 | 81 ±20 |
| **PICO DE LAS NIEVES** Canary Islands | PLN | International 1924 | -251 | -0.14192702 | 1 | -307 ±25 | -92 ±25 | 127 ±25 |
| **PORTO SANTO 1936** Porto Santo and Madeira Islands | POS | International 1924 | -251 | -0.14192702 | 2 | -499 ±25 | -249 ±25 | 314 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **PUERTO RICO** Puerto Rico and Virgin Islands | PUR | Clarke 1866 | -69.4 | -0.37264639 | 11 | 11 $\pm 3$ | 72 $\pm 3$ | -101 $\pm 3$ |
| **QORNOQ** South Greenland | QUO | International 1924 | -251 | -0.14192702 | 2 | 164 $\pm 25$ | 138 $\pm 25$ | -189 $\pm 32$ |
| **SAO BRAZ** Sao Miguel, Santa Maria Islands (Azores) | SAO | International 1924 | -251 | -0.14192702 | 2 | -203 $\pm 25$ | 141 $\pm 25$ | 53 $\pm 25$ |
| **SAPPER HILL 1943** East Falkland Island | SAP | International 1924 | -251 | -0.14192702 | 5 | -355 $\pm 1$ | 21 $\pm 1$ | 72 $\pm 1$ |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.8
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **ATLANTIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **SELVAGEM GRANDE 1938** Salvage Islands | SGM | International 1924 | -251 | -0.14192702 | 1 | -289 ±25 | -124 ±25 | 60 ±25 |
| **TRISTAN ASTRO 1968** Tristan da Cunha | TDC | International 1924 | -251 | -0.14192702 | 1 | -632 ±25 | 438 ±25 | -609 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.9
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **INDIAN OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ANNA 1 ASTRO 1965** Cocos Islands | ANO | Australian National | -23 | -0.00081204 | 1 | -491 $\pm$25 | -22 $\pm$25 | 435 $\pm$25 |
| **GAN 1970** Republic of Maldives | GAA | International 1924 | -251 | -0.14192702 | 1 | -133 $\pm$25 | -321 $\pm$25 | 50 $\pm$25 |
| **ISTS 073 ASTRO 1969** Diego Garcia | IST | International 1924 | -251 | -0.14192702 | 2 | 208 $\pm$25 | -435 $\pm$25 | -229 $\pm$25 |
| **KERGUELEN ISLAND 1949** Kerguelen Island | KEG | International 1924 | -251 | -0.14192702 | 1 | 145 $\pm$25 | -187 $\pm$25 | 103 $\pm$25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.9
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **INDIAN OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **MAHE 1971** Mahe Island | MIK | Clarke 1880 | -112.145 | -0.54750714 | 1 | 41 $\pm$25 | -220 $\pm$25 | -134 $\pm$25 |
| **REUNION** Mascarene Islands | REU | International 1924 | -251 | -0.14192702 | 1 | 94 $\pm$25 | -948 $\pm$25 | -1262 $\pm$25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **ASTRO BEACON "E" 1945** Iwo Jima | ATF | International 1924 | -251 | -0.14192702 | 1 | 145 $\pm$25 | 75 $\pm$25 | -272 $\pm$25 |
| **ASTRO TERN ISLAND (FRIG) 1961** Tern Island | TRN | International 1924 | -251 | -0.14192702 | 1 | 114 $\pm$25 | -116 $\pm$25 | -333 $\pm$25 |
| **ASTRONOMICAL STATION 1952** Marcus Island | ASQ | International 1924 | -251 | -0.14192702 | 1 | 124 $\pm$25 | -234 $\pm$25 | -25 $\pm$25 |
| **BELLEVUE (IGN)** Efate and Erromango Islands | IBE | International 1924 | -251 | -0.14192702 | 3 | -127 $\pm$20 | -769 $\pm$20 | 472 $\pm$20 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **CANTON ASTRO 1966** Phoenix Islands | CAO | International 1924 | -251 | -0.14192702 | 4 | 298 ±15 | -304 ±15 | -375 ±15 |
| **CHATHAM ISLAND ASTRO 1971** Chatham Island (New Zealand) | CHI | International 1924 | -251 | -0.14192702 | 4 | 175 ±15 | -38 ±15 | 113 ±15 |
| **DOS 1968** Gizo Island (New Georgia Islands) | GIZ | International 1924 | -251 | -0.14192702 | 1 | 230 ±25 | -199 ±25 | -752 ±25 |
| **EASTER ISLAND 1967** Easter Island | EAS | International 1924 | -251 | -0.14192702 | 1 | 211 ±25 | 147 ±25 | 111 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **GEODETIC DATUM 1949** New Zealand | GEO | International 1924 | -251 | -0.14192702 | 14 | 84 $\pm 5$ | -22 $\pm 3$ | 209 $\pm 5$ |
| **GUAM 1963** Guam | GUA | Clarke 1866 | -69.4 | -0.37264639 | 5 | -100 $\pm 3$ | -248 $\pm 3$ | 259 $\pm 3$ |
| **GUX 1 ASTRO** Guadalcanal Island | DOB | International 1924 | -251 | -0.14192702 | 1 | 252 $\pm 25$ | -209 $\pm 25$ | -751 $\pm 25$ |
| **JOHNSTON ISLAND 1961** Johnston Island | JOH | International 1924 | -251 | -0.14192702 | 2 | 189 $\pm 25$ | -79 $\pm 25$ | -202 $\pm 25$ |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **KUSAIE ASTRO 1951** Caroline Islands, Fed. States of Micronesia | KUS | International 1924 | -251 | -0.14192702 | 1 | 647 ±25 | 1777 ±25 | -1124 ±25 |
| **LUZON** | LUZ | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Philippines (Excluding Mindanao Island) | LUZ-A | | | | 6 | -133 ±8 | -77 ±11 | -51 ±9 |
| Mindanao Island | LUZ-B | | | | 1 | -133 ±25 | -79 ±25 | -72 ±25 |
| **MIDWAY ASTRO 1961** Midway Islands | MID | International 1924 | -251 | -0.14192702 | 1 | 912 ±25 | -58 ±25 | 1227 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **OLD HAWAIIAN** | OHA | Clarke 1866 | -69.4 | -0.37264639 | | | | |
| Mean Solution | OHA-M | | | | 15 | 61 ±25 | -285 ±20 | -181 ±20 |
| Hawaii | OHA-A | | | | 2 | 89 ±25 | -279 ±25 | -183 ±25 |
| Kauai | OHA-B | | | | 3 | 45 ±20 | -290 ±20 | -172 ±20 |
| Maui | OHA-C | | | | 2 | 65 ±25 | -290 ±25 | -190 ±25 |
| Oahu | OHA-D | | | | 8 | 58 ±10 | -283 ±6 | -182 ±6 |
| **PITCAIRN ASTRO 1967** | PIT | International 1924 | -251 | -0.14192702 | | | | |
| Pitcairn Island | | | | | 1 | 185 ±25 | 165 ±25 | 42 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix B.10
Transformation Parameters
- Local Geodetic Datums to WGS 84 -

