NATO STANDARDIZATION OFFICE
BUREAU OTAN DE NORMALISATION

13 April 2016 NSO/0504(2016)C3/4294

STANAG 4294 C3 (EDITION 3) - NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)– PART I : SYSTEM CHARACTERISTICS

References:
a. AC/322(SC/8)N(2007)0005 dated 4 May 2007 (Edition 3) (Ratification Draft 1)
b. MAS/446-EL/4294 (PART I) dated 5 December 1997(Edition 2)

1. The enclosed NATO Standardization Agreement, which has been ratified by nations as reflected in the NATO Standardization Document Database (NSDD), is promulgated herewith.

2. The references listed above are to be destroyed in accordance with local document destruction procedures.

ACTION BY NATIONAL STAFFS

3. National staffs are requested to examine their ratification status of the STANAG and, if they have not already done so, advise the NSO, through their national delegation as appropriate of their intention regarding its ratification and implementation.

4. It should be noted that this standard entered ratification under AAP-03(I) and therefore is promulgated in its current format.

for
Dieter Schmaglowski
Deputy Director NSO
Branch Head P&C

Edvardas MAŽEIKIS
Major General, LTUAF
Director, NATO Standardization Office

Enclosure:
STANAG 4294 (Edition 3)

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STANAG 4294
PART I
(EDITION 3)

NORTH ATLANTIC TREATY ORGANIZATION
(NATO)

NATO STANDARDIZATION OFFICE
(NSO)

STANDARDIZATION AGREEMENT
(STANAG)

SUBJECT: NAVSTAR GLOBAL POSITIONING SYSTEM (GPS) – PART I : SYSTEM CHARACTERISTICS

Promulgated on 13 April 2016

Dieter Schmaglowski
Deputy Director NSO
Branch Head P&C

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Director, NATO Standardization Office

RECORD OF AMENDMENTS

No.	Reference/date of Amendment	Date Entered	Signature

EXPLANATORY NOTES

AGREEMENT

1. This NATO Standardization Agreement (STANAG) is promulgated by the Director NATO Standardization Office under the authority vested in him by the NATO Standardization Organisation Charter.

2. No departure may be made from the agreement without informing the tasking authority in the form of a reservation. Nations may propose changes at any time to the tasking authority where they will be processed in the same manner as the original agreement.

3. Ratifying nations have agreed that national orders, manuals and instructions implementing this STANAG will include a reference to the STANAG number for purposes of identification.

RATIFICATION, IMPLEMENTATION AND RESERVATIONS

4. Ratification, implementation and reservation details are available on request or through the NSO websites (internet http://nso.nato.int; NATO Secure WAN http://nso.hq.nato.int).

FEEDBACK

5. Any comments concerning this publication should be directed to NATO/NSO – Bvd Leopold III - 1110 Brussels – BE.

NATO STANDARDIZATION AGREEMENT
(STANAG)
NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)
Part I - SYSTEM CHARACTERISTICS

Annex:

A. General System Characteristics

Related Documents:

a.	STANAG 4159	NATO Configuration Management Plan (Draft)
b.	MC 139/1	(Final) Navigation System Support for NATO Military Operations
c.	ANP-1	The NATO Master Navigation Document [NATO SECRET]
d.	ANP-2	Introduction to Navstar GPS User Equipment
e.	ANP-4	The NATO Guideline for IFR Certification of Navigation Systems Using GPS PPS
f.	DMA TR 8350.2	Department of Defense World Geodetic

System 1984

g. DATM-5-241-1 1967 (Plates updated 1976 and 1981) Grid and Grid References

h. C-M(55)15 (Final) Security within the North Atlantic Treaty Organization

i. CZE 93-237 Navstar Global Positioning System Security Classification Manual

j. SS-GPS-300G System Specification for the Navstar Global Positioning System

k. IS-GPS-200D Navstar GPS Space Segment/Navigation User Interfaces (U)

l. ICD-GPS-222 Interface Control Document for the Navstar Global Positioning System User Equipment Auxiliary Output Chip (U) [SECRET document]

m. ICD-GPS-224 Navstar GPS Selective Availability and Anti-Spoofing Receiver Design Requirements (U) [SECRET document]

n. ICD-GPS-225 Navstar GPS Selective Availability and Anti-Spoofing Receiver Design Requirements with the Precise Positioning Security Module (U) [SECRET document]

o. ICD-GPS-227 Navstar GPS Host Application Equipment Design Requirements with the Selective Availability / Anti-Spoofing Module (SAASM) (U) [SECRET document]

p. ICD-GPS-700A Navstar GPS Military-Unique Space Segment/User Segment Interfaces (For Official Use Only)

q. Precise Positioning Service (PPS) Performance Standard (PS),Edition 1 (U)

r. Standard Positioning Service (SPS) Performance Standard (PS), Edition 1(U)

