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NATIONAL IMAGERY AND MAPPING AGENCY

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Its Definition and Relationships with Local Geodetic Systems

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This technical report presents an update to the Department of Defense (DoD) World Geodetic System 1984 (WGS 84). The update of WGS 84 was initiated for the purpose of providing more accurate geodetic and gravitational data required by DoD navigation and weapon systems, particularly through the development of a more accurate reference frame, Earth Gravitational Model (EGM96) and corresponding geoid. This update represents the National Imagery and Mapping Agency's modeling of the Earth from a geometric, geodetic, and gravitational standpoint using data, techniques, and technology available through 1996.

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

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NIMA DEFINITION

On 1 October 1996 the Defense Mapping Agency (DMA) was incorporated into a new agency, the National Imagery and Mapping Agency (NIMA).

NATIONAL IMAGERY AND MAPPING AGENCY

The National Imagery and Mapping Agency provides timely, relevant and accurate imagery, imagery intelligence and geospatial information in support of national security objectives.

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National Imagery and Mapping Agency

NATIONAL IMAGERY AND MAPPING AGENCY TECHNICAL REPORT 8350.2
Third Edition

Department of Defense
World Geodetic System 1984

Its Definition and Relationships
with Local Geodetic Systems

FOREWORD

1. This technical report defines the Department of Defense (DoD) World Geodetic System 1984 (WGS 84). This third edition reflects improvements which have been made to the WGS 84 since the second edition. The present WGS represents the National Imagery and Mapping Agency's (NIMA) latest geodetic and geophysical modeling of the Earth based on data, techniques and technology available through 1996.

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PREFACE

This technical report defines the Department of Defense (DoD) World Geodetic System 1984 (WGS 84). Significant changes incorporated in the third edition include:

- Refined realization of the reference frame
- Development of a refined Earth Gravitational Model and geoid
- Updated list of datum tranformations

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Since WGS 84 is comprised of a coherent set of parameters, DoD organizations should not make a substitution for any of the WGS 84 related parameters or equations. Such a substitution may lead to degraded WGS 84 products, interoperability problems and may have other adverse effects.

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EXECUTIVE SUMMARY

The global geocentric reference frame and collection of models known as the World Geodetic System 1984 (WGS 84) has evolved significantly since its creation in the mid-1980s. The WGS 84 continues to provide a single, common, accessible 3-dimensional coordinate system for geospatial data collected from a broad spectrum of sources. Some of this geospatial data exhibits a high degree of 'metric' fidelity and requires a global reference frame which is free of any significant distortions or biases. For this reason, a series of improvements to WGS 84 were developed in the past several years which served to refine the original version.

A consistent global set of 3-dimensional station coordinates infers the location of an origin, the orientation of an orthogonal set of Cartesian axes, and a scale. In essence, a set of station coordinates infers a particular realization of a reference frame. The station coordinates which compose the operational WGS 84 reference frame are those of the permanent DoD GPS monitor stations.

Within the last three years, the coordinates for these DoD GPS stations have been refined two times, once in 1994, and again in 1996. The two sets of self-consistent GPS-realized coordinates (Terrestrial Reference Frames) derived to date have been designated: 'WGS 84 (G730)' and 'WGS 84 (G873),' where the 'G' indicates these coordinates were obtained through GPS techniques and the number following the 'G' indicates the GPS week number when these coordinates were implemented in the NIMA precise GPS ephemeris estimation process. The dates when these refined station coordinate sets were implemented in the GPS Operational Control Segment (OCS) were: 29 June 1994 and 29 January 1997, respectively.

<u>These reference frame enhancements, as well as the previous set of enhancements, implemented in 1994, are negligible (less than 30 centimeters) in the context of mapping, charting and enroute navigation. Therefore, users should consider the WGS 84 reference frame unchanged for applications involving mapping, charting and enroute navigation.</u>

In addition to these reference frame enhancements, an intensive joint effort has been conducted during the last three years involving analysts and resources of NIMA, the NASA Goddard Space Flight Center (GSFC) and The Ohio State University. The result of this joint effort is a new, global model of the Earth's gravitational field: Earth Gravitational Model 1996 (EGM96). In the case of DoD applications, this model replaces the now-outdated original WGS 84 gravitational model developed more than ten years ago. The form of the EGM96 model is a spherical harmonic expansion of the gravitational potential. The model, complete through degree (n) and order (m) 360, is comprised of 130,676 coefficients. NIMA recommends use of an appropriately truncated (less than or equal to n=m=70) copy of this geopotential model for high accuracy orbit determination.

A refined WGS 84 geoid has been determined from the new gravitational model and is available as a 15 minute grid of geoid undulations which exhibit an absolute accuracy of 1.0 meters or better, anywhere on the Earth. This refined geoid is referred to as the WGS 84 (EGM96) geoid.

The following names and the associated implementation dates have been officially designated for use in all NIMA products:

1. **FOR TOPOGRAPHIC MAPPING** :

A. **Horizontal Datum**

WGS 84	From 1 Jan 1987

B. **Vertical Datum**

WGS 84 Geoid or Local Mean Sea Level (MSL)	From 1 Jan 1987

2. **FOR AERONAUTICAL CHARTS** :

A. **Horizontal Datum**

WGS 84	From 1 Jan 1987

B. **Vertical Datum**

WGS 84 Geoid or Local Mean Sea Level (MSL)	From 1 Jan 1987

3. **FOR NAUTICAL CHARTS** :

A. **Horizontal Datum**

WGS 84	From 1 Jan 1987

B. **Vertical Datum**

For Land Areas -

WGS 84 Geoid or Local Mean Sea Level (MSL)	From 1 Jan 1987

For Ocean Areas -

Local Sounding Datums

4. **<u>FOR GEODETIC, GIS DATA AND OTHER HIGH-ACCURACY APPLICATIONS</u>** :

A. **Reference Frame**

WGS 84	1 Jan 87 - 1 Jan 94
WGS 84 (G730)	2 Jan 94 - 28 Sept 96
WGS 84 (G873)	From 29 Sept 96

These dates represent implementation dates in the NIMA GPS precise ephemeris estimation process.

B. **Coordinates**

As of 2 Jan 94, a set of geodetic coordinates shall include a designation of the reference frame and epoch of the observations.

C. **<u>Earth Gravitational Model</u>**

WGS 84	1 Jan 1987
WGS 84 EGM96	1 Oct 1996

D. **<u>WGS 84 Geoid</u>**

WGS 84	1 Jan 1987
WGS 84 (EGM96)	1 Oct 1996

In summary, the refinements which have been made to WGS 84 have reduced the uncertainty in the coordinates of the reference frame, the uncertainty of the gravitational model and the uncertainty of the geoid undulations. <u>They have not changed WGS 84</u>. As a result, the refinements are most important to the users requiring increased accuracies over capabilities provided by the previous editions of WGS 84. For mapping, charting and navigational users, these improvements are generally negligible. They are most relevant for the geodetic user and other high accuracy applications. Thus, modern geodetic positioning within the DoD is now carried out in the WGS 84 (G873) reference frame. The Earth Gravitational Model 1996 (EGM96) replaces the original WGS 84 geopotential model and serves as the basis for the WGS 84 (EGM96) geoid, available from NIMA on a 15 minute grid. As additional data become available, NIMA may develop further refinements to the geopotential model and the geocentric reference frame. NIMA continues, as in the past, to update and develop new datum transformations as additional data become available to support mapping, charting and navigational users.

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1. INTRODUCTION

The National Imagery and Mapping Agency (NIMA) supports a large number and variety of products and users, which makes it imperative that these products all be related to a common worldwide geodetic reference system. This ensures interoperability in relating information from one product to another, supports increasingly stringent accuracy requirements and supports military and humanitarian activities worldwide. The refined World Geodetic System 1984 (WGS 84) represents NIMA's best geodetic model of the Earth using data, techniques and technology available through 1996.

The definition of the World Geodetic System has evolved within NIMA and its predecessor agencies from the initial WGS 60 through subsequent improvements embodied in WGS 66, WGS 72 and WGS 84. The refinement described in this technical report has been possible due to additional global data from precise and accurate geodetic positioning, new observations of land gravity data, the availability of extensive altimetry data from the GEOSAT, ERS-1 and TOPEX/POSEIDON satellites and additional satellite tracking data from geodetic satellites at various inclinations. The improved Earth Gravitational Model 1996 (EGM96), its associated geoid and additional datum transformations have been made possible by the inclusion of these new data. EGM96 was developed jointly by NIMA, the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA/GSFC), The Ohio State University and the Naval Surface Warfare Center Dahlgren Division (NSWCDD).

Commensurate with these modeling enhancements, significant improvements in the realization of the WGS 84 reference frame have been achieved through the use of the NAVSTAR Global Positioning System (GPS). WGS 84 is realized by the coordinates assigned to the GPS tracking stations used in the calculation of precise GPS orbits at NIMA. NIMA currently utilizes the five globally dispersed Air Force operational GPS tracking stations augmented by seven tracking stations operated by NIMA. The coordinates of these tracking stations have been determined to an absolute accuracy of ±5 cm (1σ).

The WGS 84 represents the best global geodetic reference system for the Earth available at this time for practical applications of mapping, charting, geopositioning and navigation. This report includes the definition of the coordinate system, fundamental and derived constants, the EGM96, the ellipsoidal (normal) gravity model and a current list of local datum transformations. NIMA recommendations regarding the practical implementation of WGS 84 are given in Chapter Nine of this report.

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2. WGS 84 COORDINATE SYSTEM

2.1 Definition

The WGS 84 Coordinate System is a Conventional Terrestrial Reference System (CTRS). The definition of this coordinate system follows the criteria outlined in the International Earth Rotation Service (IERS) Technical Note 21 [1]. These criteria are repeated below:

- It is geocentric, the center of mass being defined for the whole Earth including oceans and atmosphere
- Its scale is that of the local Earth frame, in the meaning of a relativistic theory of gravitation
- Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation of 1984.0
- Its time evolution in orientation will create no residual global rotation with regards to the crust

The WGS 84 Coordinate System is a right-handed, Earth-fixed orthogonal coordinate system and is graphically depicted in Figure 2.1.

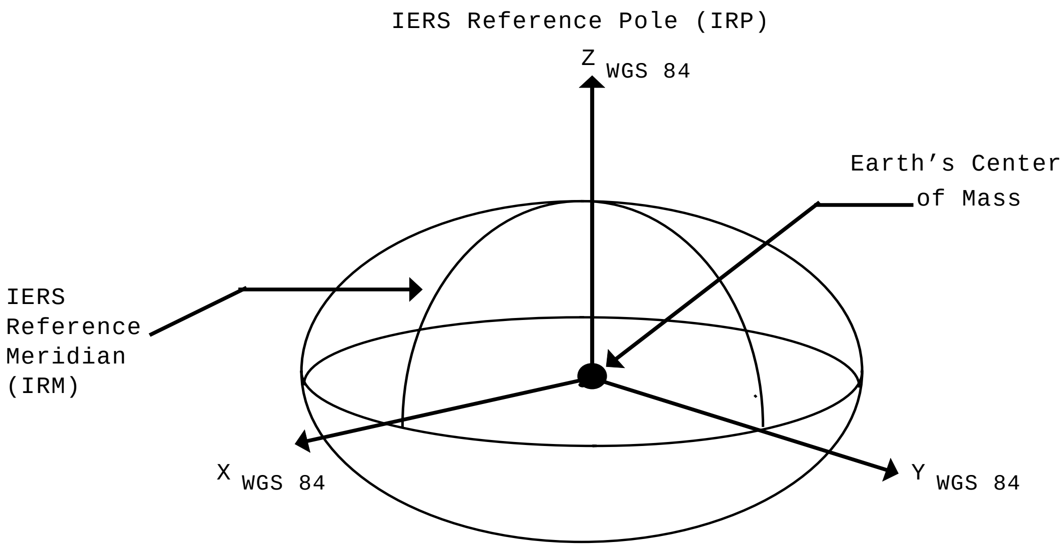


Figure 2.1 The WGS 84 Coordinate System Definition

In Figure 2.1, the origin and axes are defined as follows:

Origin = Earth's center of mass

Z-Axis = The direction of the IERS Reference Pole (IRP). This direction corresponds to the direction of the BIH Conventional Terrestrial Pole (CTP) (epoch 1984.0) with an uncertainty of 0.005" [1]

X-Axis = Intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-axis. The IRM is coincident with the BIH Zero Meridian (epoch 1984.0) with an uncertainty of 0.005" [1]

Y-Axis = Completes a right-handed, Earth-Centered Earth-Fixed (ECEF) orthogonal coordinate system.

The WGS 84 Coordinate System origin also serves as the geometric center of the WGS 84 Ellipsoid and the Z-axis serves as the rotational axis of this ellipsoid of revolution.

Readers should note that the definition of the WGS 84 CTRS has not changed in any fundamental way. This CTRS continues to be defined as a right-handed, orthogonal and Earth-fixed coordinate system which is intended to be as closely coincident as possible with the CTRS defined by the International Earth Rotation Service (IERS) or, prior to 1988, its predecessor, the Bureau International de l'Heure (BIH).

2.2 Realization

Following terminology proposed in [2], an important distinction is needed between the definition of a coordinate system and the practical realization of a reference frame. Section 2.1 contains a definition of the WGS 84 Coordinate System. To achieve a practical realization of a global geodetic reference frame, a set of station coordinates must be established. A consistent set of station coordinates infers the location of an origin, the orientation of an orthogonal set of Cartesian axes, and a scale. In modern terms, a globally distributed set of consistent station coordinates represents a realization of an ECEF Terrestrial Reference Frame (TRF). The original WGS 84 reference frame established in 1987 was realized through a set of Navy Navigation Satellite System (NNSS) or TRANSIT (Doppler) station coordinates which were described in [3]. Moreover, this original WGS 84 TRF was developed by exploiting results from the best available comparisons of the DoD reference frame in existence during the early 1980s, known as NSWC 9Z-2, and the BIH Terrestrial System (BTS).

The main objective in the original effort was to align, as closely as possible, the origin, scale and orientation of the WGS 84 frame with the BTS frame at an epoch of 1984.0. The establishment of accurate transformation parameters (given in DMA TR 8350.2, First Edition and Second Edition) between NSWC 9Z-2 and the BTS achieved this objective with remarkable precision. The scale of the transformed NSWC 9Z-2 frame, for example, is coincident with the BTS at the 10-centimeter level [4]. The set of estimated station coordinates put into practical use and described in [3], however, had an uncertainty of 1-2 meters with respect to the BTS.

The TRANSIT-realized WGS 84 reference frame was used beginning in January 1987 in the Defense Mapping Agency's (DMA) TRANSIT precise ephemeris generation process. These TRANSIT ephemerides were then used in an absolute point positioning process with Doppler tracking data to determine the WGS 84 positions of the permanent DoD Global Positioning System (GPS) monitor stations. These TRANSIT-realized WGS 84 coordinates remained in use by DoD groups until 1994. Specifically, they remained in use until 2 January 1994 by DMA and until 29 June 1994 by the GPS Operational Control Segment (OCS).

Several independent studies, [4], [5], [6], [7] and [8], have demonstrated that a systematic ellipsoid height bias (scale bias) exists between GPS-derived coordinates and Doppler-realized WGS 84 coordinates for the same site. This scale bias is most likely attributable to limitations in the techniques used to estimate the Doppler-derived positions [4]. To remove this bias and obtain a self-consistent GPS-realization of the WGS 84 reference frame, DMA, with assistance from the Naval Surface Warfare Center Dahlgren Division (NSWCDD), developed a revised set of station coordinates for the DoD GPS tracking network. These revised station coordinates provided an improved realization of the WGS 84 reference frame. To date, this process has been carried out twice, once in 1994 and again in 1996.

Using GPS data from the Air Force and DMA permanent GPS tracking stations along with data from a number of selected core stations from the International GPS Service for Geodynamics (IGS), DMA estimated refined coordinates for the permanent Air Force and DMA stations. In this geodetic solution, a subset of selected IGS station coordinates was held fixed to their IERS Terrestrial Reference Frame (ITRF) coordinates. A complete description of the estimation techniques used to derive these new DoD station coordinates is given in [8] and [9]. These refined DoD coordinates have improved accuracy due primarily to the elimination of the ellipsoid height bias and have improved precision due to the advanced GPS techniques used in the estimation process. The accuracy of each individual estimated position component derived in 1996 has been shown to be on the order of 5 cm (1σ) for each permanent DoD station [9]. The corresponding accuracy achieved in the 1994 effort, which is now outdated, was 10 cm (1σ) [8]. By constraining the solution to the appropriate ITRF, the improved coordinates for these permanent DoD stations represent a refined GPS-realization of the WGS 84 reference frame.

The two sets of self-consistent GPS-realized coordinates (Terrestrial Reference Frames) derived to date have been designated 'WGS 84 (G730)' and 'WGS 84 (G873)'. The 'G' indicates these coordinates were obtained through GPS techniques and the number following the 'G' indicates the GPS week number when these coordinates were implemented in the NIMA precise ephemeris estimation process. The dates when these refined station coordinate sets were implemented in the GPS OCS were 29 June 1994 and 29 January 1997, respectively.

The most recent set of coordinates for these globally distributed stations is provided in Table 2.1. The changes between the G730 and G873 coordinate sets are given in Table 2.2. Note that the most recent additions to the NIMA station network, the station located at the US Naval Observatory (USNO) and the station located near Beijing China, exhibit the largest change between coordinate sets. This result is due to the fact that these two stations were not part of the G730 general geodetic solution conducted in 1994. Instead, these two stations were positioned using NIMA's 'GASP' geodetic point positioning algorithm [10], which was shown, at the time in 1994, to produce geodetic positions with an uncertainty of 30 cm (1σ, each component). The results shown in Table 2.2 corroborate this belief.

Table 2.1
WGS 84 Station Set G873: Cartesian Coordinates*, 1997.0 Epoch

Station Location	NIMA Station Number	X (km)	Y (km)	Z (km)
Air Force Stations				
Colorado Springs	85128	-1248.597221	-4819.433246	3976.500193
Ascension	85129	6118.524214	-1572.350829	-876.464089
Diego Garcia(<2 Mar 97)	85130	1917.032190	6029.782349	-801.376113
Diego Garcia(>2 Mar 97)	85130	1916.197323	6029.998996	-801.737517
Kwajalein	85131	-6160.884561	1339.851686	960.842977
Hawaii	85132	-5511.982282	-2200.248096	2329.481654
NIMA Stations				
Australia	85402	-3939.181976	3467.075383	-3613.221035
Argentina	85403	2745.499094	-4483.636553	-3599.054668
England	85404	3981.776718	-89.239153	4965.284609
Bahrain	85405	3633.910911	4425.277706	2799.862677
Ecuador	85406	1272.867278	-6252.772267	-23.801890
US Naval Observatory	85407	1112.168441	-4842.861714	3985.487203
China	85409	-2148.743914	4426.641465	4044.656101

*Coordinates are at the antenna electrical center.

Table 2.2
Differences between WGS 84 (G873) Coordinates and Prior WGS 84 (G730) Coordinates Being Used in Orbital Operations * (Compared at 1994.0 Epoch)

Station Location	NIMA Station Number	Δ East (cm)	Δ North (cm)	Δ Ellipsoid Height (cm)
Air Force Stations				
Colorado Springs	85128	0.1	1.3	3.3
Ascension	85129	2.0	4.0	-1.1
Diego Garcia(<2 Mar 97)	85130	-3.3	-8.5	5.2
Kwajalein	85131	4.7	0.3	4.1
Hawaii	85132	0.6	2.6	2.7
NIMA Stations				
Australia	85402	-6.2	-2.7	7.5
Argentina	85403	-1.0	4.1	6.7
England	85404	8.8	7.1	1.1
Bahrain	85405	-4.3	-4.8	-8.1
Ecuador	85406	-2.0	2.5	10.7
US Naval Observatory	85407	39.1	7.8	-3.7
China	85409	31.0	-8.1	-1.5

*Coordinates are at the antenna electrical center.

In summary, these improved station coordinate sets, in particular, WGS 84 (G873), represent the most recent realization(s) of the WGS 84 reference frame. Further improvements and future realizations of the WGS 84 reference frame are anticipated. When new stations are added to the permanent DoD GPS tracking network or when existing stations (and/or antennas) are moved or replaced, new station coordinates will be required. As these changes occur, NIMA will take steps to ensure that the highest possible degree of fidelity is maintained and changes are identified to the appropriate organizations using the naming conventions described above.

2.2.1 Agreement with the ITRF

The WGS 84 (G730) reference frame was shown to be in agreement, after the adjustment of a best fitting 7-parameter transformation, with the ITRF92 at a level approaching 10 cm [10]. While similar comparisons of WGS 84 (G873) and ITRF94 are still underway, extensive daily orbit comparisons between the NIMA precise ephemerides (WGS 84 (G873) reference frame) and corresponding IGS ephemerides (ITRF94 reference frame) reveal systematic differences no larger than 2 cm [40]. The day-to-day dispersion on these parameters indicates that these differences are statistically insignificant. Note that a set of ephemerides represents a unique realization of a reference frame that may differ slightly from a corresponding realization obtained from stations on the Earth.