Continent: **PACIFIC OCEAN**

| Local Geodetic Datums* | | Reference Ellipsoids and Parameter Differences** | | | No. of Doppler Stations Used | Transformation Parameters** | | |
|---|---|---|---|---|---|---|---|---|
| Name | Code*** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **SANTO (DOS) 1965** Espirito Santo Island | SAE | International 1924 | -251 | -0.14192702 | 1 | 170 ±25 | 42 ±25 | 84 ±25 |
| **VITI LEVU 1916** Viti Levu Island (Fiji Islands) | MVS | Clarke 1880 | -112.145 | -0.54750714 | 1 | 51 ±25 | 391 ±25 | -36 ±25 |
| **WAKE-ENIWETOK 1960** Marshall Islands | ENW | Hough | -133 | -0.14192702 | 10 | 102 ±3 | 52 ±3 | -38 ±3 |
| **WAKE ISLAND ASTRO 1952** Wake Atoll | WAK | International 1924 | -251 | -0.14192702 | 2 | 276 ±25 | -57 ±25 | 149 ±25 |

* Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic datums.

** WGS 84 minus local geodetic datum

*** Identifies datum codes to be used in software applications.

Appendix C.1

Local Geodetic Datums
Related to World Geodetic System 1984
(Through non-Satellite Ties)

| Local Geodetic Datum | Associated* Reference Ellipsoid | Code |
|---|---|---|
| Bukit Rimpah | Bessel 1841 | BR |
| Camp Area Astro | International 1924 | IN |
| European 1950 | International 1924 | IN |
| Gunung Segara | Bessel 1841 | BR |
| Herat North | International 1924 | IN |
| Tananarive Observatory 1925 | International 1924 | IN |
| Yacare | International 1924 | IN |

* See Appendix A.1 for associated constants a,f.