AIM

1. The aim of this Standardization Agreement (STANAG) is to define the system characteristics of the Navstar Global Positioning System (GPS) essential to the design of receivers and use of the system by all military services of the nations belonging to NATO.

AGREEMENT

2. Participating nations agree that:

a. The GPS is as defined in Annex A.

b. The algorithms defined in Annex A are used within NATO as a standard to evaluate the GPS system.

No departure may be made from this Agreement without consultation with the Military Agency for Standardization.

3. Nations may propose changes to the STANAG should they consider the characteristics, or part thereof, to have become obsolete or require improvements. Such proposals should be submitted, at the earliest opportunity, to the Interoperability and Co-operative Programme Section; Command, Control and Communications Directorate; Defence Support Division; NATO International Staff.

DEFINITIONS AND ABBREVIATIONS

4. The definitions and abbreviations used in this Agreement are given in Appendix 1 to Annex A.

PROTECTION OF PROPRIETARY RIGHTS

Not Applicable.

DETAILS OF THE AGREEMENT

5. The Navstar GPS is a satellite-based radio-positioning, navigation, and time transfer system that operates on two D-band frequencies, 1575.42 MHz (L1) and

1227.6 MHz (L2), using spread spectrum modulation. Two navigation accuracy levels will be provided:

a. The Precise Positioning Service (PPS)

b. The Standard Positioning Service (SPS).

IMPLEMENTATION OF THE AGREEMENT

6. This STANAG is considered to be implemented when the United States has issued instructions that the Space and Control Segments of the GPS meet the requirements detailed in this Agreement and a participating nation has issued instructions that all future equipment used by its forces will operate in accordance with these requirements.

STANAG 4294 - NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

Part I - SYSTEM CHARACTERISTICS

ANNEX A: GENERAL SYSTEM CHARACTERISTICS

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ANNEX A: GENERAL SYSTEM CHARACTERISTICS

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2. P(Y)-Code and C/A-Code Characteristics
3. M-Code Characteristics
4. Reserved
5. Geometric Dilution of Precision
6. Standard Algorithms
7. Summary of Performance Requirements*

1. GENERAL SYSTEM DESCRIPTION

The Navstar GPS is a satellite-based radio-positioning, navigation, and time-transfer system that operates on two D-band frequencies, 1575.42 MHz (L1) and 1227.6 MHz (L2), using spread spectrum modulation. Two navigation accuracy levels will be provided: the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The PPS will provide the greater degree of accuracy. Access to the PPS will be controlled by cryptographic techniques.

The GPS is comprised of three segments: Space, Control and User. The fully operational Space Segment (SS) consists of a nominal constellation of 24 satellites in six orbital planes, four satellites in each plane. The satellites may be moved around in their orbits as necessary. Each satellite transmits L1 and L2 frequencies. L1 is modulated by both a

*Appendix 7 is classified and maintained as a separate document.

precise code (either P-code or Y-code) and a coarse/acquisition ranging code (C/A-code), and in Block IIR-M/IIF satellites also by an encrypted military code (M-code). L2 is modulated by P-code or Y-code (denoted as P(Y)-code), and in Block IIR-M/IIF satellites also by M-code. (The capability also exists in Block IIR-M/IIF satellites to modulate L2 with the C/A-code or an additional civil code in addition to the P(Y)-code and M-code.) Superimposed on these signals will be navigation data including satellite ephemeris and satellite clock information.

The Control Segment (CS) includes a number of Monitor Stations and Ground Antennas located throughout the world. The Monitor Stations use GPS receivers to passively track all satellites in view and thus accumulate ranging data from the satellite signals. The information from the Monitor Stations is processed at the Master Control Station to determine satellite orbits and to update the navigation message of each satellite. This updated information is transmitted to the satellites via the Ground Antennas, which are also used for transmitting and receiving satellite control information.