2.2.2 Temporal Effects

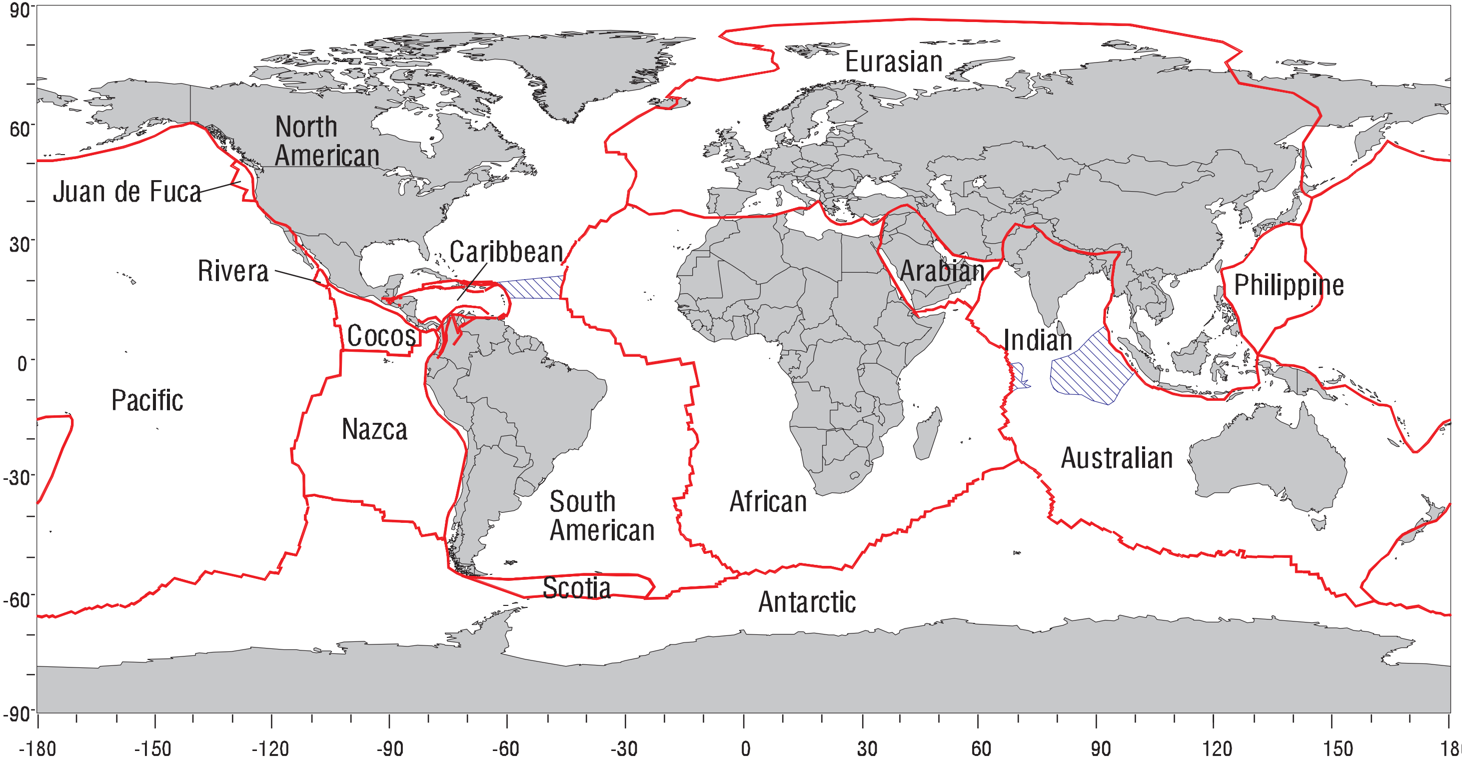
Since the fidelity of the current realization of the WGS 84 reference frame is now significantly better than a decimeter, previously ignored phenomena must now be taken into account in precise geodetic applications. Temporal changes in the crust of the Earth must now be modeled or estimated. The most important changes are plate tectonic motion and tidal effects on the Earth's crust. These are each discussed briefly below. Temporal effects may also require an epoch to be designated with any set of absolute station coordinates. The epoch of the WGS 84 (G730) reference frame, for example, is 1994.0 while the epoch associated with the WGS 84 (G873) reference frame is 1997.0.

2.2.2.1 Plate Tectonic Motion

To maintain centimeter-level stability in a CTRS, a given set of station positions represented at a particular epoch must be updated for the effects of plate tectonic motion. Given sets of globally distributed station coordinates, represented at a particular epoch, their positions slowly degrade as the stations ride along on the tectonic plates. This motion has been observed to be as much as 7 cm/year at some DoD GPS tracking stations. One way to handle these horizontal motions is to estimate velocity parameters along with the station position parameters. For most DoD applications, this approach is not practical since the observation period is not sufficiently long and the geodetic surveying algorithms in common use are not equipped to perform this function. Instead, if the accuracy requirements of a DoD application warrant it, DoD practitioners must decide which tectonic plate a given station is on and apply a plate motion model to account for these horizontal effects. The current recommended plate motion model is known as NNR-NUVEL1A and can be found in [1]. A map of the sixteen major tectonic plates is given in Figure 2.2. [12]

The amount of time elapsed between the epoch of a station's coordinates and the time of interest will be a dominant factor in deciding whether application of this plate motion model is warranted. For example, a station on a plate that moves at a rate of 5 cm/year may not require this correction if the epoch of the coordinates is less than a year in the past. If, however, these same coordinates are used over a 5-year period, 25 cm of horizontal displacement will have accumulated in that time and application of this correction may be advisable, depending on the accuracy requirements of the geodetic survey.

Figure 2.2 Tectonic Plate Map



Present-day Major Tectonic Plates and Plate Boundaries

*Several minor plates not shown

2.2.2.2 Tidal Effects

Tidal phenomena are another source of temporal and permanent displacement of a station's coordinates. These displacements can be modeled to some degree. In the most demanding applications (cm-level or better accuracy), these displacements should be handled as outlined in the IERS Conventions (1996) [1]. The results of following these conventions lead to station coordinates in a 'zero-tide' system. In practice, however, the coordinates are typically represented in a 'tide-free' system. This is the procedure followed in the NIMA GPS precise ephemeris estimation process. In this 'tide-free' system, both the temporal and permanent displacements are removed from a station's coordinates.

Note that many practical geodetic surveying algorithms are not equipped to rigorously account for these tidal effects. Often, these effects are completely ignored or allowed to 'average-out.' This approach may be adequate if the data collection period is long enough since the majority of the displacement is diurnal and semi-diurnal. Moreover, coordinates determined from GPS differential (baseline) processing will typically contain whatever tidal components are present in the coordinates of the fixed (known) end of the baseline. If decimeter level or better absolute accuracy is required, careful consideration must be given to these station displacements since the peak absolute, instantaneous effect can be as large as 42 cm [11]. In the most demanding applications, the rigorous model outlined in [1] should be applied.

2.3 Mathematical Relationship Between the Conventional Celestial Reference System (CCRS) and the WGS 84 Coordinate System

Since satellite equations of motion are appropriately handled in an inertial coordinate system, the concept of a Conventional Celestial Reference System (CCRS) (Alternately known as a Conventional Inertial System (CIS)) is employed in most DoD orbit determination operations. In practical orbit determination applications, analysts often refer to the J2000.0 Earth-Centered Inertial (ECI) reference frame which is a particular, widely adopted CCRS that is based on the Fundamental Katalog 5 (FK5) star catalog. Since a detailed definition of these concepts is beyond the scope of this document, the reader is referred to [1], [13], [14] and [15] for in-depth discussions of this topic.

Traditionally, the mathematical relationship between the CCRS and a CTRS (in this case, the WGS 84 Coordinate System) is expressed as:

$$\text{CTRS} = [A]\,[B]\,[C]\,[D]\,\text{CCRS} \qquad (2\text{-}1)$$

where the matrices A, B, C and D represent the effects of polar motion, Earth rotation, nutation and precession, respectively. The specific formulations for the generation of matrices A, B, C and D can be found in the references cited above. Note that for near-real-time orbit determination applications, Earth Orientation Parameters (polar motion and Earth rotation variations), that are needed to build the A and B matrices, must be predicted values. Because the driving forces that influence polar motion and Earth rotation variations are difficult to characterize, these Earth orientation predictions are performed weekly. Within the DoD, NIMA and the USNO supply these predictions on a routine basis. The NIMA Earth orientation predictions adhere to a specific formulation documented in ICD-GPS-211 [16]. When this ICD-GPS-211 prediction model is evaluated at a specific time, these predictions represent offsets from the IRP in the direction of 0° and 270° longitude, respectively. The UT1-UTC predictions represent the difference between the actual rotational time scale, UT1, and the uniform time scale, UTC (Coordinated Universal Time). Further details on the prediction algorithm can be found in [17], while recent assessments of the algorithm's performance can be found in [18] and [19].

2.3.1 Tidal Variations in the Earth's Rotation

The actual Earth rotation rate (represented by UT1) undergoes periodic variations due to tidal deformation of the polar moment of inertia. These highly predictable periodic variations have a peak-to-peak amplitude of 3 milliseconds and can be modeled by using the formulation found in Chapter 8 of [1]. If an orbit determination application requires extreme accuracy and uses tracking data from stations on the Earth, these UT1 variations should be modeled in the orbit estimation process.

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3. WGS 84 ELLIPSOID

3.1 General

Global geodetic applications require three different surfaces to be clearly defined. The first of these is the Earth's topographic surface. This surface includes the familiar landmass topography as well as the ocean bottom topography**.** In addition to this highly irregular topographic surface, a definition is needed for a geometric or mathematical reference surface, the ellipsoid, and an equipotential surface called the geoid (Chapter 6).

While selecting the WGS 84 Ellipsoid and associated parameters, the original WGS 84 Development Committee decided to closely adhere to the approach used by the International Union of Geodesy and Geophysics (IUGG), when the latter established and adopted Geodetic Reference System 1980 (GRS 80) [20]. Accordingly, a geocentric ellipsoid of revolution was taken as the form for the WGS 84 Ellipsoid. The parameters selected to originally define the WGS 84 Ellipsoid were the semi-major axis (a), the Earth's gravitational constant (GM), the normalized second degree zonal gravitational coefficient ($\bar{C}_{2,0}$) and the angular velocity (ω) of the Earth (Table 3.1). These parameters are identical to those of the GRS 80 Ellipsoid with one minor exception. The form of the coefficient used for the second degree zonal is that of the original WGS 84 Earth Gravitational Model rather than the notation 'J_2' used with GRS 80.

In 1993, two efforts were initiated which resulted in significant refinements to these original defining parameters. The first refinement occurred when DMA recommended, based on a body of empirical evidence, a refined value for the GM parameter [21],[10]. In 1994, this improved GM parameter was recommended for use in all high-accuracy DoD orbit determination applications. The second refinement occurred when the joint NIMA/NASA Earth Gravitational Model 1996 (EGM96) project produced a new estimated dynamic value for the second degree zonal coefficient.

A decision was made to retain the original WGS 84 Ellipsoid semi-major axis and flattening values (a = 6378137.0 m, and 1/f = 298.257223563). For this reason the four defining parameters were chosen to be: a, f, GM and ω. Further details regarding this decision are provided below. The reader should also note that the refined GM value is within 1σ of the original (1987) GM value. Additionally there are now two distinct values for the $\bar{C}_{2,0}$ term. One dynamicaly derived $\bar{C}_{2,0}$ as part of the EGM96 and the other, geometric $\bar{C}_{2,0}$, implied by the defining parameters. Table 3.1 contains the revised defining parameters.

3.2 Defining Parameters

3.2.1 Semi-major Axis (a)

The semi-major axis (a) is one of the defining parameters for WGS 84. Its adopted value is:

$$a = 6378137.0 \text{ meter} \tag{3-1}$$

This value is the same as that of the GRS 80 Ellipsoid. As stated in [22], the GRS 80, and thus the WGS 84 semi-major axis is based on estimates from the 1976-1979 time period, determined using laser, Doppler and radar altimeter data and techniques. Although more recent, improved estimates of this parameter have become available, these new estimates differ from the above value by only a few decimeters. More importantly, the vast majority of practical applications, such as GPS receivers and mapping processes use the ellipsoid as a convenient reference surface. In these applications, it is not necessary to define the ellipsoid that best fits the geoid. Instead, common sense and the expense of numerous software modifications to GPS receivers and mapping processes guided the decision to retain the original reference ellipsoid. Moreover, this approach obviates the need to transform or re-compute coordinates for the large body of accurate geospatial data which has been collected and referenced to the WGS 84 Ellipsoid in the last decade. Highly specialized applications and experiments which require the 'best-fitting' ellipsoid parameters can be handled separately, outside the mainstream of DoD geospatial information generation.

3.2.2 Flattening (f)

The flattening (f) is now one of the defining parameters for WGS 84 and remains the same as in previous editions of TR8350.2. Its adopted value is:

$$1/f = 298.257223563 \tag{3-2}$$

As discussed in 3.2.1 , there are numerous practical reasons for retaining this flattening value along with the semi-major axis as part of the definition of the WGS 84 ellipsoid.

The original WGS 84 development effort used the normalized second degree zonal harmonic dynamic ($\overline{C}_{2,0}$) value as a defining parameter. In this case, the ellipsoid flattening value was derived from ($\overline{C}_{2,0}$) through an accepted, rigorous expression. Incidentally, this derived flattening turned out to be slightly different than the GRS 80 flattening because the ($\overline{C}_{2,0}$) value was truncated in the normalization process. Although this slight difference has no practical consequences, the flattening of the WGS 84 Ellipsoid is numerically distinct from the GRS 80 flattening.

3.2.3 Earth's Gravitational Constant (GM)

3.2.3.1 GM with Earth's Atmosphere Included (GM)

The central term in the Earth's gravitational field (GM) is known with much greater accuracy than either 'G', the universal gravitational constant, or 'M', the mass of the Earth. Significant improvement in the knowledge of GM has occurred since the original WGS 84 development effort. The refined value of the WGS 84 GM parameter, along with its 1σ uncertainty is:

$$GM = (3986004.418 \pm 0.008) \times 10^8 \text{ m}^3/\text{s}^2 \qquad (3\text{-}3)$$

This value includes the mass of the atmosphere and is based on several types of space measurements. This value is recommended in the IERS Conventions (1996) [1] and is also recommended by the International Association of Geodesy (IAG) Special Commission SC3, Fundamental Constants, XXI IAG General Assembly [23]. The estimated accuracy of this parameter is discussed in detail in [24].

3.2.3.2 Special Considerations for GPS

Based on a recommendation in a DMA letter to the Air Force [21], the refined WGS 84 GM value (3986004.418 x 10^8 m^3/s^2) was implemented in the GPS Operational Control Segment (OCS) during the fall of 1994. This improvement removed a 1.3 meter radial bias from the OCS orbit estimates. The process that generates the predicted broadcast navigation messages in the OCS also uses a GM value to create the quasi-Keplerian elements from the predicted Cartesian state vectors. The broadcast elements are then interpolated by a GPS receiver to obtain the satellite position at a given epoch.

To avoid any loss of accuracy, the GPS receiver's interpolation process must use the same GM value that was used to generate the fitted parameters of the broadcast message. Note that this fitting process is somewhat arbitrary but must be commensurate with the algorithm in the receiver. Because there are many thousands of GPS receivers in use around the world and because proposed, coordinated software modifications to these receivers would be a costly, unmanageable endeavor, Aerospace Corporation [25] suggested that the original WGS 84 GM value (3986005.0 x 10^8 m^3/s^2) be retained in GPS receivers and in the OCS process which fits a set of broadcast elements to the Cartesian vectors. This approach takes advantage of the improved orbit accuracy for both the estimated and predicted states facilitated by the refined GM value and avoids the expense of software modifications to all GPS receivers.

For the above reasons, the GPS interface control document (ICD-GPS-200) which defines the space segment to user segment interface should retain the original WGS 84 GM value. The refined WGS 84 GM value should continue to be used in the OCS orbit estimation process. Most importantly, this approach avoids the introduction of any error to a GPS user.

3.2.3.3 GM of the Earth's Atmosphere

For some applications, it is necessary to either have a GM value for the Earth that does not include the mass of the atmosphere, or have a GM value for the atmosphere itself. To achieve 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 [26] by the IAG, and the accepted value for M_A [27], the product GM to two significant digits yields the value recommended by the IAG for this constant. This value, with an assigned accuracy estimate, was adopted for use with WGS 84 and has not changed from the previous editions of this report:

$$GM_A = (3.5 \pm 0.1) \times 10^8 \; m^3/s^2 \qquad (3\text{-}4)$$

3.2.3.4 GM with Earth's Atmosphere Excluded (GM')

The Earth's gravitational constant with the mass of the Earth's atmosphere excluded (GM'), can be obtained by simply subtracting GM_A, Equation (3-4), from GM, Equation (3-3):

$$GM' = (3986000.9 \pm 0.1) \times 10^8 \; m^3/s^2 \qquad (3\text{-}5)$$

Note that GM' is known with much less accuracy than GM due to the uncertainty introduced by GM_A.

3.2.4 Angular Velocity of the Earth (ω)

The value of ω used as one of the defining parameters of the WGS 84 (and GRS 80) is:

$$\omega = 7292115 \times 10^{-11} \text{ radians/second} \qquad (3\text{-}6)$$

This value represents a standard Earth rotating with a constant angular velocity. Note that the actual angular velocity of the Earth fluctuates with time. Some geodetic applications that require angular velocity do not need to consider these fluctuations.

Although ω 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 (ω')

$$\omega' = 7292115.1467 \times 10^{-11} \text{ radians/second} \quad (3\text{-}7)$$

that was used with the new definition of time [28].

For consistent satellite applications, the value of the Earth's angular velocity (ω') from equation (3-7), rather than ω, should be used in the formula

$$\omega^* = \omega' + m \quad (3\text{-}8)$$

to obtain the angular velocity of the Earth in a precessing reference frame (ω^*). In the above equation [28] [14], the precession rate in right ascension (m) is:

$$m = (7.086 \times 10^{-12} + 4.3 \times 10^{-15}\, T_U) \text{ radians/second} \quad (3\text{-}9)$$

where:

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 $\pm 0.5, \pm 1.5, \pm 2.5$...

d_U = JD - 2451545

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

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

Note that values for ω, ω', and ω^* have remained unchanged from the previous edition.

Table 3.1
WGS 84 Four Defining Parameters

Parameter	Notation	Magnitude
Semi-major Axis	a	6378137.0 meters
Reciprocal of Flattening	1/f	298.257223563
Angular Velocity of the Earth	ω	$7292115.0 \times 10^{-11}$ rad sec^{-1}
Earth's Gravitational Constant (Mass of Earth's Atmosphere Included)	GM	$3986004.418 \times 10^{8} m^3/s^2$

Table 3.2
WGS 84
Parameter Values for Special Applications

Parameter	**Notation**	**Magnitude**	**Accuracy (1σ)**
Gravitational Constant (Mass of Earth's Atmosphere Not Included)	GM'	3986000.9×10^8 m^3/s^2	$\pm 0.1 \times 10^8$ m^3/s^2
GM of the Earth's Atmosphere	GM_A	3.5×10^8 m^3/s^2	$\pm 0.1 \times 10^8$ m^3/s^2
Angular Velocity of the Earth (In a Precessing Reference frame)	ω*	$(7292115.8553 \times 10^{-11} + 4.3 \times 10^{-15} T_U)$ rad s^{-1}	$\pm 0.15 \times 10^{-11}$ rad s^{-1}

3.3 Derived Geometric and Physical Constants

Many constants associated with the WGS 84 Ellipsoid, other than the four defining parameters (Table 3.1), are needed for geodetic 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 3.3 and 3.4. The formulas used in the calculation of these constants are primarily from [20] and [29]. Derived constants should retain the listed significant digits if consistency among the precision levels of the various parameters is to be maintained.

3.3.1 Derived Geometric Constants

The original WGS 84 definition, as represented in the two previous editions of this document, designated the normalized second degree zonal gravitational coefficient ($\overline{C}_{2,0}$) as a defining parameter. Now that the ellipsoid flattening is used as a defining parameter, the geometric $\overline{C}_{2,0}$ is derived through the defining parameter set (a, f, GM and ω). The new derived geometric $\overline{C}_{2,0}$ equals $-0.484166774985 \times 10^{-3}$ which differs from the original WGS 84 $\overline{C}_{2,0}$ by 7.5015×10^{-11}. This difference is within the accuracy of the original WGS 84 $\overline{C}_{2,0}$, which was $\pm 1.30 \times 10^{-9}$.

The differences between the dynamic and geometric even degree zonal harmonics to degree 10 are used in spherical harmonic expansions to calculate the geoid and other geodetic quantities as described in Chapters 5 and 6 of this report. The dynamic ($\overline{C}_{2,0}$) value provided in Table 5.1 should be used in orbit determination applications. A complete description of the EGM96 geopotential coefficients can be found in Chapter 5.