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# APPENDIX C

## DATUM TRANSFORMATIONS DERIVED USING NON-SATELLITE INFORMATION

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## DATUM TRANSFORMATION CONSTANTS
## - LOCAL GEODETIC DATUMS TO WGS 84 -
## (THROUGH NON-SATELLITE TIES)

### 1. GENERAL

This appendix provides the details about the reference ellipsoids (Appendix A) used as defining parameters for the local geodetic datums which are related to WGS 84 through non-satellite ties to the local control.

There are six such local geodetic datums, and one special area under the European Datum 1950 (ED 50).

### 2. LOCAL DATUM ELLIPSOIDS

Appendix C.1 lists alphabetically the local geodetic datums and their associated ellipsoids. Two letter ellipsoidal codes (Appendix A) have also been included to clearly indicate which "version" of the ellipsoid has been used to determine the transformation constants.

### 3. TRANSFORMATION CONSTANTS

Appendix C.2 alphabetically lists the local geodetic datums and the special area under ED 50 with the associated shift constants.

### 4. ERROR ESTIMATES

The error estimates are not available for the datum transformation constants listed in the Appendix C.2.

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Appendix C.2
Non-Satellite Derived Transformation Parameters
- Local Geodetic Datums to WGS 84 -

| Local Geodetic Datums | | Reference Ellipsoids and Parameter Differences* | | | Transformation Parameters* | | |
|---|---|---|---|---|---|---|---|
| Name | Code** | Name | $\Delta a$ (m) | $\Delta f \times 10^4$ | $\Delta X$ (m) | $\Delta Y$ (m) | $\Delta Z$ (m) |
| **BUKIT RIMPAH** Bangka and Belitung Islands (Indonesia) | BUR | Bessel 1841 | 739.845 | 0.10037483 | -384 | 664 | -48 |
| **CAMP AREA ASTRO** Camp McMurdo Area, Antarctica | CAZ | International 1924 | -251 | -0.14192702 | -104 | -129 | 239 |
| **EUROPEAN 1950** Iraq, Israel, Jordan, Kuwait, Lebanon, Saudi Arabia, and Syria | EUR-S | International 1924 | -251 | -0.14192702 | -103 | -106 | -141 |
| **GUNUNG SEGARA** Kalimantan (Indonesia) | GSE | Bessel 1841 | 739.845 | 0.10037483 | -403 | 684 | 41 |
| **HERAT NORTH** Afghanistan | HEN | International 1924 | -251 | -0.14192702 | -333 | -222 | 114 |
| **TANANARIVE OBSERVATORY 1925** Madagascar | TAN | International 1924 | -251 | -0.14192702 | -189 | -242 | -91 |
| **YACARE** Uruguay | YAC | International 1924 | -251 | -0.14192702 | -155 | 171 | 37 |

* WGS 84 minus local geodetic datum

** Identifies datum codes to be used in software applications.

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Appendix D

# MULTIPLE REGRESSION EQUATIONS

# FOR

# SPECIAL CONTINENTAL SIZE LOCAL GEODETIC DATUMS

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## MULTIPLE REGRESSION EQUATIONS

### 1. GENERAL

This appendix provides the Multiple Regression Equations (MRE's) parameters for continental size datums and for contiguous large land areas (Table D.1).

Table D.1

DATUMS WITH MULTIPLE REGRESSION EQUATIONS

| DATUM NAME | AREA COVERED |
|---|---|
| Australian Geodetic 1966 | Australian Mainland |
| Australian Geodetic 1984 | Australian Mainland |
| Campo Inchauspe | Argentina |
| Corrego Alegre | Brazil |
| European 1950 | Western Europe<br>Austria, Denmark, France, W. Germany*, The Netherlands, and Switzerland. |
| North American 1927 | CONUS<br>Canadian Mainland |
| South American 1969 | South American Mainland<br>Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Peru, Paraguay, Uruguay, and Venezuela. |

* Prior to October 1990.

### 2. APPLICATIONS

The coverage area for MRE's application are defined in detail in Appendices D.1 through D.6. MRE's coverage area should never be extrapolated and are not to be used over islands and/or isolated land areas.

The main advantage of MRE's lies in their modeling of distortions for datums, which cover continental size land areas, to obtain better transformation fit in geodetic applications.