The User Segment consists of GPS receivers that utilize data transmitted by the satellites to derive navigation and time information. The PPS enables authorized users to access full system accuracy. The SPS enables all users to access reduced system accuracy.

2. SATELLITE CONSTELLATION CHARACTERISTICS

The reference orbital values of operational (Block II, Block IIA, Block IIR, Block IIR-M, and Block IIF) satellites are given in Table I. Each satellite is assigned a nominal orbit slot defined by the reference orbital position parameters. The orbital slot tolerances with respect to reference orbit parameters are selectable at launch from the range of values listed in Table II.

Table I. Baseline Orbit Slot Reference Values

Orbit Slot Identifier	Argument of Latitude, degrees	Geographic Longitude of Ascending Node, degrees	Right Ascension of Ascending Node, degrees*
A1	268.126	127.85	272.847
A2	161.786	74.68	272.847
A3	11.676	179.63	272.847
A4	41.806	14.69	272.847
B1**	80.956	94.27	332.847
B2	173.336	140.46	332.847
B3	309.976	28.78	332.847
B4	204.376	155.98	332.847
C1	111.876	169.73	32.847
C2	11.796	119.69	32.847
C3	339.666	103.62	32.847
C4	241.556	54.57	32.847
D1	135.226	61.40	92.847
D2**	265.446	126.51	92.847
D3	35.156	11.37	92.847
D4	167.356	77.47	92.847
E1	197.046	152.31	152.847
E2	302.596	25.09	152.847
E3	66.066	86.82	152.847
E4	333.686	40.63	152.847
F1	238.886	53.23	212.847
F2**	345.226	106.40	212.847
F3	105.206	166.39	212.847
F4	135.346	1.46	212.847

Epoch of 01 July 93, 0 hours, 0 minutes and 0 seconds

* Referenced to FK5/J2000.00 coordinates

** Orbital slots marked by a double asterisk are expandable

Table II. Nominal Orbit Tolerances

Parameter	Value	Operational Range	Required Tolerance Over Satellite Lifetime
Semi-Major Axis, km	26,559.7	± 50 KM (Note 1)	± 50 KM (Notes 1, 2)
Eccentricity	0.0	0.0 to 0.020	0.0 to 0.020
Inclination, deg	55.0	± 3	± 3 (Note 4)
Right Ascension of Ascending Node, deg E of Vernal Equinox	Note 3	± 180	± 2.5 deg (Note 5)
Argument of Latitude at Epoch, deg	Note 3	± 180	± 2 deg (Note 2)
Argument of Perigee, deg	0.0	±180	NA
Time of Epoch	Note 3	NA	NA

Note 1: Block II/IIA satellites operate within ± 17 km of nominal. Blocks IIR, IIR-M and IIF satellites will operate within 50km of nominal semi-major axis values.

Note 2: The semi-major axis and orbital period is adjusted to maintain the relative spacing of the satellite ground track equatorial crossings to within ± 2 deg of chosen values, with one year or more between orbital adjustments. The nominal value shown provides stationary ground tracks.

Note 3: Reference Table I.

Note 4: Block II/IIA, Block IIR/IIR-M, and Block IIF.

Note 5: Block II/IIA is ± 2; Block IIR/IIR-M is -2.0/+ 2.5; and Block IIF is ± 2.5.

Each expandable slot identified in Table I may be occupied by either a single satellite in the baseline position defined in Table I or by a pair of satellites in the expanded positions defined in Table III. The fore (F) and aft (A) positions in an expanded baseline slot are defined relative to the baseline slot the direction of satellite motion.

Table III. Expandable Orbit Slots

Expandable Slot		Argument of Latitude, degrees	Geographic Longitude of Ascending Node, degrees	Right Ascension of Ascending Node, degrees*
B1 Expands To:	B1F	94.916	101.25	332.847
	B1A	66.356	86.97	332.847
D2 Expands To:	D2F	282.676	135.13	92.847
	D2A	257.976	122.78	92.847
F2 Expands To:	F2F	0.456	114.02	212.847
	F2A	334.016	100.80	212.847

It can be shown that all variations of the expanded 24-slot constellation defined by Tables I and III provide global performance that is at least as good as the fully-occupied baseline 24-slot constellation when all orbital locations in the expanded 24-slot constellation variation (baseline slots and expanded slots) are occupied by healthy satellites. Expandable slots occupied by a pair of healthy satellites enhance the overall performance; but no credit can be taken for them relative to the baseline 24-slot constellation performance. There are no defined probabilities of any of the expandable slots being in their expanded configurations and occupied by pairs of healthy satellites.