Table 3.3

WGS 84 Ellipsoid Derived Geometric Constants

Constant	Notation	Value
Second Degree Zonal Harmonic	$\overline{C}_{2,0}$	$-0.484166774985 \times 10^{-3}$
Semi-minor Axis	b	6356752.3142 m
First Eccentricity	e	$8.1819190842622 \times 10^{-2}$
First Eccentricity Squared	e^2	$6.69437999014 \times 10^{-3}$
Second Eccentricity	e'	$8.2094437949696 \times 10^{-2}$
Second Eccentricity Squared	e'^2	$6.73949674228 \times 10^{-3}$
Linear Eccentricity	E	$5.2185400842339 \times 10^{5}$
Polar Radius of Curvature	c	6399593.6258 m
Axis Ratio	b/a	0.996647189335
Mean Radius of Semi-axes	R_1	6371008.7714 m
Radius of Sphere of Equal Area	R_2	6371007.1809 m
Radius of Sphere of Equal Volume	R_3	6371000.7900 m

Table 3.4
Derived Physical Constants

Constant	Notation	Value
Theoretical (Normal) Gravity Potential of the Ellipsoid	U_0	$62636860.8497 \text{ m}^2/\text{s}^2$
Theoretical (Normal) Gravity at the Equator (on the Ellipsoid)	γ_e	$9.7803253359 \text{ m/s}^2$
Theoretical (Normal) Gravity at the pole (on the Ellipsoid)	γ_p	$9.8321849378 \text{ m/s}^2$
Mean Value of Theoretical(Normal) Gravity	$\bar{\gamma}$	$9.7976432222 \text{ m/s}^2$
Theoretical (Normal) Gravity Formula Constant	k	0.00193185265241
Mass of the Earth (Includes Atmosphere)	M	5.9733328×10^{24} kg
$m=\omega^2a^2b/GM$	m	0.00344978650684

3.3.2 Physical Constants

In addition to the above constants, two other 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 [30], [1], [23]:

$$c = 299792458 \text{ m/s} \qquad (3\text{-}11)$$

This value is officially recognized by both the IAG [26] and IAU [14], 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 1983 IAG report on fundamental geodetic constants [31], the following value for the reciprocal of H was given in the discussion of moments of inertia:

$$l/H = 305.4413 \pm 0.0005 \qquad (3\text{-}12)$$

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 3.5 along with other WGS 84 associated constants used in special applications.

Table 3.5
Relevant Miscellaneous Constants

Constant	**Symbol**	**Numerical Value**
Velocity of Light (in a Vacuum)	c	299792458 m/s
Dynamical Ellipticity	H	1/305.4413
Universal Constant of Gravitation	G	6.673×10^{-11} $m^3 kg^{-1} s^{-2}$
Earth's Principal Moments of Inertia (Dynamic Solution)	A B C	8.0091029×10^{37} kg m^2 8.0092559×10^{37} kg m^2 8.0354872×10^{37} kg m^2

4. WGS 84 ELLIPSOIDAL GRAVITY FORMULA

4.1 General

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 the value of the gravity potential is the same everywhere. The WGS 84 ellipsoid of revolution is defined as an equipotential surface with a specific theoretical 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 in the case of the WGS 84 Ellipsoid (Chapter 3), these are the semi-major axis (a), the inverse of the flattening (1/f), the Earth's angular velocity (ω), and the Earth's gravitational constant (GM).

4.2 Normal Gravity on Ellipsoidal Surface

Theoretical normal gravity (γ), the magnitude of the gradient of the normal potential function U, is given on (at) the surface of the ellipsoid by the closed formula of Somigliana [33]:

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

where

$$k = \frac{b\gamma_p}{a\gamma_e} - 1$$

a, b = semi-major and semi-minor axes of the ellipsoid, respectively

γ_e, γ_p = theoretical gravity at the equator and poles, respectively

e^2 = square of the first ellipsoidal eccentricity

ϕ = geodetic latitude.

This form of the normal gravity equation is the WGS 84 Ellipsoidal Gravity Formula. The equipotential ellipsoid not only serves as the reference for horizontal and vertical surfaces, or geometric figure of the Earth, but also serves as the reference surface for the normal gravity of the Earth.

If the MKS (Meter-Kilogram-Second) unit system is used to evaluate Equation (4-1), or for that matter any gravity formula in this Chapter, the gravity unit will be m/sec^2 which can be converted to milligals (abbreviated mgal) by the conversion factor, $1\ m/sec^2 = 10^5$ mgal.

4.3 Normal Gravity Above the Ellipsoid

When the geodetic height (h) is small, normal gravity above the ellipsoid can be estimated by upward continuing γ at the ellipsoidal surface using a truncated Taylor series expansion:

$$\gamma_h = \gamma + \frac{\partial\gamma}{\partial h}h + \frac{1}{2}\frac{\partial^2\gamma}{\partial h^2}h^2 . \qquad (4\text{-}2)$$

A frequently used Taylor series expansion for normal gravity above the ellipsoid with a positive direction downward along the geodetic normal to the reference ellipsoid is:

$$\gamma_h = \gamma\left[1 - \frac{2}{a}\left(1 + f + m - 2f\sin^2\phi\right)\cdot h + \frac{3}{a^2}h^2\right] \qquad (4\text{-}3)$$

where

$$m = \frac{\omega^2 a^2 b}{GM}$$

f = ellipsoidal flattening

a = semi-major axis

ϕ = geodetic latitude

γ = normal gravity on the ellipsoid at geodetic latitude ϕ.

The derivation of Equation (4-3) can be found in [33].

At moderate and high geodetic heights where Equation (4-3) may yield results with less than desired accuracy, an alternate approach based on formulating normal gravity in the ellipsoidal coordinate system (u, β, λ) is recommended over the Taylor series method. The coordinate u is the semi-minor axis of an ellipsoid of revolution whose surface passes through the point P in Figure 4.1. This ellipsoid is confocal with the reference ellipsoid and therefore has the same linear eccentricity $E = \sqrt{a^2 - b^2}$. Its semi-major axis (a') is given by the radical expression $\sqrt{u^2 + E^2}$

which reduces to the semi-major axis (a) of the reference ellipsoid when u=b. The β coordinate is known in geodesy as the "reduced latitude" (The definition is seen in Figure 4.1.), and λ is the usual geocentric longitude with a value in the open interval [0°E, 360°E).

The component (γ_h) of the total normal gravity vector ($\vec{\gamma}_{total}$) that is colinear with the geodetic normal line for point P in Figure 4.2 and directed positively downward can be estimated with sub-microgal precision to geodetic heights of at least 20,000 meters by using the normal gravity components, γ_u, γ_β, and γ_λ in the ellipsoidal coordinate system:

$$\gamma_h \cong \left|\vec{\gamma}_{total}\right| = \sqrt{\gamma_u^2 + \gamma_\beta^2 + \gamma_\lambda^2}\ . \qquad (4\text{-}4)$$

The normal gravity field from the ellipsoidal representation is symmetrical about the rotation axis and therefore $\gamma_\lambda = 0$. The radical expression in Equation (4-4) is the true magnitude of the total normal gravity vector $\vec{\gamma}_{total}$ that is perpendicular to the equipotential surface passing through the point P at geodetic height h. The fact that the angular separation (ε) in the Inset of Figure 4.2 between the component γ_h and the total normal gravity vector $\vec{\gamma}_{total}$ at the point P is small, even for large geodetic heights, is the basis for using Equation (4-4) to approximate the component γ_h. On the reference ellipsoidal surface where h=0, $\gamma_\beta = 0$ and u=b, Equation (4-4) is equivalent to Somigliana's Equation (4-1).

The two ellipsoidal components (γ_u, γ_β) of the normal gravity vector $\vec{\gamma}_{total}$ that are needed in Equation (4-4) are shown in [33] to be functions of the ellipsoidal coordinates (u,β) shown in Figure 4.1. These two components can be computed with unlimited numerical accuracy by the closed expressions:

$$\gamma_u(u,\beta) = -\frac{1}{w}\left[\frac{GM}{u^2+E^2} + \frac{\omega^2 a^2 E}{u^2+E^2}\cdot\frac{q'}{q_o}\cdot\left(\frac{1}{2}\sin^2\beta - \frac{1}{6}\right)\right] + \frac{1}{w}\omega^2\cdot u\cdot\cos^2\beta \qquad (4\text{-}5)$$

$$\gamma_\beta(u,\beta) = \frac{1}{w}\frac{\omega^2 a^2}{\sqrt{u^2+E^2}}\cdot\frac{q}{q_o}\sin\beta\cos\beta - \frac{1}{w}\omega^2\sqrt{u^2+E^2}\sin\beta\cos\beta \qquad (4\text{-}6)$$

where

$$E = \sqrt{a^2 - b^2} \qquad (4\text{-}7)$$

$$u = \left[\frac{1}{2}\left(x^2 + y^2 + z^2 - E^2\right) \cdot \left\{ 1 + \sqrt{1 + \frac{4E^2 z^2}{\left(x^2 + y^2 + z^2 - E^2\right)^2}} \right\} \right]^{1/2} \tag{4-8}$$

$$\beta = \arctan\left(\frac{z\sqrt{u^2 + E^2}}{u\sqrt{x^2 + y}} \right) \tag{4-9}$$

$$w = \sqrt{\frac{u^2 + E^2 \sin^2 \beta}{u^2 + E^2}} \tag{4-10}$$

$$q = \frac{1}{2}\left[\left(1 + 3\frac{u^2}{E^2}\right) \arctan\left(\frac{E}{u}\right) - 3\frac{u}{E} \right] \tag{4-11}$$

$$q_o = \frac{1}{2}\left[\left(1 + 3\frac{b^2}{E^2}\right) \arctan\left(\frac{E}{b}\right) - 3\frac{b}{E} \right] \tag{4-12}$$

$$q' = 3\left[1 + \frac{u^2}{E^2}\right] \cdot \left[1 - \frac{u}{E}\arctan\left(\frac{E}{u}\right)\right] - 1 . \tag{4-13}$$

The rectangular coordinates x,y,z required in Equations (4-8) and (4-9) can be computed from known geodetic coordinates (ϕ, λ, h) through the equations:

$$x = (N + h)\cos\phi\cos\lambda$$

$$y = (N + h)\cos\phi\sin\lambda \tag{4-14}$$

$$z = \left(\left(b^2/a^2\right) \cdot N + h\right)\sin\phi$$

where the radius of curvature in the prime vertical (N) is defined by the equation:

$$N = \frac{a}{\left(1 - e^2 \sin^2 \phi\right)^{1/2}} . \tag{4-15}$$

The description of the coordinate system defined by Equations (4-14) is given in Chapter 2.

To compute the component γ_h at point P in Figure 4.2 exactly, (account for the angle ε in Figure 4.2 that is being treated as negligible in Equation (4-4)), the ellipsoidal normal gravity components γ_u and γ_β are rotated to a spherical coordinate system (r, ψ, λ) resulting in the spherical normal gravity components, γ_r and γ_ψ. Then, the spherical components are projected onto the geodetic normal line through point P using the angular difference ($\alpha = \phi - \psi$) between geodetic (ϕ) and geocentric(ψ) latitudes. The equations to calculate the exact value of γ_h at point P follow:

$$\gamma_h = -\gamma_r \cos(\alpha) - \gamma_\psi \sin(\alpha) \qquad (4\text{-}16)$$

where from [33]

$$\underset{\substack{\text{Ellipsoidal}\\ \text{System}}}{\vec{\gamma}_E \begin{Bmatrix} \gamma_u \\ \gamma_\beta \\ \gamma_\lambda \end{Bmatrix}} \xrightarrow{\vec{\gamma}_R = R_1 \cdot \vec{\gamma}_E} \underset{\substack{\text{Rectangular}\\ \text{System}}}{\vec{\gamma}_R \begin{Bmatrix} \gamma_x \\ \gamma_y \\ \gamma_z \end{Bmatrix}} \xrightarrow{\vec{\gamma}_S = R_2 \cdot \vec{\gamma}_R} \underset{\substack{\text{Spherical}\\ \text{System}}}{\vec{\gamma}_S \begin{Bmatrix} \gamma_r \\ \gamma_\psi \\ \gamma_\lambda \end{Bmatrix}} \Rightarrow \vec{\gamma}_s = R_2 R_1 \cdot \vec{\gamma}_E$$

$$(4\text{-}17)$$

$$R_1 = \begin{bmatrix} \dfrac{u}{w\sqrt{u^2+E^2}}\cos\beta\cos\lambda & -\dfrac{1}{w}\sin\beta\cos\lambda & -\sin\lambda \\ \dfrac{u}{w\sqrt{u^2+E^2}}\cos\beta\sin\lambda & -\dfrac{1}{w}\sin\beta\sin\lambda & \cos\lambda \\ \dfrac{1}{w}\sin\beta & \dfrac{u}{w\sqrt{u^2+E^2}}\cos\beta & 0 \end{bmatrix} \qquad (4\text{-}18)$$

$$R_2 = \begin{bmatrix} \cos\psi\cos\lambda & \cos\psi\sin\lambda & \sin\psi \\ -\sin\psi\cos\lambda & -\sin\psi\sin\lambda & \cos\psi \\ -\sin\lambda & \cos\lambda & 0 \end{bmatrix} \qquad (4\text{-}19)$$

$$\alpha = \phi - \psi. \qquad (4\text{-}20)$$

The γ_λ component in the two normal gravity vectors, $\vec{\gamma}_E$ and $\vec{\gamma}_S$, in Equation (4-17) is zero since the normal gravity potential is not a function of longitude λ. The definitions for the other two relevant angles depicted in the Inset of Figure 4.2 are:

$$\varepsilon = \theta - \alpha \qquad (4\text{-}21)$$

$$\theta = \arctan\left(\frac{\gamma_\psi}{\gamma_r}\right) \qquad (4\text{-}22)$$

such that $-\pi/2 \le \theta \le \pi/2$.

The equations listed here for the angles ($\alpha, \varepsilon, \theta$) are applicable to both the northern and southern hemispheres. For positive h each of these angles is zero when point P is directly above one of the poles or lies in the equatorial plane. Elsewhere for h > 0 they have the same sign as the geodetic latitude for point P. For h = 0 the angles, α and θ, are equal and $\varepsilon = 0$. Numerical results have indicated that the angular separation (ε) between the component γ_h and the total normal gravity vector $\vec{\gamma}_{total}$ satisfies the inequality, $|\varepsilon| < 4$ arcseconds, for geodetic heights up to 20,000 meters. For completeness the component (γ_ϕ) of the total normal gravity vector $\vec{\gamma}_{total}$ at point P in Figure 4.2 that is orthogonal to γ_h and lies in the meridian plane for point P is given by the expression:

$$\gamma_\phi = -\gamma_r \sin(\alpha) + \gamma_\psi \cos(\alpha). \tag{4-23}$$

The component γ_ϕ has a positive sense northward. For geodetic height h=0 the γ_ϕ component is zero. Numerical testing with whole degree latitudes showed that the magnitude of γ_ϕ remains less than 0.002% of the value of γ_h for geodetic heights up to 20,000 meters. Equations (4-16) and (4-23) provide an alternative way to compute the magnitude $|\vec{\gamma}_{total}|$ of the total normal gravity vector through the equation

$$|\vec{\gamma}_{total}| = \sqrt{\gamma_h^2 + \gamma_\phi^2}\ .$$

In summary then, for near-surface geodetic heights when sub-microgal precision is not necessary, the Taylor series expansion (4-3) for γ_h should suffice. But, when the intended application for γ_h requires high accuracy, Equation (4-4) will be a close approximation to the exact Equation (4-16) for geodetic heights up to 20,000 meters. Of course, γ_h can be computed using the exact Equation (4-16) but this requires that the computational procedure include the two transformations, R_1 and R_2, that are shown in Equation (4-17). Because the difference in results between Equations (4-4) and (4-16) is less than one μgal(10^{-6} gal) for geodetic heights to 20,000 meters, the transformation approach would probably be unnecessary in most situations. For applications requiring pure attraction (attraction without centrifugal force) due to the normal gravitational potential V, the u- and β- vector components of normal gravitation can be computed easily in the ellipsoidal coordinate system by omitting the last term in equations (4-5) and (4-6) respectively. These last attraction terms account for the centrifugal force due to the angular velocity ω of the reference ellipsoid.

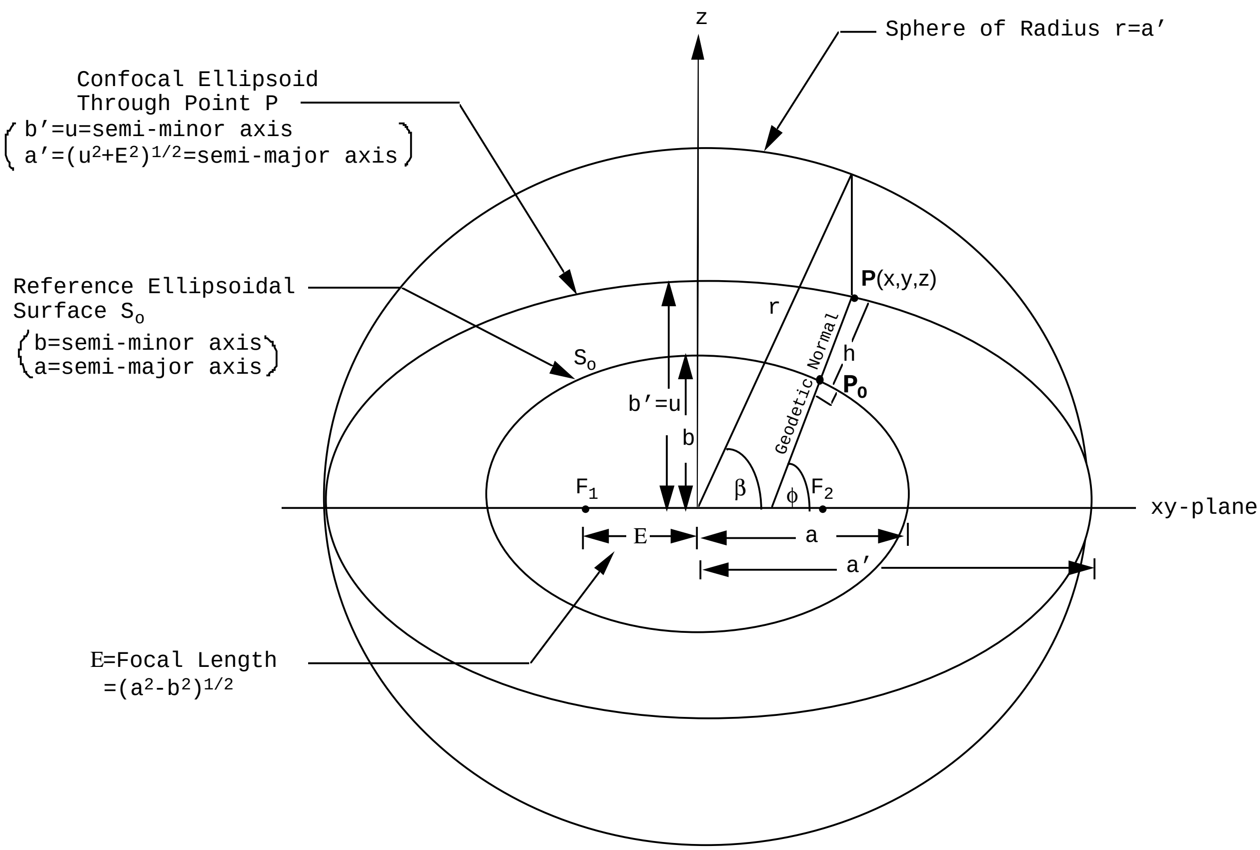

Figure 4.1 Ellipsoidal Coordinates(u,β)

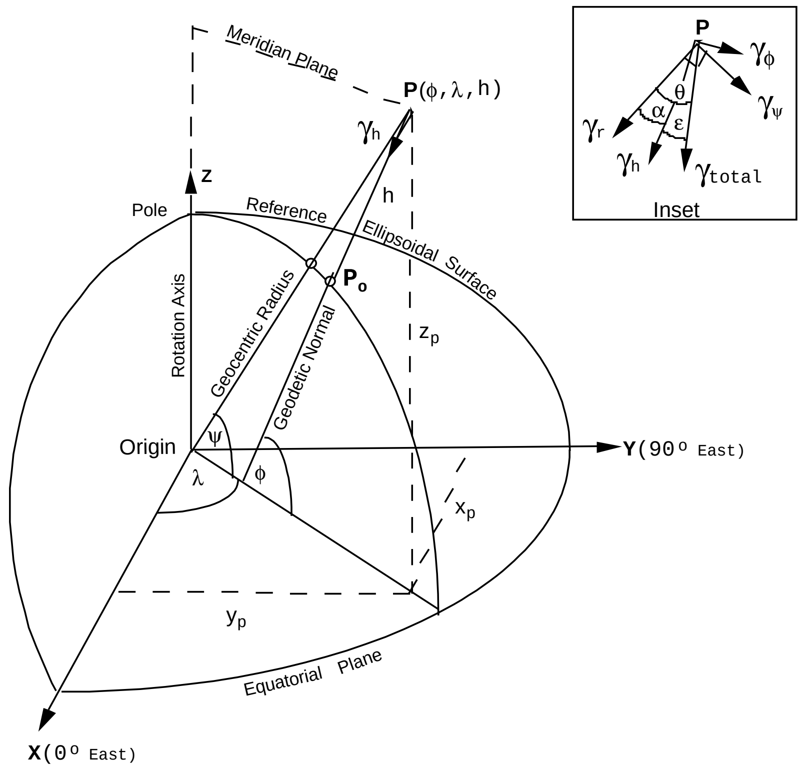

Figure 4.2 Normal Gravity Component γ_h

5. WGS 84 EGM96 Gravitational Modeling

5.1 Earth Gravitational Model (EGM96)

The form of the WGS 84 EGM96 Earth Gravitational Model is a spherical harmonic expansion (Table 5.1) of the gravitational potential (V). The WGS 84 EGM96, complete through degree (n) and order (m) 360, is comprised of 130,321 coefficients.