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Multiple Regression Equations (MRE's)
for Transforming
Australian Geodetic Datum 1966 (AUA) to WGS 84

Area of Applicability : **Australian Mainland (excluding Tasmania)**

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = {} & 5.19238 + 0.12666\,U + 0.52309\,V - 0.42069\,U^2 \\ & - 0.39326\,UV + 0.93484\,U^2V + 0.44249\,UV^2 - 0.30074\,UV^3 \\ & + 1.00092\,U^5 - 0.07565\,V^6 - 1.42988\,U^9 - 16.06639\,U^4V^5 \\ & + 0.07428\,V^9 + 0.24256\,UV^9 + 38.27946\,U^6V^7 \\ & - 62.06403\,U^7V^8 + 89.19184\,U^9V^8\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = {} & 4.69250 - 0.87138\,U - 0.50104\,V + 0.12678\,UV \\ & - 0.23076\,V^2 - 0.61098\,U^2V - 0.38064\,V^3 + 2.89189\,U^6 \\ & + 5.26013\,U^2V^5 - 2.97897\,U^8 + 5.43221\,U^3V^5 \\ & - 3.40748\,U^2V^6 + 0.07772\,V^8 + 1.08514\,U^8V + 0.71516\,UV^8 \\ & + 0.20185\,V^9 + 5.18012\,U^2V^8 - 1.72907\,U^3V^8 \\ & - 1.24329\,U^2V^9\end{aligned}$$

where : $U = K\,(\phi + 27°)$; $V = K\,(\lambda - 134°)$; $K = 0.05235988$

NOTE : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

| AUA | Shift | WGS 84 |
|---|---|---|
| $\phi$= (-)17°00'32.78"S | $\Delta\phi$= 5.48" | $\phi$= (-)17°00'27.30"S |
| $\lambda$= 144°11'37.25"E | $\Delta\lambda$= 3.92" | $\lambda$= 144°11'41.17"E |

Multiple Regression Equations (MRE's)
for Transforming
Australian Geodetic Datum 1984 (AUG) to WGS 84

Area of Applicability : **Australian Mainland (excluding Tasmania)**

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = {} & 5.20604 + 0.25225\ U + 0.58528\ V - 0.41584\ U^2 \\ & - 0.38620\ UV - 0.06820\ V^2 + 0.38699\ U^2V + 0.07934\ UV^2 \\ & + 0.37714\ U^4 - 0.52913\ U^4V + 0.38095\ V^7 + 0.68776\ U^2V^6 \\ & - 0.03785\ V^8 - 0.17891\ U^9 - 4.84581\ U^2V^7 - 0.35777\ V^9 \\ & + 4.23859\ U^2V^9\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = {} & 4.67877 - 0.73036\ U - 0.57942\ V + 0.28840\ U^2 \\ & + 0.10194\ U^3 - 0.27814\ UV^2 - 0.13598\ V^3 + 0.34670\ UV^3 \\ & - 0.46107\ V^4 + 1.29432\ U^2V^3 + 0.17996\ UV^4 - 1.13008\ U^2V^5 \\ & - 0.46832\ U^8 + 0.30676\ V^8 + 0.31948\ U^9 + 0.16735\ V^9 \\ & - 1.19443\ U^3V^9\end{aligned}$$

Where : $U = K\ (\phi + 27°)$; $V = K\ (\lambda - 134°)$; $K = 0.05235988$

<u>NOTE</u> : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

<u>Test Case</u> :

| AUG | Shift | WGS 84 |
|---|---|---|
| $\phi$= (-)20°38'00.67"S | $\Delta\phi$= 5.50" | $\phi$= (-)20°37'55.17"S |
| $\lambda$= 144°24'29.29"E | $\Delta\lambda$= 4.11" | $\lambda$= 144°24'33.40"E |

Multiple Regression Equations (MRE's)
for Transforming
Campo Inchauspe Datum (CAI) to WGS 84

Area of Applicability : Argentina (Continental land areas only)