Constellation parameters may be modified in pursuance of US/NATO security interests. The actual constellation right ascension of ascending node values will change over a satellite's lifetime due to perturbation forces and variations in each unique orbit's nodal regression rate. Maintenance of the geographic longitude of ascending node values and relative spacing of the slots are the controls employed to compensate for orbit plane drift and sustain constellation geometry at acceptable levels. It is also possible for the inclination to drift out of the operational range.

3. SATELLITE NAVIGATION MODES

3.1 Extended Navigation Mode (Block II/IIA)

The Block II and IIA satellites are capable of being uploaded by the CS with a minimum of 60 days of navigation data to support a 60 day positioning service. Due to memory retention limitations, the Block II satellites may not transmit correct data for the entire 180 days but are guaranteed to transmit correct data for at least 14 days to support short-term extended operations. Under normal conditions, the CS will provide daily uploads to each satellite, which will allow the satellite to maintain normal operations. During normal operations, the satellites will have a PPS User Range Error (URE) that is at or below a level required to support a positioning accuracy of 13.5 metres (95%) horizontal and 26.9 metres (95%) vertical. In addition, the almanac data, UTC parameters and ionospheric data will be maintained current to meet the accuracy specified in this STANAG.

If the CS is unable to upload the satellites (the CS is unavailable or the satellite is unable to accept and process the upload), each satellite will individually transition to the short-term extended operations and eventually to long-term extended operations (based on time from each satellite's last upload) as further described throughout this STANAG. As time from upload continues through these three operational intervals, the URE of the satellite will increase, causing a degradation of accuracy. The rate of accuracy degradation is slow over the short-term extended operations interval, such that at the end of this interval (approximately 14 days after upload) the User Segment will be able to achieve a positioning accuracy of 575 metres (95%) horizontal and 1150 metres (95%) vertical. During these intervals the URA will continue to provide the proper estimate of the URE. During short-term extended operations (approximately day 2 through day 14 after an upload), the almanac data, UTC parameters and ionospheric data will not be maintained current and will degrade in accuracy from the time of last upload for each satellite.

3.2 Block IIA Mode (Block IIR/IIR-M)

The Block IIR/IIR-M satellites, when operating in the Block IIA mode, will perform similarly to the Block IIA satellites and will provide at least 14 days of positioning service (through short-term extended operations) without contact from the CS.

4. SATELLITE SIGNAL MODULATION CHARACTERISTICS

4.1 General

The L1 and L2 carriers are modulated by one or more bit streams, each of which is the Modulo-2 addition of a pseudorandom noise (PRN) ranging code and navigation data.

4.2 Ranging Codes

4.2.1 General

Appropriate code-division-multiplexing techniques allow differentiation between the satellites even though they all transmit at the same D-band frequencies. Three PRN ranging codes may be transmitted: the P (precision) code; the Y-code, used in place of the P-code whenever the anti-spoofing (A-S) mode of operation is activated by the Control Segment (reference paragraph 4.5); the C/A (coarse/acquisition) code, which is used primarily for acquisition of the P(Y)-code; and the Military-Unique (MU) M-code. Internal failures detected by a satellite will cause the satellite to transmit codes which do not correspond to those of any working satellite, and which are designed to protect users from using incorrect information. These failure-mode codes are termed non-standard C/A (NSC), non-standard Y (NSY) and non-standard M (NSM) codes. The satellites are capable of independently initiating and terminating the broadcast of NSC, NSY and/or NSM code(s) in response to the Control Segment command.

4.2.2 P-code

The PRN P-code is 7 days in duration at a chipping rate of 10.23 Mbps. P-code characteristics are defined in Appendix 2 and IS-GPS-200.

4.2.3 Y-Code

The PRN Y-code, used in place of the P-code at the same chipping rate when the A-S mode of operation is activated, is defined in ICD-GPS-224 (SECRET) and/or in ICD-GPS-225 (SECRET) and/or in ICD-GPS-227 (SECRET). Y-code characteristics are described in paragraph 4.5.