EGM96 was a joint effort that required NIMA gravity data, NASA/GSFC satellite tracking data, and DoD tracking data in its development. The NIMA effort consisted of developing worldwide 30' and 1° mean gravity anomaly databases from its Point Gravity Anomaly file and 5' x 5' mean GEOSAT Geodetic Mission geoid height file using least-squares collocation with the Forsberg Covariance Model [32] to estimate the final 30' x 30' mean gravity anomaly directly with an associated accuracy. The GSFC effort consisted of satellite orbit modeling by tracking over 30 satellites including new satellites tracked by Satellite Laser Ranging (SLR) , Tracking and Data Relay Satellite System (TDRSS), and GPS techniques, in the development of EGM96S (the satellite only model of EGM96 to degree and order 70). The development of the combination model to 70 x 70 incorporated direct satellite altimetry (TOPEX/POSEIDON, ERS-1, and GEOSAT) with EGM96S and surface gravity normal equations. Major additions to the satellite tracking data used by GSFC included new observations of Lageos, Lageos-2, Ajisai, Starlette, Stella, TOPEX, GPSMET along with GEOS-1 and GEOSAT. Finally, GSFC developed the high degree EGM96 solution by blending the combination solution to degree and order 70 with a block diagonal solution from degree and order 71 to 359 and a quadrature solution at degree and order 360. A complete description of EGM96 can be found in [41].

The EGM96 through degree and order 70 is recommended for high accuracy satellite orbit determination and prediction purposes. An Earth orbiting satellite's sensitivity to the geopotential is strongly influenced by the satellite's altitude range and other orbital parameters. DoD programs performing satellite orbit determination are advised to determine the maximum degree and order that is most appropriate for their particular mission and orbit accuracy requirements.

The WGS 84 EGM96 coefficients through degree and order 18 are provided in Table 5.1 in normalized form. An error covariance matrix is available for those coefficients through degree and order 70 determined from the weighted least squares combination solution. Coefficient sigmas are available to degree and order 360. Gravity anomaly degree variances are given in Table 5.2 for the WGS 84 EGM96 (degree and order 360). Requesters having a need for the full WGS 84 EGM96, its error data and associated software should forward their correspondence to the address listed in the PREFACE.

5.2 Gravity Potential (W)

The Earth's total gravity potential (W) is defined as

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

where Φ is the potential due to the Earth's rotation. If ω is the angular velocity [Equation (3-6)], then

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

where x and y are the geocentric coordinates of a given point in the WGS 84 reference frame (See Figure 2.1).

The gravitational potential function (V) is defined as:

$$V = \frac{GM}{r}\left[1 + \sum_{n=2}^{n_{max}} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^n \overline{P}_{nm}\left(\sin\phi'\right)\left(\overline{C}_{nm}\ \cos m\lambda + \overline{S}_{nm}\ \sin m\lambda\right)\right] \qquad (5\text{-}3)$$

where:

V = Gravitational potential function (m^2/s^2)

GM = Earth's gravitational constant

r = Distance from the Earth's center of mass

a = Semi-major axis of the WGS 84 ellipsoid

n,m = Degree and order, respectively

ϕ' = Geocentric latitude

λ= 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

$$P_{nm}(\sin\phi') = (\cos\phi')^m \frac{d^m}{d(\sin\phi')^m}\left[P_n(\sin\phi')\right]$$

$P_n(\sin\phi')$ = Legendre polynomial

$$= \frac{1}{2^n n!} \frac{d^n}{d(\sin\phi')^n} \left(\sin^2\phi' - 1\right)^n$$

Note:

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

where:

C_{nm}, S_{nm} = Conventional gravitational coefficients
For $m=0$, $k=1$;
$m>1$, $k=2$

The series is theoretically valid for $r \geq a$, though it can be used with probably negligible error near or on the Earth's surface, i.e., $r \geq$ Earth's surface. But the series should not be used for $r <$ Earth's surface.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	**m**	$\bar{C}_{nm}$	$\bar{S}_{nm}$
2	0	-.484165371736E-03	
2	1	-.186987635955E-09	.119528012031E-08
2	2	.243914352398E-05	-.140016683654E-05
3	0	.957254173792E-06	
3	1	.202998882184E-05	.248513158716E-06
3	2	.904627768605E-06	-.619025944205E-06
3	3	.721072657057E-06	.141435626958E-05
4	0	.539873863789E-06	
4	1	-.536321616971E-06	-.473440265853E-06
4	2	.350694105785E-06	.662671572540E-06
4	3	.990771803829E-06	-.200928369177E-06
4	4	-.188560802735E-06	.308853169333E-06
5	0	.685323475630E-07	
5	1	-.621012128528E-07	-.944226127525E-07
5	2	.652438297612E-06	-.323349612668E-06
5	3	-.451955406071E-06	-.214847190624E-06
5	4	-.295301647654E-06	.496658876769E-07
5	5	.174971983203E-06	-.669384278219E-06
6	0	-.149957994714E-06	
6	1	-.760879384947E-07	.262890545501E-07
6	2	.481732442832E-07	-.373728201347E-06
6	3	.571730990516E-07	.902694517163E-08
6	4	-.862142660109E-07	-.471408154267E-06
6	5	-.267133325490E-06	-.536488432483E-06
6	6	.967616121092E-08	-.237192006935E-06
7	0	.909789371450E-07	
7	1	.279872910488E-06	.954336911867E-07
7	2	.329743816488E-06	.930667596042E-07
7	3	.250398657706E-06	-.217198608738E-06
7	4	-.275114355257E-06	-.123800392323E-06
7	5	.193765507243E-08	.177377719872E-07
7	6	-.358856860645E-06	.151789817739E-06
7	7	.109185148045E-08	.244415707993E-07
8	0	.496711667324E-07	

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	**m**	$\overline{C}_{nm}$	$\overline{S}_{nm}$
8	1	.233422047893E-07	.590060493411E-07
8	2	.802978722615E-07	.654175425859E-07
8	3	-.191877757009E-07	-.863454445021E-07
8	4	-.244600105471E-06	.700233016934E-07
8	5	-.255352403037E-07	.891462164788E-07
8	6	-.657361610961E-07	.309238461807E-06
8	7	.672811580072E-07	.747440473633E-07
8	8	-.124092493016E-06	.120533165603E-06
9	0	.276714300853E-07	
9	1	.143387502749E-06	.216834947618E-07
9	2	.222288318564E-07	-.322196647116E-07
9	3	-.160811502143E-06	-.742287409462E-07
9	4	-.900179225336E-08	.194666779475E-07
9	5	-.166165092924E-07	-.541113191483E-07
9	6	.626941938248E-07	.222903525945E-06
9	7	-.118366323475E-06	-.965152667886E-07
9	8	.188436022794E-06	-.308566220421E-08
9	9	-.477475386132E-07	.966412847714E-07
10	0	.526222488569E-07	
10	1	.835115775652E-07	-.131314331796E-06
10	2	-.942413882081E-07	-.515791657390E-07
10	3	-.689895048176E-08	-.153768828694E-06
10	4	-.840764549716E-07	-.792806255331E-07
10	5	-.493395938185E-07	-.505370221897E-07
10	6	-.375885236598E-07	-.795667053872E-07
10	7	.811460540925E-08	-.336629641314E-08
10	8	.404927981694E-07	-.918705975922E-07
10	9	.125491334939E-06	-.376516222392E-07
10	10	.100538634409E-06	-.240148449520E-07
11	0	-.509613707522E-07	
11	1	.151687209933E-07	-.268604146166E-07
11	2	.186309749878E-07	-.990693862047E-07
11	3	-.309871239854E-07	-.148131804260E-06
11	4	-.389580205051E-07	-.636666511980E-07
11	5	.377848029452E-07	.494736238169E-07

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	**m**	$\overline{C}_{nm}$	$\overline{S}_{nm}$
11	6	-.118676592395E-08	.344769584593E-07
11	7	.411565188074E-08	-.898252808977E-07
11	8	-.598410841300E-08	.243989612237E-07
11	9	-.314231072723E-07	.417731829829E-07
11	10	-.521882681927E-07	-.183364561788E-07
11	11	.460344448746E-07	-.696662308185E-07
12	0	.377252636558E-07	
12	1	-.540654977836E-07	-.435675748979E-07
12	2	.142979642253E-07	.320975937619E-07
12	3	.393995876403E-07	.244264863505E-07
12	4	-.686908127934E-07	.415081109011E-08
12	5	.309411128730E-07	.782536279033E-08
12	6	.341523275208E-08	.391765484449E-07
12	7	-.186909958587E-07	.356131849382E-07
12	8	-.253769398865E-07	.169361024629E-07
12	9	.422880630662E-07	.252692598301E-07
12	10	-.617619654902E-08	.308375794212E-07
12	11	.112502994122E-07	-.637946501558E-08
12	12	-.249532607390E-08	-.111780601900E-07
13	0	.422982206413E-07	
13	1	-.513569699124E-07	.390510386685E-07
13	2	.559217667099E-07	-.627337565381E-07
13	3	-.219360927945E-07	.974829362237E-07
13	4	-.313762599666E-08	-.119627874492E-07
13	5	.590049394905E-07	.664975958036E-07
13	6	-.359038073075E-07	-.657280613686E-08
13	7	.253002147087E-08	-.621470822331E-08
13	8	-.983150822695E-08	-.104740222825E-07
13	9	.247325771791E-07	.452870369936E-07
13	10	.410324653930E-07	-.368121029480E-07
13	11	-.443869677399E-07	-.476507804288E-08
13	12	-.312622200222E-07	.878405809267E-07
13	13	-.612759553199E-07	.685261488594E-07
14	0	-.242786502921E-07	
14	1	-.186968616381E-07	.294747542249E-07

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	m	$\overline{C}_{nm}$	$\overline{S}_{nm}$
14	2	-.367789379502E-07	-.516779392055E-08
14	3	.358875097333E-07	.204618827833E-07
14	4	.183865617792E-08	-.226780613566E-07
14	5	.287344273542E-07	-.163882249728E-07
14	6	-.194810485574E-07	.247831272781E-08
14	7	.375003839415E-07	-.417291319429E-08
14	8	-.350946485865E-07	-.153515265203E-07
14	9	.320284939341E-07	.288804922064E-07
14	10	.390329180008E-07	-.144308452469E-08
14	11	.153970516502E-07	-.390548173245E-07
14	12	.840829163869E-08	-.311327189117E-07
14	13	.322147043964E-07	.451897224960E-07
14	14	-.518980794309E-07	-.481506636748E-08
15	0	.147910068708E-08	
15	1	.100817268177E-07	.109773066324E-07
15	2	-.213942673775E-07	-.308914875777E-07
15	3	.521392929041E-07	.172892926103E-07
15	4	-.408150084078E-07	.650174707794E-08
15	5	.124935723108E-07	.808375563996E-08
15	6	.331211643896E-07	-.368246004304E-07
15	7	.596210699259E-07	.531841171879E-08
15	8	-.322428691498E-07	.221523579587E-07
15	9	.128788268085E-07	.375629820829E-07
15	10	.104688722521E-07	.147222147015E-07
15	11	-.111675061934E-08	.180996198432E-07
15	12	-.323962134415E-07	.155243104746E-07
15	13	-.283933019117E-07	-.422066791103E-08
15	14	.519168859330E-08	-.243752739666E-07
15	15	-.190930538322E-07	-.471139421558E-08
16	0	-.315322986722E-08	
16	1	.258360856231E-07	.325447560859E-07
16	2	-.233671404512E-07	.288799363439E-07
16	3	-.336019429391E-07	-.220418988010E-07
16	4	.402316284314E-07	.483837716909E-07
16	5	-.129501939245E-07	-.319458578129E-08

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	**m**	$\overline{C}_{nm}$	$\overline{S}_{nm}$
16	6	.140239252323E-07	-.350760208303E-07
16	7	-.708412635136E-08	-.881581561131E-08
16	8	-.209018868094E-07	.500527390530E-08
16	9	-.218588720643E-07	-.395012419994E-07
16	10	-.117529900814E-07	.114211582961E-07
16	11	.187574042592E-07	-.303161919925E-08
16	12	.195400194038E-07	.666983574071E-08
16	13	.138196369576E-07	.102778499508E-08
16	14	-.193182168856E-07	-.386174893776E-07
16	15	-.145149060142E-07	-.327443078739E-07
16	16	-.379671710746E-07	.302155372655E-08
17	0	.197605066395E-07	
17	1	-.254177575118E-07	-.306630529689E-07
17	2	-.195988656721E-07	.649265893410E-08
17	3	.564123066224E-08	.678327095529E-08
17	4	.707457075637E-08	.249437600834E-07
17	5	-.154987006052E-07	.660021551851E-08
17	6	-.118194012847E-07	-.289770975177E-07
17	7	.242149702381E-07	-.422222973697E-08
17	8	.388442097559E-07	.358904095943E-08
17	9	.381356493231E-08	-.281466943714E-07
17	10	-.388216085542E-08	.181328176508E-07
17	11	-.157356600363E-07	.106560649404E-07
17	12	.288013010655E-07	.203450136084E-07
17	13	.165503425731E-07	.204667531435E-07
17	14	-.141983872649E-07	.114948025244E-07
17	15	.542100361657E-08	.532610369811E-08
17	16	-.301992205043E-07	.365331918531E-08
17	17	-.343086856041E-07	-.198523455381E-07
18	0	.508691038332E-08	
18	1	.721098449649E-08	-.388714473013E-07
18	2	.140631771205E-07	.100093396253E-07
18	3	-.507232520873E-08	-.490865931335E-08
18	4	.548759308217E-07	-.135267117720E-08
18	5	.548710485555E-08	.264338629459E-07

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.1
EGM96
Earth Gravitational Model
Truncated at n=m=18

Degree and Order		Normalized Gravitational Coefficients	
n	**m**	$\overline{C}_{nm}$	$\overline{S}_{nm}$
18	6	.146570755271E-07	-.136438019951E-07
18	7	.675812328417E-08	.688577494235E-08
18	8	.307619845144E-07	.417827734107E-08
18	9	-.188470601880E-07	.368302736953E-07
18	10	.527535358934E-08	-.466091535881E-08
18	11	-.729628518960E-08	.195215208020E-08
18	12	-.297449412422E-07	-.164497878395E-07
18	13	-.627919717152E-08	-.348383939938E-07
18	14	-.815605336410E-08	-.128636585027E-07
18	15	-.405003412879E-07	-.202684998021E-07
18	16	.104141042028E-07	.661468817624E-08
18	17	.358771586841E-08	.448065587564E-08
18	18	.312351953717E-08	-.109906032543E-07

E-03=X10 $^{-3}$;E-05=X10^{-5};etc.

Table 5.2
EGM96 Gravity Anomaly Degree Variances

Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance
2	7.6	39	3.3	76	2.7	113	2.7
3	33.9	40	2.8	77	2.9	114	3.0
4	19.8	41	3.1	78	2.9	115	3.1
5	21.0	42	3.4	79	3.0	116	2.6
6	19.7	43	3.0	80	2.8	117	2.7
7	19.6	44	3.0	81	3.5	118	2.8
8	11.2	45	3.4	82	4.0	119	2.8
9	11.2	46	3.8	83	3.7	120	2.7
10	9.8	47	3.7	84	3.0	121	2.5
11	6.6	48	3.2	85	2.9	122	2.2
12	2.7	49	2.7	86	3.4	123	2.7
13	7.9	50	3.6	87	3.0	124	2.4
14	3.5	51	3.0	88	2.9	125	2.8
15	3.7	52	3.1	89	2.8	126	2.8
16	4.1	53	4.0	90	2.4	127	3.0
17	3.2	54	3.6	91	3.1	128	2.2
18	3.9	55	3.2	92	3.0	129	2.4
19	3.2	56	3.8	93	3.0	130	2.2
20	3.1	57	3.8	94	3.1	131	2.3
21	3.7	58	3.0	95	3.0	132	2.2
22	3.5	59	3.6	96	2.4	133	2.5
23	3.1	60	3.2	97	2.9	134	2.3
24	2.4	61	3.1	98	3.2	135	2.3
25	3.1	62	3.3	99	2.7	136	2.4
26	2.4	63	3.2	100	2.8	137	2.3
27	1.7	64	2.8	101	2.1	138	2.6
28	3.0	65	2.7	102	2.9	139	2.1
29	2.6	66	3.2	103	3.5	140	2.4
30	2.9	67	3.2	104	2.8	141	2.2
31	2.7	68	3.2	105	2.4	142	1.8
32	2.7	69	3.4	106	2.8	143	2.1
33	3.0	70	2.5	107	2.7	144	2.3
34	4.0	71	2.6	108	2.9	145	2.0
35	3.9	72	3.4	109	2.8	146	2.0
36	3.3	73	2.8	110	3.3	147	2.1
37	3.5	74	3.7	111	2.9	148	2.0
38	3.0	75	2.9	112	2.5	149	2.0

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

Table 5.2
EGM96 Gravity Anomaly Degree Variances

Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance
150	1.9	187	1.5	224	1.1	261	.7
151	2.3	188	1.5	225	1.0	262	.6
152	1.9	189	1.3	226	1.1	263	.7
153	2.0	190	1.3	227	.9	264	.6
154	1.7	191	1.4	228	1.0	265	.6
155	2.1	192	1.6	229	1.1	266	.7
156	1.9	193	1.5	230	1.0	267	.7
157	1.9	194	1.3	231	1.1	268	.6
158	1.7	195	1.4	232	1.1	269	.6
159	2.0	196	1.3	233	1.0	270	.6
160	1.7	197	1.3	234	1.0	271	.7
161	1.8	198	1.4	235	1.0	272	.6
162	2.0	199	1.3	236	1.0	273	.5
163	2.0	200	1.3	237	.9	274	.6
164	1.9	201	1.3	238	.9	275	.6
165	2.1	202	1.2	239	.9	276	.6
166	1.9	203	1.2	240	.9	277	.5
167	2.0	204	1.3	241	.9	278	.6
168	2.1	205	1.1	242	.9	279	.6
169	1.8	206	1.2	243	.8	280	.6
170	1.9	207	1.2	244	.8	281	.6
171	1.9	208	1.2	245	.9	282	.6
172	1.6	209	1.2	246	.9	283	.6
173	1.7	210	1.4	247	.8	284	.5
174	2.0	211	1.2	248	.7	285	.5
175	1.7	212	1.2	249	.8	286	.5
176	1.5	213	1.1	250	.9	287	.5
177	1.6	214	1.3	251	.8	288	.5
178	1.5	215	1.1	252	.9	289	.5
179	1.8	216	1.1	253	.8	290	.5
180	1.7	217	1.1	254	.7	291	.5
181	1.5	218	1.1	255	.8	292	.5
182	1.6	219	1.3	256	.7	293	.5
183	1.5	220	1.1	257	.7	294	.5
184	1.6	221	1.1	258	.7	295	.5
185	1.4	222	1.1	259	.7	296	.5
186	1.5	223	1.0	260	.7	297	.5

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

Table 5.2
EGM96 Gravity Anomaly Degree Variances

Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance	Degree	Degree Variance
298	.4	314	.4	330	.3	346	.3
299	.4	315	.4	331	.3	347	.3
300	.5	316	.4	332	.3	348	.3
301	.5	317	.4	333	.3	349	.3
302	.4	318	.5	334	.3	350	.3
303	.5	319	.4	335	.3	351	.3
304	.4	320	.4	336	.3	352	.3
305	.4	321	.4	337	.3	353	.3
306	.4	322	.4	338	.3	354	.3
307	.4	323	.4	339	.3	355	.3
308	.4	324	.4	340	.3	356	.3
309	.5	325	.4	341	.4	357	.3
310	.4	326	.4	342	.3	358	.3
311	.4	327	.3	343	.3	359	.3
312	.4	328	.4	344	.3	360	.3
313	.4	329	.3	345	.3		

The formula for computing gravity anomaly degree variances (c_n) is:

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

$\bar{\gamma}$ = Mean value of theoretical gravity (979764.32222 mgal).

$\bar{C}_{nm}, \bar{S}_{nm}$ = normalized gravitational coefficients of degree (n) and order (m).