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = {} & 1.67470 + 0.52924\,U - 0.17100\,V + 0.18962\,U^2 \\ & + 0.04216\,UV + 0.19709\,UV^2 - 0.22037\,U^4 - 0.15483\,U^2V^2 \\ & - 0.24506\,UV^4 - 0.05675\,V^5 + 0.06674\,U^6 + 0.01701\,UV^5 \\ & - 0.00202\,U^7 + 0.08625\,V^7 - 0.00628\,U^8 + 0.00172\,U^8V^4 \\ & + 0.00036\,U^9V^6\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = {} & - 2.93117 + 0.18225\,U + 0.69396\,V - 0.04403\,U^2 \\ & + 0.07955\,V^2 + 1.48605\,V^3 - 0.00499\,U^4 - 0.02180\,U^4V \\ & - 0.29575\,U^2V^3 + 0.20377\,UV^4 - 2.47151\,V^5 + 0.09073\,U^3V^4 \\ & + 1.33556\,V^7 + 0.01575\,U^3V^5 - 0.26842\,V^9\end{aligned}$$

Where : $U = K\,(\phi + 35°)$; $V = K\,(\lambda + 64°)$; $K = 0.15707963$

<u>NOTE</u> : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

<u>Test Case</u> :

| CAI | Shift | WGS 84 |
|---|---|---|
| $\phi$= (-)29°47'45.68"S | $\Delta\phi$= 1.95" | $\phi$= (-)29°47'43.73"S |
| $\lambda$= (-)58°07'38.20"W | $\Delta\lambda$=-1.96" | $\lambda$= (-)58°07'40.16"W |

Multiple Regression Equations (MRE's)
for Transforming
Corrego Alegre Datum (COA) to WGS 84

**Area of Applicability : Brazil (Continental land areas only)**

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = & - 0.84315 + 0.74089\ U - 0.21968\ V - 0.98875\ U^2 \\ & + 0.89883\ UV + 0.42853\ U^3 + 2.73442\ U^4 - 0.34750\ U^3V \\ & + 4.69235\ U^2V^3 - 1.87277\ U^6 + 11.06672\ U^5V \\ & - 46.24841\ U^3V^3 - 0.92268\ U^7 - 14.26289\ U^7V \\ & + 334.33740\ U^5V^5 - 15.68277\ U^9V^2 - 2428.8586\ U^8V^8\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = & - 1.46053 + 0.63715\ U + 2.24996\ V - 5.66052\ UV \\ & + 2.22589\ V^2 - 0.34504\ U^3 - 8.54151\ U^2V + 0.87138\ U^4 \\ & + 43.40004\ U^3V + 4.35977\ UV^3 + 8.17101\ U^4V \\ & + 16.24298\ U^2V^3 + 19.96900\ UV^4 - 8.75655\ V^5 \\ & - 125.35753\ U^5V - 127.41019\ U^3V^4 - 0.61047\ U^8 \\ & + 138.76072\ U^7V + 122.04261\ U^5V^4 - 51.86666\ U^9V \\ & + 45.67574\ U^9V^3\end{aligned}$$

Where : $U = K\ (\ \phi + 15°)$; $V = K\ (\ \lambda + 50°)$; $K = 0.05235988$

<u>NOTE</u> : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

<u>Test Case</u> :

| COA | Shift | WGS 84 |
|---|---|---|
| $\phi$= (-)20°29'01.02"S | $\Delta\phi$= -1.03" | $\phi$= (-)20°29'02.05"S |
| $\lambda$= (-)54°47'13.17"W | $\Delta\lambda$= -2.10" | $\lambda$= (-)54°47'15.27"W |

Multiple Regression Equations (MRE's)
for Transforming
European Datum 1950 (EUR) to WGS 84

Area of Applicability : **Western Europe* (Continental contiguous land areas only)**

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = & - 2.65261 + 2.06392\ U + 0.77921\ V + 0.26743\ U^2 \\ & + 0.10706\ UV + 0.76407\ U^3 - 0.95430\ U^2V + 0.17197\ U^4 \\ & + 1.04974\ U^4V - 0.22899\ U^5V^2 - 0.05401\ V^8 - 0.78909\ U^9 \\ & - 0.10572\ U^2V^7 + 0.05283\ UV^9 + 0.02445\ U^3V^9\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = & - 4.13447 - 1.50572\ U + 1.94075\ V - 1.37600\ U^2 \\ & + 1.98425\ UV + 0.30068\ V^2 - 2.31939\ U^3 - 1.70401\ U^4 \\ & - 5.48711\ UV^3 + 7.41956\ U^5 - 1.61351\ U^2V^3 \\ & + 5.92923\ UV^4 - 1.97974\ V^5 + 1.57701\ U^6 - 6.52522\ U^3V^3 \\ & + 16.85976\ U^2V^4 - 1.79701\ UV^5 - 3.08344\ U^7 \\ & - 14.32516\ U^6V + 4.49096\ U^4V^4 + 9.98750\ U^8V \\ & + 7.80215\ U^7V^2 - 2.26917\ U^2V^7 + 0.16438\ V^9 \\ & - 17.45428\ U^4V^6 - 8.25844\ U^9V^2 + 5.28734\ U^8V^3 \\ & + 8.87141\ U^5V^7 - 3.48015\ U^9V^4 + 0.71041\ U^4V^9\end{aligned}$$