4.2.4 C/A-Code

The PRN C/A-code for SV ID number i is a Gold code, $G_i(t)$, of 1 ms in duration at a chipping rate of 1.023 Mbps. C/A-code characteristics are defined in Appendix 2 and IS-GPS-200.

4.2.5 M-Code

The M-code provides the MU ranging code, formed by modulo-2 addition of a TRANSEC-derived PRN spreading sequence at a chipping rate of 5.115 MHz and a 10.23 MHz square wave that are synchronized in time. The characteristics of M-code are further defined in Appendix 3 and ICD-GPS-700.

4.2.6 Non-standard Codes

The NSC, the NSY, and the NSM codes, used to protect the user from a satellite malfunction, are not for utilization by the user and therefore are not defined in this document.

4.3 Navigation Data

For P(Y) and C/A-codes, the navigation (NAV) data includes satellite ephemeris, system time, satellite clock behaviour data, status messages, C/A- to P(Y)-code handover information, etc. This 50-bps data is Modulo-2 added to the P(Y) and C/A-codes; the resultant bit streams are used to modulate the L1 and L2 carriers. For a given SV, the data train, if present, is common to the P(Y) and C/A codes on both the L1 and L2 channels.

For M-code, the military navigation (MNAV) data is Modulo-2 added to the M-code at either 25-bps or 100-bps; the resultant bit streams are used to modulate the L1 M and L2 M carriers. The nominal configuration is for data content to be common, operating at 100-bps.

4.4 Selective Availability (SA)

To deny access by SPS users to the full system accuracy, the signals are transmitted from the satellites with errors added. These errors are removed by PPS users by employing SA decryption techniques. SPS users are unable to remove these errors and receive a reduced standard of service.

Beginning on 2 May 2000, the magnitude of the errors added by SA was set to zero. This action was not the same as ‘‘turning SA off’’. SA is still on; but the level of errors was reduced from the ‘‘normal peacetime level’’ to the current ‘‘discontinued level’’ of zero. PPS receivers still process SA and remove the added errors; the change is just that the magnitude of the errors added by SA and removed by PPS receivers are all zero. The US Government is committed to maintaining SA at the ‘‘discontinued level’’ of degradation.

Three options for removing the SA errors are available to a manufacturer of a GPS PPS receiver. Option 1 is to distribute the error correction capability throughout the receiver design. ICD-GPS-224, Navstar GPS Selective Availability and Anti-Spoofing Receiver Design Requirements (U)

(SECRET), together with a Communications Security (COMSEC) Agreement document (SECRET), provides the required Option 1 receiver design implementation information. Option 2 is to incorporate a separate SA module within the receiver. ICD-GPS-225, Navstar GPS Selective Availability and Anti-Spoofing Receiver Design Requirements with the Precise Positioning Security Module (U) (SECRET), together with an SA module manufacturer-provided interface control document provides the Option 2 implementation information. And Option 3 is to incorporate a separate SA module within the receiver. ICD-GPS-227, Navstar GPS Host Application Equipment Design Requirements with the Selective Availability / Anti-Spoofing Module (SAASM) (U) (SECRET) provides the Option 3 implementation information.

4.5 Anti—Spoofing

In the A-S mode of operation, the P-code is added to a cryptographic sequence to prevent code prediction by unfriendly forces. The encrypted P-code is denoted as the Y-code. In older PPS equipment, the encryption is accomplished in one A-S module per hardware channel within the receiver. The interface characteristics of this module are defined in ICD-GPS-222, Interface Control Document for the Navstar Global Positioning System User Equipment Auxiliary Output Chip (U) (SECRET). A-S techniques and characteristics are further defined in ICD-GPS-224 (SECRET) and/or ICD-GPS-227 (SECRET).

5. ELECTRICAL CHARACTERISTICS

The electrical characteristics of the D-band signals are defined in Appendix 2.

6. SYSTEM ACCURACY

All accuracies stated in this document are 95% values (as defined in Appendix 1 to Annex A) unless otherwise specified.

6.1 Positioning Accuracy

The PPS positioning accuracy at any given location and at any given time is estimated by multiplying two factors: (1) Geometric Dilution of Precision (GDOP), and (2) User Equivalent Range Error (UERE). GDOP, which depends only on the geometry of the subset of in-view satellites which the receiver tracks and uses, is defined in Appendix 5. UERE, which is independent of GDOP, represents the receiver ranging error among the satellites used in the position-time solution. (The ranging error for each satellite will be different depending upon its performance and the time since the CS last uploaded it.) A PPS UERE budget for dual frequency (L1 and L2) receivers is provided in Table IV. A PPS UERE budget for single frequency (L1 only or L2 only) receivers is provided in Table V.