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

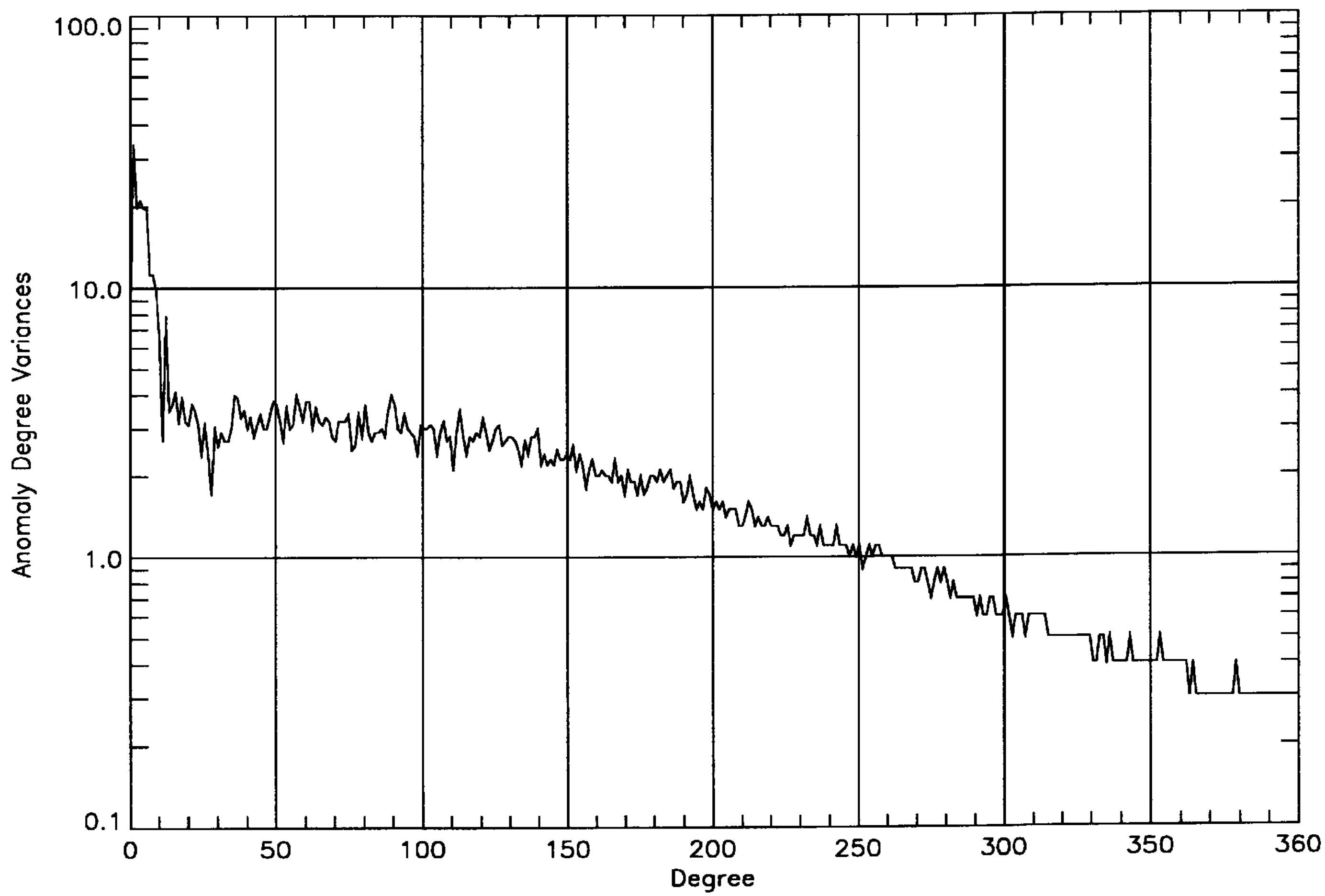

FIGURE 5.1: Plot of Anomaly degree Variances

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

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6. WGS 84 EGM96 GEOID

6.1 General

In geodetic applications three primary reference surfaces for the Earth are used: 1) the Earth's topographic surface, 2) the geometric surface taken to be an ellipsoid of revolution, and 3) the geoid.

When the gravity potential (W) is a constant, equation (6-1), defines a family of equipotential surfaces (geops) [33] of the Earth's gravity field. The geoid is that particular geop that is closely associated with the mean ocean surface.

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

Traditionally, when a geoid is developed, the constant (W), representing the potential anywhere on this surface, is constrained or assumed to be equal to the normal potential (U_0) of a 'best-fitting' ellipsoid. Throughout this refinement effort, however, the authors recognize that the WGS 84 ellipsoid no longer represents a true 'best-fitting' ellipsoid. The difference between the WGS 84 semi-major axis and the current 'best-fitting' value is 0.54 m. In terms of the geoid, this effect is handled through application of a 'zero-order' undulation (N_0) of the geoid. With this approach, the WGS 84 ellipsoid can be retained with no introduction of any additional errors by not using the "best-fitting" ellipsoid.

In common practice the geoid is expressed at a given point in terms of the distance above (+N) or below (-N) the ellipsoid. For practical reasons, the geoid has been used to serve as a vertical reference surface for mean sea level (MSL) heights. In areas where elevation data are not available from conventional leveling, an approximation of mean sea level heights, using orthometric heights, can be obtained from the following equation [33]:

$$h = H + N \qquad (6\text{-}2)$$
$$H = h - N \qquad (6\text{-}3)$$

where:

h = geodetic height (height relative to the ellipsoid)
N = geoid undulation
H = orthometric height (height relative to the geoid)

Alternatively, some countries replace orthometric heights with normal heights and geoid undulations with height anomalies. This use of height anomalies eliminates assumptions about the density of masses between the geoid and the ground. Therefore, equation (6-2) can be re-formulated as:

$$h = H + N = H^* + \zeta \quad (6\text{-}4)$$

where:

H^* = normal height

ζ = height anomaly

The telluroid is a surface defined where the normal potential U at every point Q is equal to the actual potential W at its corresponding point P on the Earth's surface [33]. The height anomaly is the distance between point Q on the telluroid and point P on the Earth's surface.

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

6.2 Formulas, Representations and Analysis

A significant departure from past practices has been implemented in the determination of geoid undulations. The WGS 84 EGM96 Geoid Undulations are based on height anomalies calculated from the WGS 84 EGM96 spherical harmonic coefficients complete to degree and order 360. To transform from height anomalies to geoid undulations, the zero degree undulation term of -0.53 meters, and the WGS 84 EGM96 correction coefficients through degree and order 360 are applied [34]. The value of -0.53 meters is based on the difference between an "ideal" Earth ellipsoid in a tide free system and the WGS 84 ellipsoid. The "ideal" ellipsoid was defined from the report of the International Association of Geodesy (IAG) Special Commission on Fundamental Constants [23]. The "ideal" Earth ellipsoid, in a 'tide-free' system, is defined by a = 6378136.46 meters and 1/f = 298.25765.

6.2.1 Formulas

The formula for calculating the WGS 84 EGM96 Geoid Undulations starts with the calculation of the height anomaly ζ [34]:

$$\zeta(\phi,\lambda,r) = \frac{GM}{\gamma(\phi)r}\left[\sum_{n=2}^{m}\left(\frac{a}{r}\right)^{n}\sum_{m=0}^{n}\left(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda\right)\bar{P}_{nm}(\sin\phi)\right] \quad (6\text{-}5)$$

where: $\overline{C}_{nm}$ and $\overline{S}_{nm}$ are the fully normalized potential coefficients of degree n and order m from EGM96. Equation (6-5) is evaluated at a point P(ϕ,λ,r) on or above the surface of the earth:

GM = The Earth's gravitational constant

r = Geocentric distance to the point P

a = Semi-major axis of the reference ellipsoid.

ϕ = Geocentric latitude

All quantities in formula (6-5) are defined for the WGS 84 EGM96 with one exception. In equation (6-5), the even zonal coefficients of subscripts 2 through 10 are coefficient differences between the dynamic WGS84 EGM96 and geometrically implied coefficients.

$$\overline{C}_{n,0} = \overline{C}_{n,0(dynamic)} - \overline{C}_{n,0(geometric)}$$

Table 6.1
Geometric Coefficients

$\overline{C}_{2,0(geometric)}$	-0.484166774985E-03
$\overline{C}_{4,0(geometric)}$	0.790303733511E-06
$\overline{C}_{6,0(geometric)}$	-0.168724961151E-08
$\overline{C}_{8,0(geometric)}$	0.346052468394E-11
$\overline{C}_{10,0(geometric)}$	-0.265002225747E-14

To calculate the geoid undulation N(in meters) we use the formula [41]:

$$N(\phi,\lambda) = N_0 + \zeta(\phi,\lambda,r) + \frac{\Delta g_{BA}(\phi,\lambda)}{\overline{\gamma}} H(\phi,\lambda) \qquad (6\text{-}6)$$

where:

N_0 = -0.53 meters (zero degree term)

and the parameters to compute the correction term discussed in section 6.2 above are:

$\Delta g_{BA}(\phi,\lambda)$ = Bouguer gravity anomaly from EGM96

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

$H(\phi,\lambda)$ = defined from harmonic analysis of JGP95E (Joint Gravity Project 95) elevation database

The Bouguer anomaly can be computed from the EGM96 spherical harmonic set and the harmonic analysis of the JGP95E elevation database. JGP95E is the worldwide 5' digital elevation file developed by NIMA and NASA/GSFC from best available sources for the EGM96 project.

$$\Delta g_{BA}(\phi,\lambda) = \Delta g_{FA}(\phi,\lambda) - 0.1119 \times H(\phi,\lambda) \qquad (6\text{-}7)$$

where:

$\Delta g_{FA}(\phi,\lambda)$ = Free-air gravity anomaly from EGM96

6.2.2 Permanent Tide Systems

In the calculation of geoid undulations from the EGM96 Geopotential Model the second degree zonal coefficient is given in the tide-free system. The tide-free definition means that any geoid undulations calculated from EGM96 exist for a tide-free Earth with all (direct and indirect) effects of the sun and moon removed. Other geoids to consider are the mean geoid (geoid which would exist in the presence of the sun and moon) and the zero geoid (geoid which exists if the permanent direct effects of the sun and moon are removed but the indirect effect related to the Earth's elastic deformation is retained). A complete set of equations to convert from one tide system to another can be found in [35].

To calculate the geoid in the zero tide system use the formula:

$$N_Z = N_n + 2.97 - 8.88 \sin^2 \phi \text{ cm} \qquad (6\text{-}8)$$

where:

N_Z = zero-tide geoid

N_n = tide-free geoid

6.2.3 Representations and Analysis

The geoid undulations 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 EGM96 Geoid Undulation Contour Chart developed from a worldwide 15'x15' grid of geoid undulations calculated by using WGS 84 parameters and the WGS 84 EGM96 coefficients through n=m=360 in Equation (6-6).

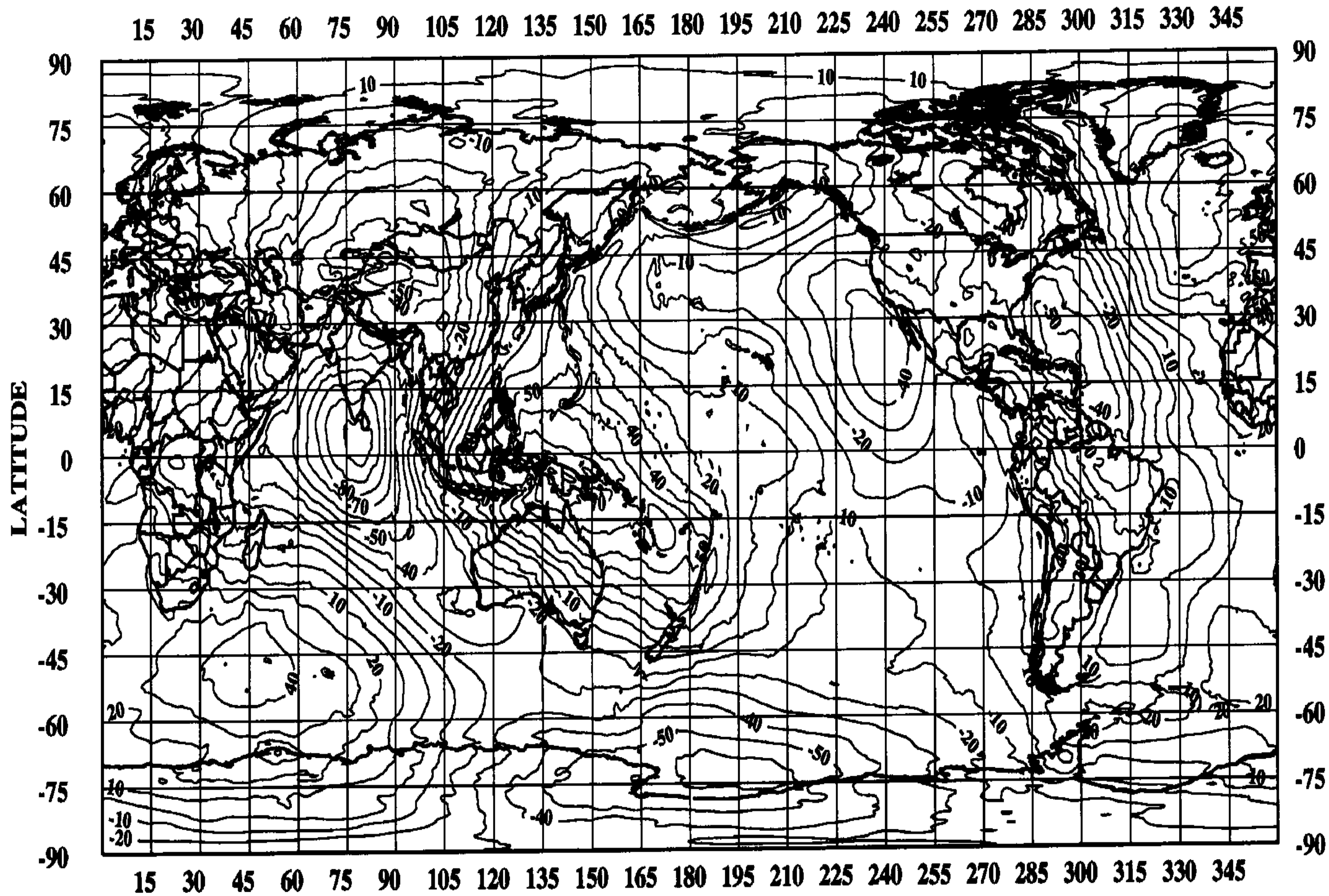

FIGURE 6.1 EGM96 Geoid(n=m=360) Referenced to WGS 84 Ellipsoid;Units = Meters

The WGS 84 EGM96 Geoid Undulations, taken worldwide on the basis of a 15’x15’ grid, exhibit the following statistics:

Mean	=	-0.57 meters
Standard Deviation	=	30.56 meters
Minimum	=	-106.99 meters
Maximum	=	85.39 meters

Location of	Minimum: ϕ	=	4.75° N ,	λ =	78.75° E
	Maximum: ϕ	=	8.25° S ,	λ =	147.25° E

This standard deviation indicates the typical difference between the geoid and the reference ellipsoid.

The WGS 84 EGM96 Geoid Undulations have an error range of +0.5 to +1.0 meters (one sigma) worldwide.

6.3 Availability of WGS 84 EGM96 Data Products

The WGS 84 EGM96 standard products are:

- A 15’ x 15’ WGS 84 EGM96 Geoid Undulation file calculated from equation (6-6).

- The EGM96 spherical harmonic coefficients complete to degree and order 360.

Additional information on the WGS 84 EGM96 Geoid Undulations, associated software and data files can be obtained from the location and addresses in the PREFACE.

7. WGS 84 RELATIONSHIPS WITH OTHER GEODETIC SYSTEMS

7.1 General

One of the principal purposes of a world geodetic system is to eliminate the use of local horizontal geodetic datums. Although the number of local horizontal geodetic datums, counting island and astronomic-based datums, exceeds several hundred, the number of local horizontal datums in current use is significantly less and continues to decrease. Until a global geodetic datum is accepted, used and implemented worldwide, a means to convert between geodetic datums is required. 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 a local geodetic datum to WGS datum shift can be computed. Satellite stations positioned within WGS 84, with known local geodetic datum coordinates, were the basic ingredients in the development of local geodetic datum to WGS 84 datum shifts.

Local horizontal datums were developed in the past to satisfy mapping and navigation requirements for specific regions of the Earth. A geocentric datum of large geographic extent is the North American Datum 1983 (NAD 83). In the past couple of decades, development of global geocentric datums has become possible. WGS 84 and the ITRF are examples of such datums.

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 GPS positioning techniques. Direct occupation of the site is not always possible or warranted. In these cases, a datum transformation can be used to convert coordinates from the local system to WGS 84.

7.2 Relationship of WGS 84 to the ITRF

As discussed in Chapter 2, the WGS 84 is consistent with ITRF. The differences between WGS 84 and ITRF are in the centimeter range worldwide. Therefore, for all mapping and charting purposes, they can be considered the same.

In recent years, some countries and regions have been converting to datums based on the ITRF. Such national or regional datums that are rigorously based on the ITRF can also be considered as identical to WGS 84. An example of such a datum is the European Terrestrial Reference Frame 1989 (EUREF89).

7.3 Relationship of WGS 84 to NAD 83

The North American Datum 1983 (NAD 83) is a geocentric datum that was established in 1986 for the United States, Canada, Mexico, Central America and the Caribbean Islands. Hawaii and Greenland were also connected to this datum. It is based on a horizontal adjustment of conventional survey data and the inclusion of Transit Satellite Doppler data and Very Long Baseline Interferometry (VLBI) data. The global Doppler and VLBI observations were used to orient the NAD 83 reference frame to the BIH Terrestrial System of 1984. The orientation of the ECEF coordinate axes of the NAD 83 reference frame is identical to that of the *original* WGS 84 reference frame.

NAD 83 uses the Geodetic Reference System 1980 (GRS 80) ellipsoid as its reference ellipsoid with the geometric center of the ellipsoid coincident with the center of mass of the Earth and the origin of the coordinate system. The semi-major axis and flattening parameters are adopted directly as

$$a = 6378137 \text{ m}$$
$$1/f = 298.257222101$$

The WGS 84 ellipsoid is for all practical purposes identical to the GRS 80 ellipsoid. They use the same value for the semi-major axis and have the same orientation with respect to the center of mass and the coordinate system origin. However, WGS 84 uses a derived value for the flattening that is computed from the normalized second-degree zonal harmonic gravitational coefficient $\overline{C}_{2,0}$. $\overline{C}_{2,0}$ was derived from the GRS 80 value for J_2 and truncated to 8 significant digits as:

$$\overline{C}_{2,0} = -J_2/(5)^{1/2}. \qquad (7\text{-}1)$$

The resulting WGS 84 value for 1/f is 298.257223563. The difference between the GRS 80 and WGS 84 values for f creates a difference of 0.1 mm in the derived semi-minor axes of the two ellipsoids.

Based on these definitions, geodetic positions determined with respect to NAD 83 or WGS 84 have uncertainties of about one meter in each component. For mapping, charting and navigation, the two systems are indistinguishable at scales of 1:5,000 or smaller and with accuracies of about 2 m. Note that the National Map Accuracy Standard requires points to be horizontally accurate to 0.51 mm (1/50 in.) for scales of 1:20,000 or larger and 0.84 mm (1/30 in.) for scales less than 1:20,000. For example, this corresponds to 2.5 m at 1:5,000 and 42 m at 1:50,000. For geodetic applications, one can expect to see a difference of a meter or more between the WGS 84 and NAD 83 positions of the same point. This is due to the uncertainty associated with each independent determination and the fact that the errors are additive when comparing the difference in the coordinates.

WGS 84 has undergone several enhancements since its original definition. The practical realization of the reference frame is determined by a network of permanent GPS tracking stations which are aligned with the ITRF, the successor to the BIH Terrestrial System, through a globally distributed set of stations with very high accuracy

ITRF coordinates. The improved WGS 84 reference frame is coincident with the ITRF at the 5 cm level. WGS 84 geodetic positions can be determined with uncertainties at the 25-50 cm level or better in a component depending upon the technique. These enhancements have had no effect on mapping, charting and navigation applications since they are at the meter level or smaller.

Meanwhile, the NOAA's National Geodetic Survey has established High Accuracy Reference Networks (HARNs) in many states in the U.S. using GPS techniques. HARNs in effect represent an upgrading of the original NAD 83 geodetic control networks. The new networks have relative accuracies 1-2 orders of magnitude better than the original networks that define NAD 83. Each state's HARN is adjusted separately but is tied to a national network of the highest accuracy points. There can be differences of 0.3 to 0.8 m between the original NAD 83 coordinates and the new ones. Thus, although both NAD 83 and WGS 84 have undergone improvements in accuracy and precision, coordinates determined in one system will differ from coordinates determined in the other system for a specific point. These differences may be on the order of one meter or less and are due to systematic differences of the reference frames combined with random errors associated with the GPS observations.

7.4 Local Geodetic Datum to WGS 84 Datum Transformations

For most applications and DoD operations involving maps, charts, navigation and geospatial information, WGS 84 coordinates will be obtained from a Local Geodetic Datum to WGS 84 Datum Transformation. This transformation can be performed in curvilinear (geodetic) coordinates:

$$\begin{aligned} \phi_{WGS\,84} &= \phi_{Local} + \Delta\phi \\ \lambda_{WGS\,84} &= \lambda_{Local} + \Delta\lambda \\ h_{WGS\,84} &= h_{Local} + \Delta h \end{aligned} \qquad (7\text{-}2)$$

where $\Delta\phi$, $\Delta\lambda$, Δh are provided by the Standard Molodensky transformation formulas [36], [37]:

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

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

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

where: ϕ, λ, h = geodetic coordinates (old ellipsoid)

ϕ = 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).