Where : $U = K\ (\ \phi - 52°)$; $V = K\ (\ \lambda - 10°)$; $K = 0.05235988$

<u>NOTE</u> : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

<u>Test Case</u> :

| EUR | Shift | WGS 84 |
|---|---|---|
| $\phi$= 46°41'42.89"N | $\Delta\phi$= -3.08" | $\phi$= 46°41'39.81"N |
| $\lambda$= 13°54'54.09"E | $\Delta\lambda$= -3.49" | $\lambda$= 13°54'50.60"E |

* See Table D.1 (Page D-3) for the list of countries covered by the above set of MRE's.

Multiple Regression Equations (MRE's)
for Transforming
North American Datum 1927 (NAS) to WGS 84

Area of Applicability : **Canada (Continental contiguous land areas only)**

MRE coefficients for $\phi$ and $\lambda$ are :

$$
\begin{aligned}
\Delta\phi'' = {} & 0.79395 + 2.29199\ U + 0.27589\ V - 1.76644\ U^2 \\
& + 0.47743\ UV + 0.08421\ V^2 - 6.03894\ U^3 - 3.55747\ U^2V \\
& - 1.81118\ UV^2 - 0.20307\ V^3 + 7.75815\ U^4 - 3.1017\ U^3V \\
& + 3.58363\ U^2V^2 - 1.31086\ UV^3 - 0.45916\ V^4 + 14.27239\ U^5 \\
& + 3.28815\ U^4V + 1.35742\ U^2V^3 + 1.75323\ UV^4 + 0.44999\ V^5 \\
& - 19.02041\ U^4V^2 - 1.01631\ U^2V^4 + 1.47331\ UV^5 \\
& + 0.15181\ V^6 + 0.41614\ U^2V^5 - 0.80920\ UV^6 - 0.18177\ V^7 \\
& + 5.19854\ U^4V^4 - 0.48837\ UV^7 - 0.01473\ V^8 - 2.26448\ U^9 \\
& - 0.46457\ U^2V^7 + 0.11259\ UV^8 + 0.02067\ V^9 \\
& + 47.64961\ U^8V^2 + 0.04828\ UV^9 + 36.38963\ U^9V^2 \\
& + 0.06991\ U^4V^7 + 0.08456\ U^3V^8 + 0.09113\ U^2V^9 \\
& + 5.93797\ U^7V^5 - 2.36261\ U^7V^6 + 0.09575\ U^5V^8
\end{aligned}
$$

$$
\begin{aligned}
\Delta\lambda'' = {} & - 1.36099 + 3.61796\ V - 3.97703\ U^2 + 3.09705\ UV \\
& - 1.15866\ V^2 - 13.28954\ U^3 - 3.15795\ U^2V + 0.68405\ UV^2 \\
& - 0.50303\ V^3 - 8.81200\ U^3V - 2.17587\ U^2V^2 - 1.49513\ UV^3 \\
& + 0.84700\ V^4 + 31.42448\ U^5 - 14.67474\ U^3V^2 \\
& + 0.65640\ UV^4 + 17.55842\ U^6 + 6.87058\ U^4V^2 - 0.21565\ V^6 \\
& + 62.18139\ U^5V^2 + 1.78687\ U^3V^4 + 2.74517\ U^2V^5 \\
& - 0.30085\ UV^6 + 0.04600\ V^7 + 63.52702\ U^6V^2 \\
& + 7.83682\ U^5V^3 + 9.59444\ U^3V^5 + 0.01480\ V^8 \qquad + \\
& + 10.51228\ U^4V^5 - 1.42398\ U^2V^7 - 0.00834\ V^9 \\
& + 5.23485\ U^7V^3 - 3.18129\ U^3V^7 + 8.45704\ U^9V^2 \\
& - 2.29333\ U^4V^7 + 0.14465\ U^2V^9 + 0.29701\ U^3V^9 \\
& + 0.17655\ U^4V^9
\end{aligned}
$$