Tables VI, VII, and VIII contain a summary of PPS and SPS positioning accuracies under various conditions of SA and A-S. The accuracy values presented define the system performance from the unexpanded constellation of 24 satellites. For comparison purposes, SPS accuracies are given for both the ''normal peacetime'' level of SA which existed prior to 2 May 2000 and the ''discontinued'' level of SA which has been in effect since 2 May 2000.

The 95th percentile values presented in the tables are based on accuracy distributions, which are cumulative over 24 hours, worldwide, for a mask angle of 5 degrees. These values may be used for planning purposes and are derived using the following factors and assumptions in computer simulations:

a. Specification for dual-frequency performance is 13.5 metres 95% horizontal, and 26.9 metres 95% vertical at 99% availability.
b. Specification for single-frequency performance (ignoring single-frequency ionospheric delay model errors) is 15.5 metres 95% horizontal, and 31.0 metres vertical at 99% availability.

c. User correctly implements ICD-GPS-200 and if PPS, also correctly implements ICD-GPS-224 or ICD-GPS-225 or ICD-GPS-227.

d. The URE distribution is assumed to be Gaussian and the age of the data (AOD) broadcast by the satellites during normal operations is assumed to be uniformly distributed between 0 and 24 hours.

e. The 95% URE sampled across an entire constellation of satellites in normal operations with uniformly distributed AODs is specified as 5.9 m for dual-frequency operation and 7.8 m for single-frequency operation ignoring single-frequency ionospheric delay correction model errors. (The assumed 95% URE for single-frequency operation including single-frequency ionospheric delay correction model errors ranges from 12.5 m to 21.1 m).

f. The dual-frequency User Equipment Error (UEE) is assumed to be Gaussian with an accuracy of 7.1 m 95%, and the single-frequency UEE is also assumed to be Gaussian with an accuracy of 7.1 m 95%.

g Unless otherwise noted, users track and use all satellites from the 24-slot constellation in view at their location above a mask angle of 5 degrees.

h Unless otherwise noted, Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP) are based on the long-term geometry averaged across all constellation slot occupancy

Table IV. Dual-Frequency PPS UERE Budget

Segment	Error Source	UERE Contribution (95%)(meters)	
		24 Hours Without Upload	14 Days Without Upload
Space	Clock Stability	8.9	257
	Group Delay Stability	0.6	0.6
	Diff'l Group Delay Stability	2.0	2.0
	Satellite Acceleration Uncertainty	2.0	204
	Other Space Segment Errors	1.0	1.0
Control	Clock/Ephemeris Estimation	2.0	2.0
	Clock/Ephemeris Prediction	6.7	206
	Clock/Ephemeris Curve Fit	0.8	1.2
	Iono Delay Model Terms	N/A	N/A
	Group Delay Time Estimate	N/A	N/A
	Other Control Segment Errors	1.0	1.0
User*	Ionospheric Delay Compensation	4.5	4.5
	Tropospheric Delay Compensation	3.9	3.9
	Receiver Noise and Resolution	2.9	2.9
	Multipath	2.4	2.4
	Other User Segment Errors	1.0	1.0
95% System UERE (PPS)		13.8	388

* For illustration only, actual PPS receiver performance varies significantly

Table V. Single-Frequency PPS UERE Budget

Segment	Error Source	UERE Contribution (95%) (meters) 24 Hours Without Upload	UERE Contribution (95%) (meters) 14 Days Without Upload
Space	Clock Stability	8.9	257
	Group Delay Stability	1.6	1.6
	Differential Group Delay Stability	0.0	0.0
	Satellite Acceleration Uncertainty	2.0	204
	Other Space Segment Errors	1.0	1.0
Control	Clock/Ephemeris Estimation	2.0	2.0
	Clock/Ephemeris Prediction	6.7	206
	Clock/Ephemeris Curve Fit	0.8	1.2
	Iono Delay Model Terms	9.8-19.6	9.8-19.6
	Group Delay Time Estimate	4.5	4.5
	Other Control Segment Errors	1.0	1.0
User*	Ionospheric Delay Compensation	N/A	N/A
	Tropospheric Delay Compensation	3.9	3.9
	Receiver Noise and Resolution	2.9	2.9
	Multipath	2.4	2.4
	Other User Segment Errors	1.0	1.0
95% System UERE (PPS)		16.8 - 23.9	388