λ = 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).

$h = N + H$

where:

h = geodetic height (height relative to the ellipsoid)

N = geoid height

H = orthometric height (height relative to the geoid)

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

NOTE: AS "h's" ARE NOT AVAILABLE FOR LOCAL GEODETIC DATUMS, THE Δh CORRECTION WILL NOT BE APPLICABLE WHEN TRANSFORMING TO WGS 84.

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

a = semi-major axis of the local geodetic datum ellipsoid.

b = semi-minor 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 semi-major 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.

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

R_M = radius of curvature in the meridian.

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

NOTE: All Δ-quantities are formed by subtracting local geodetic datum ellipsoid values from WGS 84 Ellipsoid values.

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

Appendix B contains horizontal transformation parameters for the geodetic datums/systems which have been generated from satellite ties to the local geodetic control. Due to the errors and distortion that affect most local geodetic datums, use of mean datum shifts (ΔX, ΔY, ΔZ) 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.

Updates to the datum transformation parameters are identified through the use of cycle numbers and issue dates. Cycle numbers have been set to the numerical value of zero for all datum transformations appearing in the August 1993 Insert 1 and the WGS 84 TR8350.2 Second Edition. All new datum transformations will carry a cycle number of zero. As updates are made the cycle number will increment by one.

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

7.5 Datum Transformation Multiple Regression Equations (MRE)

The development of Local Geodetic Datum to WGS 84 Datum Transformation Multiple Regression Equations [38] was initiated to obtain better fits over continental size land areas than could be achieved using the Standard Molodensky formula with datum shifts (ΔX, ΔY, ΔZ).

For $\Delta\phi$, the general form of the Multiple Regression Equation is (also see [38]):

$$\Delta\phi = A_0 + A_1 U + A_2 V + A_3 U^2 + A_4 UV + A_5 V^2 + ... + A_{99} U^9 V^9 \quad (7\text{-}3)$$

where:

A_0 = constant

$A_0, A_1, ... A_{n n}$ = 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

ϕ, λ = local geodetic latitude and local geodetic longitude (in degrees), respectively, of the computation point

ϕ_m, λ_m = mid-latitude and mid-longitude values, respectively, of the local geodetic datum area (in degrees).

Similar equations are obtained for $\Delta\lambda$ and Δh by replacing $\Delta\phi$ in the left portion of Equation (7-3) by $\Delta\lambda$ and Δh, 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 MREs lies in modeling of distortion for better fit in geodetic applications. However, caution must be used to ensure that MREs are not extrapolated outside of the area of intended use. Large distortions can be realized in very short distances outside of the area where the stations that were used in the development of the MREs exist.

7.6 WGS 72 to WGS 84

See Appendix E.

8. ACCURACY OF WGS 84 COORDINATES

8.1 Discussion

Numerous techniques now exist to establish WGS 84 coordinates for a given site. The accuracy and precision achieved by these various techniques vary significantly. The most common, currently-available techniques are listed below:

- General geodetic solution for station coordinates, orbits, and other parameters of interest.

- Direct geodetic point positioning at a stationary, solitary station using a 'geodetic-quality', dual frequency GPS receiver and NIMA Precise Ephemerides and Satellite Clock states (note that the effects of Selective Availability (SA) must be removed).

- Same as above but using the Broadcast GPS Ephemerides and Clock States.

- GPS differential (baseline) processing from known WGS 84 sites

- GPS Precise Positioning Service (PPS) navigation solutions
  - Instantaneous
  - Mean over some averaging interval

- GPS Standard Positioning Service (SPS) navigation solutions
  - Instantaneous
  - Mean over some averaging interval

- Photogrammetrically-derived coordinates from NIMA products

- Map-derived coordinates from digital or paper NIMA products

Clearly, the above positioning techniques do not provide WGS 84 coordinates with uniform accuracy and statistical properties. Even within a given technique, accuracy variations can occur, due for example, to the treatment of certain error sources such as the troposphere. Because of these variations and periodic algorithm improvements, full characterization of the accuracy achieved by all the above techniques would be quite challenging and beyond the scope of this document.

In the terminology of Chapter 2, a network of stations obtained from one of these techniques yields a unique realization of the WGS 84 reference frame. Currently, within the DoD, almost all operational geodetic survey requirements can be met with direct geodetic point positioning with GPS. The NIMA-developed technique [39] which performs this function has been demonstrated to achieve an accuracy at a single station of:

1994-present: 30 cm (1σ), in each of the 3 position components (ϕ,λ,h)

1989-1994: 100 cm (1σ), in each of the 3 position components (ϕ,λ,h)

Under special circumstances, such as the refinement of the permanent DoD GPS tracking network coordinates, a general geodetic solution is performed where the positions of the entire permanent global DoD network are estimated simultaneously with many other parameters. This type of special technique, which was used to develop the WGS 84 (G873) reference frame, has demonstrated an accuracy of:

5cm (1σ), in each of the 3 position components (ϕ,λ,h)

Other techniques which are based on older, previously-established survey coordinates can also yield 'WGS 84' coordinates with limited accuracy. These techniques may be suitable for certain mapping applications but must be treated very cautiously if a high level of accuracy is required. Some of these alternate techniques to obtain WGS 84 coordinates are listed below:

TRANSIT Point Positioning directly in WGS 84 (1σ= 1-2 m)

TRANSIT Point Positions transformed from NSWC-9Z2

GPS differential (baseline) processing from a known (TRANSIT-determined) WGS 84 geodetic point position

By a WGS 72 to WGS 84 Coordinate Transformation

By a Local Geodetic Datum to WGS 84 Datum Transformation

Because geospatial information within the DoD often originates from multiple sources and processes, the absolute accuracy of a given WGS 84 position becomes very important when information from these various sources is combined in 'Geographic Information Systems' or 'geospatial databases'. Because of their high fidelity, surveyed WGS 84 geodetic control points can often serve to improve or validate the accuracy of maps, image products or other geospatial information. Even GPS navigation solutions can serve a similar role, as long as the accuracy of these solutions is well-understood.

8.2 Summary

In summary, while WGS 84 provides a common global framework for all geospatial information within the DoD, the accuracy of each 'layer' of information depends largely on the metric fidelity of the process used to collect that information. WGS 84 surveyed control points provide an accuracy level which meets or exceeds all current operational DoD requirements.

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9. IMPLEMENTATION GUIDELINES

9.1 Introduction

WGS 84 represents the current state-of-the-art DoD operational reference system which has been derived from the best available satellite tracking, satellite altimeter and surface gravity data. It supports the most stringent accuracy requirements for geodetic positioning, navigation and mapping within DoD. It is the policy of NIMA to continually improve components of the WGS 84 system to maintain it as a state-of-the-art DoD operational World Geodetic System. This will lead to improvements in the definition and realization of the system as:

- The basic tracking stations which are used are updated, repositioned or their number is increased.
- Additional data makes it possible to improve the accuracy of individual local datum relationships to WGS 84.
- Additional surface gravity data become available in various areas of the world to improve the gravity and geoid models.

The current definition of WGS 84 recognizes the continually changing physical Earth, shifting of internal masses and continental plate motions, and accommodates this time dependency in its definition through a plate motion model. For the high accuracy geodetic positioning requirements, this requires a time epoch to be defined for all station coordinates, since they are in continual motion. As mentioned previously in this report, the coordinates of the fixed GPS tracking stations (WGS 84(G873)) were implemented into the production of the NIMA precise orbits starting at GPS week 873 (September 29, 1996), with an epoch of 1997.0.

As a consequence of the inherent high accuracy and continual refinement of the definition and realization of WGS 84, considerable care should be taken in the implementation of this system into existing and future weapons systems and geospatial information systems. This Chapter will address some of the considerations that should be made prior to the implementation of WGS 84 to ensure that the full benefits of WGS 84 are realized and are consistent with the operational product accuracy and interoperability requirements of the users. Careful consideration by the user of the products and accuracy supported by the implementation can lead to reduced costs and reduced effort in the implementation of WGS 84 with no loss of accuracy of the product. The guidelines presented in this Chapter are organized around basic classes of users: precise high accuracy geodetic users, cartographic users, navigation users, and geospatial information users. The absolute accuracy requirements vary significantly between these applications ranging from centimeter requirements for precise geodetic positioning to hundreds of meters for small scale maps. These recommendations are provided to stimulate users to analyze their specific implementation to determine how best to implement WGS 84 data and information, rather than a complete implementation which may not be necessary.

9.1.1 General Recommendations

Before satellite geodetic techniques became available, the local horizontal datum was defined independently of the local vertical datum. NIMA has developed datum transformations to convert over 120 local horizontal datums to WGS 84. This generally entails making survey ties between a number of local geodetic control points and their corresponding geodetic positions derived from satellite observations. NIMA did this for many years with Doppler observations from TRANSIT satellites and continues to do it now with GPS. Aside from the countless maps and charts which are still based on these classical local datums, numerous land records, property boundaries and other geographic information in many countries are referenced to local datums. There is currently no world vertical system defined to unify and tie together these local vertical systems. Generally the vertical datum is defined by a series of tide gauges in the area or by approximating mean sea level by the geoid leading to numerous realizations of mean sea level. Unfortunately, the local geodetic coordinates on these datums are of limited use for modern survey, navigation and mapping operations. Modern maps, navigation systems and geodetic applications require a single accessible, global, 3-dimensional reference frame. It is important for global operations and interoperability that DoD systems implement and operate as much as possible on WGS 84. It is equally important that systems implement the WGS 84 information relative to the gravity field, geoid and datum transformations in a manner that will allow future update of specific portions of the data.

These data will change with future refinements of WGS 84, as improved information becomes available to NIMA, and this may necessitate updates to existing implementations as future operational accuracy requirements become known. For example, implementations of the geoid undulation values as a grid in a lookup table would facilitate easier future updates than implementation as spherical harmonic coefficients.

9.1.2 Precise Geodetic Applications

For precise surveying applications, full implementation is recommended. This will provide the user with the ultimate positioning accuracy in WGS 84. It is further recommended that in these applications coordinates be maintained with an epoch assigned to each coordinate determination along with an indication of the fixed station GPS coordinate set used for the realization, such as WGS 84(G873). The EGM 96 through degree and order 70 is recommended for high accuracy satellite orbit determination and prediction purposes. An Earth orbiting satellite's sensitivity to the geopotential is strongly influenced by the satellite's altitude range and other orbital parameters. DoD programs performing satellite orbit determination are advised to determine the maximum degree and order most appropriate for their particular mission and orbit accuracy requirements.

9.1.3 Cartographic Applications

The original definition and realization of WGS 84 still satisfies the DoD's mapping and charting requirements. The 1-2 meter accuracy (1σ) of the WGS 84 reference frame, as defined in TR8350.2, Second Edition, is more than adequate for large scale mapping. The current national horizontal map accuracy standard indicates that well defined points should be located with an accuracy better than 1/30 of an inch (0.84 mm) at a 90 percent confidence level on maps with scales greater than 1:20,000. This translates to 8.4 m on a 1:10,000 scale map which is easily met by WGS 84, TR8350.2, Second Edition, assuming, of course, that the mapping products are on WGS 84 and not a local datum. If the maps or charts are on local datums, then the application of appropriate datum transformations is necessary to preserve interoperability with other geospatial information. Depending on the local datum, the accuracy of the datum transformations can vary from 1 meter to over 25 meters in each component.

The vertical accuracy of geospatial information and resulting map products depends on how the elevations were compiled. If the elevations are based on first order geodetic leveling, the control heights are very accurate, probably good to centimeters with respect to 'local mean sea level'. A height bias in the local mean sea level would be the major potential error source. If no leveling data are available for vertical control, elevations are estimated from height above the WGS 84 reference ellipsoid and a geoid height derived from the WGS 84 geoid model. For mapping processes which use imagery, the orthometric heights (height above the geoid) are substituted for elevations above mean sea level. For these products the Earth Gravitational Model 1996 (EGM96), which provides a geoid with an accuracy of 0.5 - 1.0 m. worldwide, should be implemented, especially for scales 1:10,000 or larger.

Consequently, for mapping implementation, it is very important to have the product accuracy in mind when implementing the refinements as defined in this document. Specifically, all datum transformations listed in this report may not be necessary, especially the regional values. The full resolution of the geoid may also not be necessary based on the changes of this geoid from the geoid documented in WGS 84, TR8350.2, Second Edition. Implementation on a 30 minute or 1 degree grid may be more than adequate. Neither does there appear to be a reason to implement the geoid as spherical harmonics.

9.1.4 Navigation Applications

The navigator represents a user with applications distinct from those discussed above. The navigator is moving and positioning in real-time or after the fact on land, air and sea platforms. Accuracy requirements may vary from the centimeter level for precise geodetic applications, such as aerial photogrammetry, to meters for combined integrated GPS/Inertial Navigation Systems, to tens of meters for the SPS GPS user. Navigation applications are also characterized by large numbers of systems in the field, e.g. more than 100,000 GPS military receivers, with legacy systems having different implementations of WGS 84 than the newer systems. Implementation and update of WGS 84 in these platforms are costly and almost impossible to accomplish simultaneously. Therefore, a careful analysis must be done for each implementation to determine the essential elements of the refined definition of WGS 84 that need to be implemented. A few suggestions are offered:

The implementation of the geoid in these applications should be as a lookup table with an appropriate interpolation scheme. To help in deciding the grid interval, a comparison should be made of the errors introduced in the geoid heights utilizing various grid sizes. All applications may not require the maximum resolution.

Cycle numbers have been provided to document the datum transformation changes. This makes it possible for the user to tell if an update has been made to a specific transformation.

In some cases, the mean datum transformations may be sufficient for the user's requirements. Implementation of regional datum transformations may not be required. Use of the regional transformations versus the mean datum transformations should be analyzed with respect to the system accuracy capabilities.

9.1.5 Geospatial Information Applications

Geospatial databases contain information from various sources as thematic layers from which imagery, imagery intelligence, and geospatial information can be derived or extracted. Since the informaton represented in the various layers has multiple uses and supports applications of different accuracies, it is important that the accuracy of the basic information be retained. Therefore, the refined WGS 84 should be implemented in geospatial systems to maintain the inherent accuracy of the basic data sources.

9.2 Summary

Users need to implement the refinements of the WGS 84 (TR8350.2, Third Edition) into application systems in a planned and well thought out manner. An analysis into what aspects of these refinements are required for specific applications should be performed. This will ensure that the applications have indeed implemented WGS 84 (TR8350.2, Third Edition), in the most effective manner.

10. CONCLUSIONS/SUMMARY

The refined World Geodetic System 1984 is based on the use of data, techniques, and technology available in early 1997. As a result, the refined WGS 84 is more accurate than its predecessor and replaces it as the three dimensional geodetic system officially authorized for DoD use.

Major changes in this report are as follows:

- Refined Earth Gravitational Model complete to degree and order 360.
- New geoid undulations accurate from ±0.5 meter to ±1.0 meter.
- Additional and improved datum transformation parameters from local to WGS 84.
- Modifications to the ellipsoidal (normal) gravity model.
- New Earth Gravitational Constant (GM).
- New realization of the WGS 84 (G873) reference frame through a more accurate determination of NIMA and Air Force GPS monitor stations.
- Inclusion of a new chapter on implementation guidance.

The value of WGS 84 will become increasingly evident with the expansion of geospatial databases and information systems. Accurate coordinates will ensure consistency, interoperability and accuracy between thematic data layers. Since the reference system for NAVSTAR GPS is WGS 84, high quality geodetic coordinates are 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 Transformations leads to an improved recovery of local coordinates.

NIMA will continually review DoD requirements and assure that WGS 84 will remain a dynamic viable system which meets or exceeds these requirements.

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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 MREs (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
Pakistan***	EF	6377309.613	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

* Refer to Appendices B, C, and D.

** As accepted by NIMA.

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

Appendix A.1
Reference Ellipsoid Names and Constants
Used for Datum Transformations*

Reference Ellipsoid Name	ID Code	a (Meters)	f^{-1}
Hough 1960	HO	6378270	297
Indonesian 1974	ID	6378160	298.247
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 NIMA.
*** Through adoption of a new yard to meter conversion factor in the referenced country.

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 109 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 with their associated ellipsoids. Two letter ellipsoidal codes (Appendix A) have also been included against each datum to indicate which specific "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.

The year of initial publication and cycle numbers have been provided as a new feature in this edition. This makes it possible for a user to determine when a particular set of transformation parameters first became available and if the current set has replaced an outdated set.

A cycle number of zero indicates that the set of parameters is as it was published in DMA TR 8350.2, Second Edition, 1 September 1991 including Insert 1, 30 August 1993 or that the parameters are new to this edition (1997 Publication Date). A cycle number of one indicates that the current parameters have replaced outdated parameters that were in the previous edition.

If transformation parameter sets are updated in future editions of this publication, the cycle numbers for each parameter set that is updated will increment by one.

4. ERROR ESTIMATES

The 1σ error estimates for the datum transformation constants (ΔX,ΔY,ΔZ), 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 four or less common control stations, the 1σ errors for shift constants are non-computed estimates.

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

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
American Samoa 1962	Clarke 1866	CC
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
Co-Ordinate System 1937 of Estonia	Bessel 1841	BR
Corrego Alegre	International 1924	IN
Dabola	Clarke 1880	CD
Deception Island	Clarke 1880	CD
Djakarta (Batavia)	Bessel 1841	BR
DOS 1968	International 1924	IN
Easter Island 1967	International 1924	IN
European 1950	International 1924	IN

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

Appendix B.1

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

Local Geodetic Datum	Associated*Reference Ellipsoid	Code
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 1960	Everest	EA
Indian 1975	Everest	EA
Indonesian 1974	Indonesian 1974	ID
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
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

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

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

Appendix B.1
Geodetic Datums/Reference Systems
Related to World Geodetic System 1984
(Through Satellite Ties)

Local Geodetic Datum	**Associated*Reference Ellipsoid**	**Code**
North American 1927	Clarke 1866	CC
North American 1983	GRS 80**	RF
North Sahara 1959	Clarke 1880	CD
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
S-42 (Pulkovo 1942)	Krassovsky 1940	KA
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
Sierra Leone 1960	Clark 1880	CD
S-JTSK	Bessel 1841	BR
South American 1969	South American 1969	SA
South Asia	Modified Fischer 1960	FA
Timbalai 1948	Everest	EB

* See Appendix A.1 for associated constants a,f.
** Geodetic Reference System 1980
*** Also known as Hito XVIII 1963

Appendix B.1
Geodetic Datums/Reference Systems
Related to World Geodetic System 1984
(Through Satellite Ties)

Local Geodetic Datum	**Associated*Reference Ellipsoid**	**Code**
Tokyo	Bessel 1841	BR
Tristan Astro 1968	International 1924	IN
Viti Levu 1916	Clarke 1880	CD
Voirol 1960	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 Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**$\Delta f \times 10^4$**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ADINDAN	ADI	Clarke 1880	-112.145	-0.54750714						
Mean Solution (Ethiopia and Sudan)	ADI-M				22	0	1991	-166 ±5	-15 ±5	204 ±3
Burkina Faso	ADI-E				1	0	1991	-118 ±25	-14 ±25	218 ±25
Cameroon	ADI-F				1	0	1991	-134 ±25	-2 ±25	210 ±25
Ethiopia	ADI-A				8	0	1991	-165 ±3	-11 ±3	206 ±3
Mali	ADI-C				1	0	1991	-123 ±25	-20 ±25	220 ±25
Senegal	ADI-D				2	0	1991	-128 ±25	-18 ±25	224 ±25
Sudan	ADI-B				14	0	1991	-161 ±3	-14 ±5	205 ±3
AFGOOYE	AFG	Krassovsky 1940	-108	0.00480795						
Somalia	AFG				1	0	1987	-43 ±25	-163 ±25	45 ±25

Appendix B.2

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: AFRICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**$\Delta f \times 10^4$**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ARC 1950	ARF	Clarke 1880	-112.145	-0.54750714						
Mean Solution (Botswana, Lesotho, Malawi, Swaziland, Zaire, Zambia, Zimbabwe)	ARF-M				41	0	1987	-143 ±20	-90 ±33	-294 ±20
Botswana	ARF-A				9	0	1991	-138 ±3	-105 ±5	-289 ±3
Burundi	ARF-H				3	0	1991	-153 ±20	-5 ±20	-292 ±20
Lesotho	ARF-B				5	0	1991	-125 ±3	-108 ±3	-295 ±8
Malawi	ARF-C				6	0	1991	-161 ±9	-73 ±24	-317 ±8
Swaziland	ARF-D				4	0	1991	-134 ±15	-105 ±15	-295 ±15
Zaire	ARF-E				2	0	1991	-169 ±25	-19 ±25	-278 ±25
Zambia	ARF-F				5	0	1991	-147 ±21	-74 ±21	-283 ±27
Zimbabwe	ARF-G				10	0	1991	-142 ±5	-96 ±8	-293 ±11