Where : $U = K\ (\ \phi - 60°)$; $V = K\ (\ \lambda + 100°)$; $K = 0.05235988$

<u>NOTE</u> : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

<u>Test Case</u> :

| | NAS | Shift | WGS 84 |
|---|---|---|---|
| | $\phi$= 54°26'08.67"N | $\Delta\phi$= 0.29" | $\phi$= 54°26'08.96"N |
| | $\lambda$= (-)110°17'02.41"W | $\Delta\lambda$= -3.16" | $\lambda$= (-)110°17'05.57"W |

Multiple Regression Equations (MRE's)
for Transforming
North American Datum 1927 (NAS) to WGS 84

Area of Applicability : USA (Continental contiguous land areas only; excluding Alaska and Islands)

MRE coefficients for $\phi$ and $\lambda$ are :

$$\begin{aligned}\Delta\phi'' = {} & 0.16984 - 0.76173\, U + 0.09585\, V + 1.09919\, U^2 \\ & - 4.57801\, U^3 - 1.13239\, U^2V + 0.49831\, V^3 - 0.98399\, U^3V \\ & + 0.12415\, UV^3 + 0.11450\, V^4 + 27.05396\, U^5 + 2.03449\, U^4V \\ & + 0.73357\, U^2V^3 - 0.37548\, V^5 - 0.14197\, V^6 - 59.96555\, U^7 \\ & + 0.07439\, V^7 - 4.76082\, U^8 + 0.03385\, V^8 + 49.04320\, U^9 \\ & - 1.30575\, U^6V^3 - 0.07653\, U^3V^9 + 0.08646\, U^4V^9\end{aligned}$$

$$\begin{aligned}\Delta\lambda'' = {} & - 0.88437 + 2.05061\, V + 0.26361\, U^2 - 0.76804\, UV \\ & + 0.13374\, V^2 - 1.31974\, U^3 - 0.52162\, U^2V - 1.05853\, UV^2 \\ & - 0.49211\, U^2V^2 + 2.17204\, UV^3 - 0.06004\, V^4 + 0.30139\, U^4V \\ & + 1.88585\, UV^4 - 0.81162\, UV^5 - 0.05183\, V^6 - 0.96723\, UV^6 \\ & - 0.12948\, U^3V^5 + 3.41827\, U^9 - 0.44507\, U^8V + 0.18882\, UV^8 \\ & - 0.01444\, V^9 + 0.04794\, UV^9 - 0.59013\, U^9V^3\end{aligned}$$

Where: $U = K(\phi - 37°)$; $V = K(\lambda + 95°)$; $K = 0.05235988$

NOTE : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

| NAS | Shift | WGS 84 |
|---|---|---|
| $\phi$= 34°47'08.83"N | $\Delta\phi$= 0.36" | $\phi$= 34°47'09.19"N |
| $\lambda$= (-) 86°34'52.18"W | $\Delta\lambda$= 0.08" | $\lambda$= (-) 86°34'52.10"W |

Multiple Regression Equations (MRE's)
for Transforming
South American Datum 1969 (SAN) to WGS 84

Area of Applicability : South America (Continental contiguous land areas only)

MRE coefficients for $\phi$ and $\lambda$ are :

$$
\begin{aligned}
\Delta\phi'' = & - 1.67504 - 0.05209\,U + 0.25158\,V + 1.10149\,U^2 \\
& + 0.24913\,UV - 1.00937\,U^2V - 0.74977\,V^3 - 1.54090\,U^4 \\
& + 0.14474\,V^4 + 0.47866\,U^5 + 0.36278\,U^3V^2 - 1.29942\,UV^4 \\
& + 0.30410\,V^5 + 0.87669\,U^6 - 0.27950\,U^5V - 0.46367\,U^7 \\
& + 4.31466\,U^4V^3 + 2.09523\,U^2V^5 + 0.85556\,UV^6 - 0.17897\,U^8 \\
& - 0.57205\,UV^7 + 0.12327\,U^9 - 0.85033\,U^6V^3 - 4.86117\,U^4V^5 \\
& + 0.06085\,U^9V - 0.21518\,U^3V^8 + 0.31053\,U^5V^7 \\
& - 0.09228\,U^8V^5 - 0.22996\,U^9V^5 + 0.58774\,U^6V^9 \\
& + 0.87562\,U^9V^7 + 0.39001\,U^8V^9 - 0.81697\,U^9V^9
\end{aligned}
$$

$$
\begin{aligned}
\Delta\lambda'' = & - 1.77967 + 0.40405\,U + 0.50268\,V - 0.05387\,U^2 \\
& - 0.12837\,UV - 0.54687\,U^2V - 0.17056\,V^3 - 0.14400\,U^3V \\
& + 0.11351\,U^5V - 0.62692\,U^3V^3 - 0.01750\,U^8 + 1.18616\,U^3V^5 \\
& + 0.01305\,U^9 + 1.01360\,U^7V^3 - 0.29059\,U^8V^3 \\
& + 5.12370\,U^6V^5 - 5.09561\,U^7V^5 - 5.27168\,U^6V^7 \\
& + 4.04265\,U^7V^7 - 1.62710\,U^8V^7 + 1.68899\,U^9V^7 \\
& + 2.07213\,U^8V^9 - 1.76074\,U^9V^9
\end{aligned}
$$

Where: $U = K\,(\phi + 20°)$; $V = K\,(\lambda + 60°)$; $K = 0.05235988$

NOTE : Input $\phi$ as (-) from 90°S to 0°N in degrees.

Input $\lambda$ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

| SAN | Shift | WGS 84 |
|---|---|---|
| $\phi$= (-) 31°56'33.95"S | $\Delta\phi$= -1.36" | $\phi$= (-) 31°56'35.31"S |
| $\lambda$= (-) 65°06'18.66"W | $\Delta\lambda$= -2.16" | $\lambda$= (-) 65°06'20.82"W |

APPENDIX E

ACRONYMS

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APPENDIX E

-ACRONYMS-

| | | |
|---|---|---|
| AGD 66 | = | Australian Geodetic Datum 1966 |
| AGD 84 | = | Australian Geodetic Datum 1984 |
| BIH | = | Bureau International de l'Heure |
| BTS | = | BIH Terrestrial System |
| CEP | = | Celestial Ephemeris Pole |
| CIS | = | Conventional Inertial System |
| CONUS | = | Contiguous United States |
| CTP | = | Conventional Terrestrial Pole |
| CTS | = | Conventional Terrestrial System |
| DMA | = | Defense Mapping Agency |
| DMAAC | = | Defense Mapping Agency Aerospace Center |
| DMAHTC | = | Defense Mapping Agency Hydrographic Topographic Center |
| DoD | = | Department of Defense |
| ECEF | = | Earth-Centered, Earth-Fixed |
| ECI | = | Earth-Centered Inertial |
| ECM | = | Earth's Center of Mass |
| ED 50 | = | European Datum 1950 |
| ED 79 | = | European Datum 1979 |
| EGM | = | Earth Gravitational Model |
| FRG | = | Federal Republic of Germany |
| GLONASS | = | Global Navigation Satellite System |
| GPS | = | Global Positioning System |
| GRS 80 | = | Geodetic Reference System 1980 |
| IAG | = | International Association of Geodesy |
| IAU | = | International Astronomical Union |
| ITS | = | Instantaneous Terrestrial System |
| IUGG | = | International Union of Geodesy and Geophysics |
| MC&G | = | Mapping, Charting, and Geodesy |
| MREs | = | Multiple Regression Equations |
| NAD 27 | = | North American Datum 1927 |
| NAD 83 | = | North American Datum 1983 |

APPENDIX E (Cont'd)

-ACRONYMS-

| | | |
|---|---|---|
| NAVOCEANO | = | Naval Oceanographic Office |
| Navstar GPS | = | Navstar Global Positioning System |
| NGS | = | National Geodetic Survey |
| NNSS | = | Navy Navigation Satellite System |
| NSWC | = | Naval Surface Warfare Center (formerly Naval Surface Weapons Center) |
| OSGB 36 | = | Ordnance Survey of Great Britain 1936 |
| OSGB SN 80 | = | Ordnance Survey of Great Britain Scientific Network 1980 |
| PSAD 56 | = | Provisional South American Datum 1956 |
| RMS | = | Root-Mean-Square |
| SAD 69 | = | South American Datum 1969 |
| TD | = | Tokyo Datum |
| TR | = | Technical Report |
| USNO | = | United States Naval Observatory |
| UK | = | United Kingdom |
| US | = | United States |
| UT | = | Universal Time |
| VLBI | = | Very Long Baseline Interferometry |
| WGS | = | World Geodetic System |
| WGS 72 | = | World Geodetic System 1972 |
| WGS 84 | = | World Geodetic System 1984 |



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