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

Continent: AFRICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ARC 1960	ARS	Clarke 1880	-112.145	-0.54750714						
Mean Solution (Kenya and Tanzania)	ARS-M				25	0	1991	-160 ±20	-6 ±20	-302 ±20
Kenya	ARS-A				24	0	1997	-157 ±4	-2 ±3	-299 ±3
Tanzania	ARS-B				12	0	1997	-175 ±6	-23 ±9	-303 ±10
AYABELLE LIGHTHOUSE	PHA	Clarke 1880	-112.145	-0.54750714						
Djibouti					1	0	1991	-79 ±25	-129 ±25	145 ±25
BISSAU	BID	International 1924	-251	-0.14192702						
Guinea-Bissau					2	0	1991	-173 ±25	253 ±25	27 ±25
CAPE	CAP	Clarke 1880	-112.145	-0.54750714						
South Africa					5	0	1987	-136 ±3	-108 ±6	-292 ±6

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

Continent: AFRICA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
CARTHAGE	CGE	Clarke 1880	-112.145	-0.54750714						
Tunisia					5	0	1987	-263 ±6	6 ±9	431 ±8
DABOLA	DAL	Clarke 1880	-112.145	-0.54750714						
Guinea					4	0	1991	-83 ±15	37 ±15	124 ±15
EUROPEAN 1950	EUR	International 1924	-251	-0.14192702						
Egypt	EUR-F				14	0	1991	-130 ±6	-117 ±8	-151 ±8
Tunisia	EUR-T				4	0	1993	-112 ±25	-77 ±25	-145 ±25
LEIGON	LEH	Clarke 1880	-112.145	-0.54750714						
Ghana					8	0	1991	-130 ±2	29 ±3	364 ±2
LIBERIA 1964	LIB	Clarke 1880	-112.145	-0.54750714						
Liberia					4	0	1987	-90 ±15	40 ±15	88 ±15
MASSAWA	MAS	Bessel 1841	739.845	0.10037483						
Eritrea (Ethiopia)					1	0	1987	639 ±25	405 ±25	60 ±25

Appendix B.2

Transformation Parameters
Local Geodetic Datums to WGS 84

Continent: AFRICA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10⁴**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
MERCHICH	MER	Clarke 1880	-112.145	-0.54750714						
Morocco					9	0	1987	31 ±5	146 ±3	47 ±3
MINNA	MIN	Clarke 1880	-112.145	-0.54750714						
Cameroon	MIN-A				2	0	1991	-81 ±25	-84 ±25	115 ±25
Nigeria	MIN-B				6	0	1987	-92 ±3	-93 ±6	122 ±5
M'PORALOKO	MPO	Clarke 1880	-112.145	-0.54750714						
Gabon					1	0	1991	-74 ±25	-130 ±25	42 ±25
NORTH SAHARA 1959	NSD	Clarke 1880	-112.145	-0.54750714						
Algeria					3	0	1993	-186 ±25	-93 ±25	310 ±25
OLD EGYPTIAN 1907	OEG	Helmert 1906	-63	0.00480795						
Egypt					14	0	1987	-130 ±3	110 ±6	-13 ±8

Appendix B.2

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: AFRICA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
POINT 58	PTB	Clarke 1880	-112.145	-0.54750714						
Mean Solution (Burkina Faso and Niger)					2	0	1991	-106 ±25	-129 ±25	165 ±25
POINTE NOIRE 1948	PTN	Clarke 1880	-112.145	-0.54750714						
Congo					1	0	1991	-148 ±25	51 ±25	-291 ±25
SCHWARZECK	SCK	Bessel 1841	653.135*	0.10037483						
Namibia					3	0	1991	616 ±20	97 ±20	-251 ±20
SIERRA LEONE 1960	SRL	Clark 1880	-112.145	-0.54750714						
Sierra Leone					8	0	1997	-88 ±15	4 ±15	101 ±15
VOIROL 1960	VOR	Clarke 1880	-112.145	-0.54750714						
Algeria					2	0	1993	-123 ±25	-206 ±25	219 ±25

* This Δa value reflects an a-value of 6377483.865 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 Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
AIN EL ABD 1970	AIN	International 1924	-251	-0.14192702						
Bahrain Island	AIN-A				2	0	1991	-150 ±25	-250 ±25	-1 ±25
Saudi Arabia	AIN-B				9	0	1991	-143 ±10	-236 ±10	7 ±10
DJAKARTA (BATAVIA)	BAT	Bessel 1841	739.845	0.10037483						
Sumatra (Indonesia)					5	0	1987	-377 ±3	681 ±3	-50 ±3
EUROPEAN 1950	EUR	International 1924	-251	-0.14192702						
Iran	EUR-H				27	0	1991	-117 ±9	-132 ±12	-164 ±11
HONG KONG 1963	HKD	International 1924	-251	-0.14192702						
Hong Kong					2	0	1987	-156 ±25	-271 ±25	-189 ±25
HU-TZU-SHAN	HTN	International 1924	-251	-0.14192702						
Taiwan					4	0	1991	-637 ±15	-549 ±15	-203 ±15

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

Continent: ASIA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
INDIAN	IND	Everest								
Bangladesh	IND-B	Everest (1830)	860.655*	0.28361368	6	0	1991	282 ±10	726 ±8	254 ±12
India and Nepal	IND-I	Everest (1956)	835.757*	0.28361368	7	0	1991	295 ±12	736 ±10	257 ±15
INDIAN 1954	INF	Everest (1830)	860.655*	0.28361368						
Thailand	INF-A				11	0	1993	217 ±15	823 ±6	299 ±12
INDIAN 1960	ING	Everest (1830)	860.655*	0.28361368						
Vietnam (near 16°N)	ING-A				2	0	1993	198 ±25	881 ±25	317 ±25
Con Son Island (Vietnam)	ING-B				1	0	1993	182 ±25	915 ±25	344 ±25
INDIAN 1975	INH	Everest (1830)	860.655*	0.28361368						
Thailand	INH-A				62	1	1997	210 ±3	814 ±2	289 ±3

* See Appendix A

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

Continent: ASIA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10[4]**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
INDONESIAN 1974	IDN	Indonesian 1974	-23	-0.00114930						
Indonesia					1	0	1993	-24 ±25	-15 ±25	5 ±25
KANDAWALA	KAN	Everest (1830)	860.655*	0.28361368						
Sri Lanka					3	0	1987	-97 ±20	787 ±20	86 ±20
KERTAU 1948	KEA	Everest (1948)	832.937*	0.28361368						
West Malaysia and Singapore					6	0	1987	-11 ±10	851 ±8	5 ±6
NAHRWAN	NAH	Clarke 1880	-112.145	-0.54750714						
Masirah Island (Oman)	NAH-A				2	0	1987	-247 ±25	-148 ±25	369 ±25
United Arab Emirates	NAH-B				2	0	1987	-249 ±25	-156 ±25	381 ±25
Saudi Arabia	NAH-C				3	0	1991	-243 ±20	-192 ±20	477 ±20

* See Appendix A

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

Continent: ASIA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
OMAN	FAH	Clarke 1880	-112.145	-0.54750714						
Oman					7	0	1987	-346 ±3	-1 ±3	224 ±9
QATAR NATIONAL	QAT	International 1924	-251	-0.14192702						
Qatar					3	0	1987	-128 ±20	-283 ±20	22 ±20
SOUTH ASIA	SOA	Modified Fischer 1960	-18	0.00480795						
Singapore					1	0	1987	7 ±25	-10 ±25	-26 ±25
TIMBALAI 1948	TIL	Everest	838.444*	0.28361368						
Brunei and East Malaysia (Sarawak and Sabah)					8	0	1987	-679 ±10	669 ±10	-48 ±12

* See Appendix A

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

Continent: ASIA

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
TOKYO	TOY	Bessel 1841	739.845	0.10037483						
Mean Solution (Japan, Okinawa, and SouthKorea)	TOY-M				31	0	1991	-148 ±20	507 ±5	685 ±20
Japan	TOY-A				16	0	1991	-148 ±8	507 ±5	685 ±8
Okinawa	TOY-C				3	0	1991	-158 ±20	507 ±5	676 ±20
South Korea	TOY-B				29	1	1997	-147 ±2	506 ±2	687 ±2

Appendix B.4

Transformation Parameters
Local Geodetic Datums to WGS 84

Continent: AUSTRALIA											
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**					
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**	
AUSTRALIAN GEODETIC 1966	AUA	Australian National	-23	-0.00081204							
Australia and Tasmania					105	0	1987	-133 ±3	-48 ±3	148 ±3	
AUSTRALIAN GEODETIC 1984	AUG	Australian National	-23	-0.00081204							
Australia and Tasmania					90	0	1987	-134 ±2	-48 ±2	149 ±2	

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
CO-ORDINATE SYSTEM 1937 OF ESTONIA	EST	Bessel 1841	739.85	0.10037483						
Estonia					19	0	1997	374 ±2	150 ±3	588 ±3
EUROPEAN 1950	EUR	International 1924	-251	-0.14192702						
Mean Solution {Austria, Belgium, Denmark, Finland, France, FRG (Federal Republic of Germany)*, Gibraltar, Greece, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, and Switzerland}	EUR-M				85	0	1987	-87 ±3	-98 ±8	-121 ±5

* Prior to 1 January 1993

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters								
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**		**ΔY(m)**		**ΔZ(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	0	1991	-87	±3	-96	±3	-120	±3	
Cyprus	EUR-E				4	0	1991	-104	±15	-101	±15	-140	±15	
Egypt	EUR-F				14	0	1991	-130	±6	-117	±8	-151	±8	
England, Channel Islands, Scotland,and Shetland Islands**	EUR-G				40	0	1991	-86	±3	-96	±3	-120	±3	
England, Ireland, Scotland, and Shetland Islands**	EUR-K				47	0	1991	-86	±3	-96	±3	-120	±3	

* Prior to 1 January 1993
** European Datum 1950 coordinates developed from Ordnance Survey of Great Britian (OSGB) Scientific Network 1980 (SN 80) coordinates.

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
EUROPEAN 1950 (cont'd)	EUR	International 1924	-251	-0.14192702						
Greece	EUR-B				2	0	1991	-84 ±25	-95 ±25	-130 ±25
Iran	EUR-H				27	0	1991	-117 ±9	-132 ±12	-164 ±11
Italy										
Sardinia	EUR-I				2	0	1991	-97 ±25	-103 ±25	-120 ±25
Sicily	EUR-J				3	0	1991	-97 ±20	-88 ±20	-135 ±20
Malta	EUR-L				1	0	1991	-107 ±25	-88 ±25	-149 ±25
Norway and Finland	EUR-C				20	0	1991	-87 ±3	-95 ±5	-120 ±3
Portugal and Spain	EUR-D				18	0	1991	-84 ±5	-107 ±6	-120 ±3
Tunisia	EUR-T				4	0	1993	-112 ±25	-77 ±25	-145 ±25

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10⁴**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
EUROPEAN 1979	EUS	International 1924	-251	-0.14192702						
Mean Solution (Austria, Finland, Netherlands, Norway, Spain, Sweden, and Switzerland)					22	0	1987	-86 ±3	-98 ±3	-119 ±3
HJORSEY 1955	HJO	International 1924	-251	-0.14192702						
Iceland					6	0	1987	-73 ±3	46 ±3	-86 ±6
IRELAND 1965	IRL	Modified Airy	796.811	0.11960023						
Ireland					7	0	1987	506 ±3	-122 ±3	611 ±3
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	0	1987	375 ±10	-111 ±10	431 ±15

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ORDNANCE SURVEY OF GREAT BRITAIN 1936 (cont'd)	OGB	Airy	573.604	0.11960023						
England	OGB-A				21	0	1991	371 ±5	-112 ±5	434 ±6
England, Isle of Man, and Wales	OGB-B				25	0	1991	371 ±10	-111 ±10	434 ±15
Scotland and Shetland Islands	OGB-C				13	0	1991	384 ±10	-111 ±10	425 ±10
Wales	OGB-D				3	0	1991	370 ±20	-108 ±20	434 ±20
ROME 1940	MOD	International 1924	-251	-0.14192702						
Sardinia					1	0	1987	-225 ±25	-65 ±25	9 ±25
S-42 (PULKOVO 1942)	SPK	Krassovsky 1940	-108	0.00480795						
Hungary	SPK-A				5	0	1993	28 ±2	-121 ±2	-77 ±2
Poland	SPK-B				11	0	1997	23 ±4	-124 ±2	-82 ±4

Appendix B.5
Transformation Parameters
Geodetic Datums to WGS 84

Continent: EUROPE										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10[4]**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
S-42 (PULKOVO 1942) (cont'd)	SPK	Krassovsky 1940	-108	0.00480795						
Czechoslovakia*	SPK-C				6	0	1997	26 ±3	-121 ±3	-78 ±2
Latvia	SPK-D				5	0	1997	24 ±2	-124 ±2	-82 ±2
Kazakhstan	SPK-E				2	0	1997	15 ±25	-130 ±25	-84 ±25
Albania	SPK-F				7	0	1997	24 ±3	-130 ±3	-92 ±3
Romania	SPK-G				4	0	1997	28 ±3	-121 ±5	-77 ±3
S-JTSK	CCD	Bessel 1841	739.845	0.10037483						
Czechoslovakia *					6	0	1993	589 ±4	76 ±2	480 ±3

* Prior to 1 January 1993

Appendix B.6

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: NORTH AMERICA											
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**					
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**	
CAPE CANAVERAL	CAC	Clarke 1866	-69.4	-0.37264639							
Mean Solution (Florida and Bahamas)					19	0	1991	-2 ±3	151 ±3	181 ±3	
NORTH AMERICAN 1927	NAS	Clarke 1866	-69.4	-0.37264639							
Mean Solution (CONUS)	NAS-C				405	0	1987	-8 ±5	160 ±5	176 ±6	
Western United States (Arizona, Arkansas, California, Colorado, Idaho, Iowa, Kansas, Montana, Nebraska, Nevada,New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming)	NAS-B				276	0	1991	-8 ±5	159 ±3	175 ±3	

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

Continent: NORTH AMERICA

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
NORTH AMERICAN 1927 (cont'd)	NAS	Clarke 1866	-69.4	-0.37264639						
Eastern United States (Alabama, Connecticut, Delaware, District of Columbia, Florida, Georgia, Illinois, Indiana, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Tennessee, Vermont, Virginia, West Virginia, and Wisconsin)	NAS-A				129	0	1991	-9 ±5	161 ±5	179 ±8

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

Continent: NORTH AMERICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
NORTH AMERICAN 1927 (cont'd)	NAS	Clarke 1866	-69.4	-0.37264639						
Alaska (Excluding Aleutian Islands)	NAS-D				47	0	1987	-5 ±5	135 ±9	172 ±5
Aleutian Islands										
East of 180°W	NAS-V				6	0	1993	-2 ±6	152 ±8	149 ±10
West of 180°W	NAS-W				5	0	1993	2 ±10	204 ±10	105 ±10
Bahamas(Excluding San Salvador Island)	NAS-Q				11	0	1987	-4 ±5	154 ±3	178 ±5
San Salvador Island	NAS-R				1	0	1987	1 ±25	140 ±25	165 ±25
Canada Mean Solution (Including Newfoundland)	NAS-E				112	0	1987	-10 ±15	158 ±11	187 ±6
Alberta and British Columbia	NAS-F				25	0	1991	-7 ±8	162 ±8	188 ±6

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

Continent: NORTH AMERICA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(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	0	1991	-22 ±6	160 ±6	190 ±3
Manitoba and Ontario	NAS-H				25	0	1991	-9 ±9	157 ±5	184 ±5
Northwest Territories and Saskatchewan	NAS-I				17	0	1991	4 ±5	159 ±5	188 ±3
Yukon	NAS-J				8	0	1991	-7 ±5	139 ±8	181 ±3
Canal Zone	NAS-O				3	0	1987	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	0	1991	-3 ±3	142 ±9	183 ±12

Appendix B.6

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: NORTH AMERICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters							
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**		**ΔY(m)**		**ΔZ(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	1987	0	±8	125	±3	194	±5
Cuba	NAS-T				1	0	1987	-9	±25	152	±25	178	±25
Greenland(Hayes Peninsula)	NAS-U				2	0	1987	11	±25	114	±25	195	±25
Mexico	NAS-L				22	0	1987	-12	±8	130	±6	190	±6
NORTH AMERICAN 1983	NAR	GRS 80	0	-0.00000016									
Alaska (Excluding Aleutian Islands)	NAR-A				42	0	1987	0	±2	0	±2	0	±2
Aleutian Islands	NAR-E				4	0	1993	-2	±5	0	±2	4	±5
Canada	NAR-B				96	0	1987	0	±2	0	±2	0	±2

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

Continent: NORTH AMERICA										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
NORTH AMERICAN 1983 (cont'd)	NAR	GRS 80	0	-0.00000016						
CONUS	NAR-C				216	0	1987	0 ±2	0 ±2	0 ±2
Hawaii	NAR-H				6	0	1993	1 ±2	1 ±2	-1 ±2
Mexico and Central America	NAR-D				25	0	1987	0 ±2	0 ±2	0 ±2

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

Continent: SOUTH AMERICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
BOGOTA OBSERVATORY	BOO	International 1924	-251	-0.14192702						
Colombia					7	0	1987	307 ±6	304 ±5	-318 ±6
CAMPO INCHAUSPE 1969	CAI	International 1924	-251	-0.14192702						
Argentina					20	0	1987	-148 ±5	136 ±5	90 ±5
CHUA ASTRO	CHU	International 1924	-251	-0.14192702						
Paraguay					6	0	1987	-134 ±6	229 ±9	-29 ±5
CORREGO ALEGRE	COA	International 1924	-251	-0.14192702						
Brazil					17	0	1987	-206 ±5	172 ±3	-6 ±5

Appendix B.7

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: SOUTH AMERICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
PROVISIONAL SOUTH AMERICAN 1956	PRP	International 1924	-251	-0.14192702						
Mean Solution (Bolivia, Chile, Colombia, Ecuador, Guyana, Peru, and Venezuela)	PRP-M				63	0	1987	-288 ±17	175 ±27	-376 -27
Bolivia	PRP-A				5	0	1991	-270 ±5	188 ±11	-388 ±14
Chile										
Northern Chile (near 19°S)	PRP-B				1	0	1991	-270 ±25	183 ±25	-390 ±25
Southern Chile (near 43°S)	PRP-C				3	0	1991	-305 ±20	243 ±20	-442 ±20
Colombia	PRP-D				4	0	1991	-282 ±15	169 ±15	-371 ±15
Ecuador	PRP-E				11	0	1991	-278 ±3	171 ±5	-367 ±3

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

Continent: SOUTH AMERICA

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
PROVISIONAL SOUTH AMERICAN 1956 (cont'd)	PRP	International 1924	-251	-0.14192702						
Guyana	PRP-F				9	0	1991	-298 ±6	159 ±14	-369 -±5
Peru	PRP-G				6	0	1991	-279 ±6	175 ±8	-379 ±12
Venezuela	PRP-H				24	0	1991	-295 -±9	173 ±14	-371 ±15
PROVISIONAL SOUTH CHILEAN 1963*	HIT	International 1924	-251	-0.14192702						
Southern Chile (near 53°S)					2	0	1987	16 ±25	196 ±25	93 ±25

*** 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 Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**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	0	1987	-57 ±15	1 ±6	-41 ±9
Argentina	SAN-A				10	0	1991	-62 ±5	-1 ±5	-37 ±5
Bolivia	SAN-B				4	0	1991	-61 ±15	2 ±15	-48 ±15
Brazil	SAN-C				22	0	1991	-60 ±3	-2 ±5	-41 ±5
Chile	SAN-D				9	0	1991	-75 ±15	-1 ±8	-44 ±11
Colombia	SAN-E				7	0	1991	-44 ±6	6 ±6	-36 ±5

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

Continent: SOUTH AMERICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters							
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**		**ΔY(m)**		**ΔZ(m)**	
SOUTH AMERICAN 1969 (cont'd)	SAN	South American 1969	-23	-0.00081204									
Ecuador (Excluding Galapagos Islands)	SAN-F				11	0	1991	-48	±3	3	±3	-44	±3
Baltra, Galapagos Islands	SAN-J				1	0	1991	-47	±25	26	±25	-42	±25
Guyana	SAN-G				5	0	1991	-53	±9	3	±5	-47	±5
Paraguay	SAN-H				4	0	1991	-61	±15	2	±15	-33	±15
Peru	SAN-I				6	0	1991	-58	±5	0	±5	-44	±5
Trinidad and Tobago	SAN-K				1	0	1991	-45	±25	12	±25	-33	±25
Venezuela	SAN-L				5	0	1991	-45	±3	8	±6	-33	±3
ZANDERIJ	ZAN	International 1924	-251	-0.14192702									
Suriname					5	0	1987	-265	±5	120	±5	-358	±8

Appendix B.8

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: ATLANTIC OCEAN

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10⁴**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ANTIGUA ISLAND ASTRO 1943	AIA	Clarke 1880	-112.145	-0.54750714						
Antigua, Leeward Islands					1	0	1991	-270 ±25	13 ±25	62 ±25
ASCENSION ISLAND 1958	ASC	International 1924	-251	-0.14192702						
Ascension Island					2	0	1991	-205 ±25	107 ±25	53 ±25
ASTRO DOS 71/4	SHB	International 1924	-251	-0.14192702						
St. Helena Island					1	0	1987	-320 ±25	550 ±25	-494 ±25
BERMUDA 1957	BER	Clarke 1866	-69.4	-0.37264639						
Bermuda Islands					3	0	1987	-73 ±20	213 ±20	296 ±20
CAPE CANAVERAL	CAC	Clarke 1866	-69.4	-0.37264639						
Mean Solution (Bahamas and Florida)					19	0	1991	-2 ±3	151 ±3	181 ±3

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

Continent: ATLANTIC OCEAN

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10⁴**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
DECEPTION ISLAND	DID	Clarke 1880	-112.145	-0.54750714						
Deception Island, Antarctica					3	0	1993	260 ±20	12 ±20	-147 ±20
FORT THOMAS 1955	FOT	Clarke 1880	-112.145	-0.54750714						
Nevis, St. Kitts, Leeward Islands					2	0	1991	-7 ±25	215 ±25	225 ±25
GRACIOSA BASE SW 1948	GRA	International 1924	-251	-0.14192702						
Faial, Graciosa, Pico, Sao Jorge, and Terceira Islands (Azores)					5	0	1991	-104 ±3	167 ±3	-38 ±3
HJORSEY 1955	HJO	International 1924	-251	-0.14192702						
Iceland					6	0	1987	-73 ±3	46 ±3	-86 ±6
ISTS 061 ASTRO 1968	ISG	International 1924	-251	-0.14192702						
South Georgia Island					1	0	1991	-794 ±25	119 ±25	-298 ±25

Appendix B.8

Transformation Parameters
Local Geodetic Datums to WGS 84

Continent: ATLANTIC OCEAN											
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**					
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**	
L. C. 5 ASTRO 1961	LCF	Clarke 1866	-69.4	-0.37264639							
Cayman Brac Island					1	0	1987	42 ±25	124 ±25	147 ±25	
MONTSERRAT ISLAND ASTRO 1958	ASM	Clarke 1880	-112.145	-0.54750714							
Montserrat, Leeward Islands					1	0	1991	174 ±25	359 ±25	365 ±25	
NAPARIMA, BWI	NAP	International 1924	-251	-0.14192702							
Trinidad and Tobago					4	0	1991	-10 ±15	375 ±15	165 ±15	
OBSERVATORIO METEOROLOGICO 1939	FLO	International 1924	-251	-0.14192702							
Corvo and Flores Islands (Azores)					3	0	1991	-425 ±20	-169 ±20	81 ±20	
PICO DE LAS NIEVES	PLN	International 1924	-251	-0.14192702							
Canary lslands					1	0	1987	-307 ±25	-92 ±25	127 ±25	

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

Continent: ATLANTIC OCEAN

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
PORTO SANTO 1936	POS	International 1924	-251	-0.14192702						
Porto Santo and Madeira Islands					2	0	1991	-499 ±25	-249 ±25	314 ±25
PUERTO RICO	PUR	Clarke 1866	-69.4	-0.37264639						
Puerto Rico and Virgin Islands					11	0	1987	11 ±3	72 ±3	-101 ±3
QORNOQ	QUO	International 1924	-251	-0.14192702						
South Greenland					2	0	1987	164 ±25	138 ±25	-189 ±32
SAO BRAZ	SAO	International 1924	-251	-0.14192702						
Sao Miguel, Santa Maria Islands (Azores)					2	0	1987	-203 ±25	141 ±25	53 ±25
SAPPER HILL 1943	SAP	International 1924	-251	-0.14192702						
East Falkland Island					5	0	1991	-355 ±1	21 ±1	72 ±1

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

Continent: ATLANTIC OCEAN

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
SELVAGEM GRANDE 1938	SGM	International 1924	-251	-0.14192702						
Salvage Islands					1	0	1991	-289 ±25	-124 ±25	60 ±25
TRISTAN ASTRO 1968	TDC	International 1924	-251	-0.14192702						
Tristan da Cunha					1	0	1987	-632 ±25	438 ±25	-609 ±25

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

Continent: Indian Ocean											
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**					
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
ANNA 1 ASTRO 1965	ANO	Australian National	-23	-0.00081204						
Cocos Islands					1	0	1987	-491 ±25	-22 ±25	435 ±25
GAN 1970	GAA	International 1924	-251	-0.14192702						
Republic of Maldives					1	0	1987	-133 ±25	-321 ±25	50 ±25
ISTS 073 ASTRO 1969	IST	International 1924	-251	-0.14192702						
Diego Garcia					2	0	1987	208 ±25	-435 ±25	-229 ±25
KERGUELEN ISLAND 1949	KEG	International 1924	-251	-0.14192702						
Kerguelen Island					1	0	1987	145 ±25	-187 ±25	103 ±25
MAHE 1971	MIK	Clarke 1880	-112.145	-0.54750714						
Mahe Island					1	0	1987	41 ±25	-220 ±25	-134 ±25
REUNION	REU	International 1924	-251	-0.14192702						
Mascarene Islands					1	0	1987	94 ±25	-948 ±25	-1262 ±25

Appendix B.10

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: PACIFIC OCEAN

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
AMERICAN SAMOA 1962	AMA	Clarke 1866	-69.4	-0.37264639						
American Samoa Islands					2	0	1993	-115 ±25	118 ±25	426 ±25
ASTRO BEACON "E" 1945	ATF	International 1924	-251	-0.14192702						
Iwo Jima					1	0	1987	145 ±25	75 ±25	-272 ±25
ASTRO TERN ISLAND (FRIG) 1961	TRN	International 1924	-251	-0.14192702						
Tern Island					1	0	1991	114 ±25	-116 ±25	-333 ±25
ASTRONOMICAL STATION 1952	ASQ	International 1924	-251	-0.14192702						
Marcus Island					1	0	1987	124 ±25	-234 ±25	-25 ±25
BELLEVUE (IGN)	IBE	International 1924	-251	-0.14192702						
Efate and Erromango Islands					3	0	1987	-127 ±20	-769 ±20	472 ±20

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

Continent: PACIFIC OCEAN										
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
CANTON ASTRO 1966	CAO	International 1924	-251	-0.14192702						
Phoenix Islands					4	0	1987	298 ±15	-304 ±15	-375 ±15
CHATHAM ISLAND ASTRO 1971	CHI	International 1924	-251	-0.14192702						
Chatham Island (New Zealand)					4	0	1987	175 ±15	-38 ±15	113 ±15
DOS 1968	GIZ	International 1924	-251	-0.14192702						
Gizo Island (New Georgia Islands)					1	0	1987	230 ±25	-199 ±25	-752 ±25
EASTER ISLAND 1967	EAS	International 1924	-251	-0.14192702						
Easter Island					1	0	1987	211 ±25	147 ±25	111 ±25
GEODETIC DATUM 1949	GEO	International 1924	-251	-0.14192702						
New Zealand					14	0	1987	84 ±5	-22 ±3	209 ±5

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

Continent: PACIFIC OCEAN														
Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**								
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**		**ΔY(m)**		**ΔZ(m)**		
GUAM 1963	GUA	Clarke 1866	-69.4	-0.37264639										
Guam					5	0	1987	-100	±3	-248	±3	259	±3	
GUX l ASTRO	DOB	International 1924	-251	-0.14192702										
Guadalcanal Island					1	0	1987	252	±25	-209	±25	-751	±25	
INDONESIAN 1974	IDN	Indonesian 1974	-23	-0.00114930										
Indonesia					1	0	1993	-24	±25	-15	±25	5	±25	
JOHNSTON ISLAND 1961	JOH	International 1924	-251	-0.14192702										
Johnston Island					2	0	1991	189	±25	-79	±25	-202	±25	
KUSAIE ASTRO 1951	KUS	International 1924	-251	-0.14192702										
Caroline Islands, Fed. States of Micronesia					1	0	1991	647	±25	1777	±25	-1124	±25	

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

Continent: PACIFIC OCEAN

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters								
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**		**ΔY(m)**		**ΔZ(m)**		
LUZON	LUZ	Clarke 1866	-69.4	-0.37264639										
Philippines (Excluding Mindanao Island)	LUZ-A				6	0	1987	-133	±8	-77	±11	-51	±9	
Mindanao Island	LUZ-B				1	0	1987	-133	±25	-79	±25	-72	±25	
MIDWAY ASTRO 1961	MID	International 1924	-251	-0.14192702										
Midway Islands					1	0	1987	912	±25	-58	±25	1227	±25	
OLD HAWAIIAN	OHA	Clarke 1866	-69.4	-0.37264639										
Mean Solution	OHA-M				15	0	1987	61	±25	-285	±20	-181	±20	
Hawaii	OHA-A				2	0	1991	89	±25	-279	±25	-183	±25	
Kauai	OHA-B				3	0	1991	45	±20	-290	±20	-172	±20	
Maui	OHA-C				2	0	1991	65	±25	-290	±25	-190	±25	
Oahu	OHA-D				8	0	1991	58	±10	-283	±6	-182	±6	

Appendix B.10

Transformation Parameters

Local Geodetic Datums to WGS 84

Continent: PACIFIC OCEAN

Local Geodetic Datums		**Reference Ellipsoids and Parameter Differences**			**No. of Satellite Stations Used**	**Transformation Parameters**				
Name	**Code**	**Name**	**Δa(m)**	**Δf x 10^4**		**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
PITCAIRN ASTRO 1967	PIT	International 1924	-251	-0.14192702						
Pitcairn Island					1	0	1987	185 ±25	165 ±25	42 ±25
SANTO (DOS) 1965	SAE	International 1924	-251	-0.14192702						
Espirito Santo Island					1	0	1987	170 ±25	42 ±25	84 ±25
VITI LEVU 1916	MVS	Clarke 1880	-112.145	-0.54750714						
Viti Levu Island (Fiji Islands)					1	0	1987	51 ±25	391 ±25	-36 ±25
WAKE-ENIWETOK 1960	ENW	Hough	-133	-0.14192702						
Marshall Islands					10	0	1991	102 ±3	52 ±3	-38 ±3
WAKE ISLAND ASTRO 1952	WAK	International 1924	-251	-0.14192702						
Wake Atoll					2	0	1991	276 ±25	-57 ±25	149 ±25

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 ten such local/regional 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.

The year of initial publication and cycle numbers have been provided as a new feature in this edition. This makes it possible for a user to determine when a particular set of transformation parameters first became available and if the current set has replaced an outdated set.

A cycle number of zero indicates that the set of parameters are as they were published in DMA TR 8350.2, Second Edition, 1 September 1991 including Insert 1, 30 August 1993 or that the parameters are new to this edition (1997 Publication Date). A cycle number of one indicates that the current parameters have replaced outdated parameters that were in the previous edition.

If transformation parameter sets are updated in future editions of this publication, the cycle numbers for each parameter set that is updated will increment by one.

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.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
Hermannskogel	Bessel 1841	BR
Indian	Everest	EF
Pulkovo 1942	Krassovsky 1940	KA
Tananarive Observatory 1925	International 1924	IN
Voirol 1874	Clarke 1880	CD
Yacare	International 1924	IN

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

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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**	**Δa(m)**	**$\Delta f \times 10^4$**	**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
BUKIT RIMPAH	BUR	Bessel 1841	739.845	0.10037483					
Bangka and Belitung Islands (Indonesia)					0	1987	-384	664	-48
CAMP AREA ASTRO	CAZ	International 1924	-251	-0.14192702					
Camp McMurdo Area, Antarctica					0	1987	-104	-129	239
EUROPEAN 1950	EUR-S	International 1924	-251	-0.14192702					
Iraq, Israel, Jordan Kuwait, Lebanon, Saudi Arabia, and Syria					0	1991	-103	-106	-141
GUNUNG SEGARA	GSE	Bessel 1841	739.845	0.10037483					
Kalimantan (Indonesia)					0	1987	-403	684	41
HERAT NORTH	HEN	International 1924	-251	-0.14192702					
Afghanistan					0	1987	-333	-222	114

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**	**Δa(m)**	**Δf x 10^4**	**Cycle Number**	**Pub. Date**	**ΔX(m)**	**ΔY(m)**	**ΔZ(m)**
HERMANNSKOGEL	HER	Bessel 1841	739.845	0.10037483					
Yugoslavia (Prior to 1990) Slovenia, Croatia, Bosnia and Herzegovina, Serbia					0	1997	682	-203	480
INDIAN	IND-P	Everest	827.387*	0.28361368					
Pakistan					0	1993	283	682	231
PULKOVO 1942	PUK	Krassovsky 1940	-108	0.00480795					
Russia					0	1993	28	-130	-95
TANANARIVE OBSERVATORY 1925	TAN	International 1924	-251	-0.14192702					
Madagascar					0	1987	-189	-242	-91
VOIROL 1874	VOI	Clarke 1880	-112.145	-0.54750714					
Tunisia/Algeria					0	1997	-73	-247	227
YACARE	YAC	International 1924	-251	-0.14192702					
Uruguay					0	1987	-155	171	37

* See Appendix A.1

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 (MREs) 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 (Austria, Denmark, France, W. Germany*, The Netherlands, and Switzerland.)
North American 1927	CONUS and Canadian Mainland
South American 1969	South American Mainland (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Peru, Paraguay, Uruguay, and Venezuela.

* Prior to October 1990.

2. APPLICATIONS

The coverage area for MREs application are defined in detail for each datum. MREs coverage area should never be extrapolated and are not to be used over islands and/or isolated land areas.

The main advantage of MREs 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 (MREs)
for Transforming
Australian Geodetic Datum 1966 (AUA) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

AUA	Shift	WGS 84
ø = (-)17° 00' 32.78"S	Δø = 5.48"	ø = (-)17° 00' 27.30"S
λ = 144° 11' 37.25"E	Δλ = 3.92"	λ = 144° 11' 41.17"E

Multiple Regression Equations (MREs)
for Transforming
Australian Geodetic Datum 1984 (AUG) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

Where : U = K (ø + 27°); V = K (λ - 134°); K = 0.05235988

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

AUG	Shift	WGS 84
ø = (-)20° 38' 00.67"S	Δø = 5.50"	ø = (-)20° 37' 55.17"S
λ = 144° 24' 29.29"E	Δλ = 4.11"	λ = 144° 24' 33.40"E

Multiple Regression Equations (MREs)
for Transforming
Campo Inchauspe Datum (CAI) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

CAI	Shift	WGS 84
ø = (-)29° 47' 45.68"S	Δø = 1.95"	ø = (-)29° 47' 43.73"S
λ = (-)58° 07' 38.20"W	Δλ =-1.96"	λ = (-)58° 07' 40.16"W

Multiple Regression Equations (MREs)
for Transforming
Corrego Alegre Datum (COA) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

COA	Shift	WGS 84
ø = (-)20° 29' 01.02"S	Δø = -1.03"	ø = (-)20° 29' 02.05"S
λ = (-)54° 47' 13.17"W	Δλ = -2.10"	λ = (-)54° 47' 15.27"W

Multiple Regression Equations (MREs)
for Transforming
European Datum 1950 (EUR) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

NOTE Input ø as (-) from 90°S to 0°N in degrees.

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

EUR	Shift	WGS 84
ø = 46° 41' 42.89"N	Δø = -3.08"	ø = 46° 41' 39.81"N
λ = 13° 54' 54.09"E	Δλ = -3.49"	λ = 13° 54' 50.60"E

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

Multiple Regression Equations (MREs)
for Transforming
North American Datum 1927 (NAS) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

NAS	Shift	WGS 84
ø = 54° 26' 08.67"N	Δø = 0.29"	ø = 54° 26' 08.96"N
λ = (-)110° 17' 02.41"W	Δλ = -3.16"	λ = (-)110° 17' 05.57"W

Multiple Regression Equations (MREs)
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 ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case :

NAS	Shift	WGS 84
ø = 34° 47' 08.83"N	Δø = 0.36"	ø = 34° 47' 09.19"N
λ = (-)86° 34' 52.18"W	Δλ = 0.08"	λ = (-)86° 34' 52.10"W

Multiple Regression Equations (MREs)
for Transforming
South American Datum 1969 (SAN) to WGS 84

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

MRE coefficients for ø and λ are :

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

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

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

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

Input λ as (-) from 180°W to 0°E in degrees.

Quality of fit = ± 2.0 m

Test Case

SAN	Shift	WGS 84
ø = (-)31° 56' 33.95"S	Δø = -1.36"	ø = (-)31° 56' 35.31"S
λ = (-)65° 06' 18.66"W	Δλ = -2.16"	λ = (-)65° 06' 20.82"W

APPENDIX E

WGS 72 TO WGS 84 TRANSFORMATION

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WGS 72 to WGS 84 TRANSFORMATIONS

1. 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 E.1 can be used with the following equations to obtain WGS 84 coordinates for the sites:

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

$$\lambda_{WGS\ 84} = \lambda_{WGS\ 72} + \Delta\lambda$$

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

2. As indicated in Table E.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 Δr), and changes in the size and shape of the ellipsoid. In addition, it is important to be aware that $\Delta\phi$, $\Delta\lambda$, Δh values calculated using Table E.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 E.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 E.1 should not be used for satellite local geodetic stations whose WGS 72 coordinates were determined using datum shifts from [36]. The preferred approach is to transform such WGS 72 coordinates, using datum shifts from [36], back to their respective local datums, and then transform the local datum coordinates to WGS 84 using Appendices B and C.

c. Table E.1 should be used only when no other approach is applicable.

Table E.1
Formulas and Parameters
to Transform WGS 72 Coordinates
to WGS 84 Coordinates

FORMULAS	$\Delta\phi'' = (4.5 \cos\phi) / (a \sin 1'') + (\Delta f \sin 2\phi) / (\sin 1'')$ $\Delta\lambda'' = 0.554$ $\Delta h = 4.5 \sin \phi + a \, \Delta f \sin^2 \phi - \Delta a + \Delta r$ (Units = Meters)
PARAMETERS	$\Delta f = 0.3121057 \times 10^{-7}$ $a = 6378135$ m $\Delta a = 2.0$ m $\Delta r = 1.4$ m
INSTRUCTIONS	To obtain WGS 84 coordinates, add the $\Delta\phi$, $\Delta\lambda$, Δh changes calculated using WGS 72 coordinates to the WGS 72 coordinates (ϕ, λ, h, respectively). Latitude is positive north and longitude is positive east (0° to 180°).

APPENDIX F

ACRONYMS

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APPENDIX F
ACRONYMS

AGD 66	= Australian Geodetic Datum 1966
AGD 84	= Australian Geodetic Datum 1984
BIH	= Bureau International de l'Heure
BTS	= BIH Terrestrial System
CCRS	= Conventional Celestial Reference System
CEP	= Celestial Ephemeris Pole
CIS	= Conventional Inertial System
CONUS	= Contiguous United States
CTP	= Conventional Terrestrial Pole
CTRS	= Conventional Terrestrial Reference System
CTS	= Conventional Terrestrial System
DMA	= Defense Mapping Agency
DoD	= Department of Defense
DoT	= Department of Transportation
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
EGM96	= Earth Gravitational Model 1996
EUREF89	= European Terrestrial Reference Frame 1989
FRG	= Federal Republic of Germany
GEOPS	= Geopotential Surfaces
GSFC	= Goddard Space Flight Center
GLONASS	= Global Navigation Satellite System
GPS	= Global Positioning System
GRS 80	= Geodetic Reference System 1980
HARNs	= High Accuracy Reference Networks
IAG	= International Association of Geodesy
IAU	= International Astronomical Union
IERS	= International Earth Rotation Service

IGeS = International Geoid Service
IGS = International GPS Service for Geodynamics
IRM = IERS Reference Meridian
IRP = IERS Reference Pole
ITRF = IERS Terrestrial Reference Frame
ITS = Instantaneous Terrestrial System
IUGG = International Union of Geodesy and Geophysics
JGP95E = Joint Gravity Project 1995 Elevation
MC&G = Mapping, Charting and Geodesy
MREs = Multiple Regression Equations
MSL = Mean Sea Level
NAD 27 = North American Datum 1927
NAD 83 = North American Datum 1983
NASA = National Aeronautics and Space Administration
NAVSTAR GPS = Navigation Satellite Timing and Ranging GPS
NGS = National Geodetic Survey
NIMA = National Imagery and Mapping Agency
NNSS = Navy Navigation Satellite System
NSWC = Naval Surface Warfare Center (formerly Naval Surface Weapons Center)
NSWCDD = Naval Surface Warfare Center Dahlgren Division
OCS = Operational Control Segment
OSGB 36 = Ordnance Survey of Great Britain 1936
OSGB SN 80 = Ordnance Survey of Great Britain Scientific Network 1980
PPS = Precise Positioning Service
PSAD 56 = Provisional South American Datum 1956
RMS = Root-Mean-Square
SAD 69 = South American Datum 1969
SLR = Satellite Laser Ranging
SPS = Standard Positioning Service
TD = Tokyo Datum
TDRSS = Tracking and Data Relay Satellite System
TR = Technical Report
TRF = Terrestrial Reference Frame
UK = United Kingdom

US	= United States
USNO	= United States Naval Observatory
UT	= Universal Time
UTC	= Universal Time Coordinated
VLBI	= Very Long Baseline Interferometry
WGS	= World Geodetic System
WGS 60	= World Geodetic System 1960
WGS 66	= World Geodetic System 1966
WGS 72	= World Geodetic System 1972
WGS 84	= World Geodetic System 1984

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