* For illustration only, actual PPS receiver performance varies significantly

Table VI. GPS Horizontal Positioning Accuracies* (Metres, 95%)

Operating Mode		Dual Frequency		Single Frequency****	
SA	A-S	PPS	SPS	PPS	SPS
DISCONTINUED	OFF	13.5	13.5	15.5	15.5
NORMAL PEACETIME	OFF	13.5	98**	15.5	100**
DISCONTINUED	ON	13.5	NA***	15.5	15.5
NORMAL PEACETIME	ON	13.5	NA***	15.5	100**

* Worldwide, 99% availability, minimum satellite elevation 5° unless otherwise noted.

** Commitment for receivers which only track the ''best 4'' subset of satellites, independent of constellation slot occupancy state, minimum satellite elevation 7.5°, includes single-frequency ionospheric delay model errors.

*** NA indicates not available with A-S on.

**** Ignores single-frequency ionospheric delay model errors unless otherwise noted.

Table VII. GPS Vertical Positioning Accuracies* (Metres, 95%)

Operating Mode		Dual Frequency		Single Frequency****	
SA	A-S	PPS	SPS	PPS	SPS
DISCONTINUED	OFF	26.9	26.9	31.0	31.0
NORMAL PEACETIME	OFF	26.9	156**	31.0	159**
DISCONTINUED	ON	26.9	NA***	31.0	31.0
NORMAL PEACETIME	ON	26.9	NA***	31.0	159**

* Worldwide, 99% availability, minimum satellite elevation 5° unless otherwise noted.

** Commitment for receivers which only track the ''best 4'' subset of satellites, independent of constellation slot occupancy state, minimum satellite elevation 7.5°, includes single-frequency ionospheric delay model errors.

*** NA indicates not available with A-S on.

**** Ignores single-frequency ionospheric delay model errors unless otherwise noted.

probabilities for all-in-view (AIV) user operation with the 24-slot unexpanded constellation; with assumed probabilities of slots being filled by healthy/operating satellites of: 24 slots at 72%, 23 slots at 17%, 22 slots at 6.4%, 21 slots at 2.6%, and 20 slots at 2.0%. With 99% availability, the HDOP is 1.655 and the VDOP is 2.925.

i. Performance is calculated at sites uniformly distributed in time and space over the surface of the earth

6.2 Timing Accuracy

Multiplying the UERE by the Time Dilution of Precision (TDOP) and dividing the result by the speed of light derive PPS timing accuracy with respect to GPS time. TDOP is defined in Appendix 5. The Control Segment maintains GPS time to be within one microsecond of UTC (USNO) modulo one second. The modulo one second requirement is due to the fact that GPS is a continuous time scale while UTC is occasionally adjusted by a leap second. The navigation data contains the requisite data for relating GPS time to UTC. The Control Segment maintains the UTC offset parameters to an accuracy within 40 ns (95%). Accuracy of time obtained by a user is a function of the individual satellite UEREs and either the TDOP or the Time Transfer Dilution of Precision (TTDOP) derived from the geometry of the visible constellation.

6.3 Velocity Accuracy

The velocity accuracy which can be derived from PPS, and from SPS under the ‘‘discontinued’’ SA level, is almost entirely dependent on receiver design and user dynamics. Space and Control Segment contributions to this error are negligible. A velocity accuracy of 0.2 m/s along any axis (95%) can be achieved.

The velocity accuracy that could be achieved using the SPS under the ‘‘normal peacetime’’ SA level is given in Appendix 7 (NATO SECRET).

6.4 Graceful Degradation of Accuracy

In case of total loss of the CS, resulting in the absence of Block II, Block IIA and Block IIR/IIF (in Block IIA mode) satellite uploads, the system ranging accuracy will degrade gracefully with time as illustrated in Figure 1 (reference paragraph 3). Tables IV and V provide the PPS UERE budgets for the 14th day after the last Block II, Block IIA and Block IIR/IIF (in Block IIA mode) satellite upload. After the 14th day without a Block II, Block IIA and Block IIR/IIF (in Block IIA mode) satellite upload, the satellite signals may be unusable for navigation.

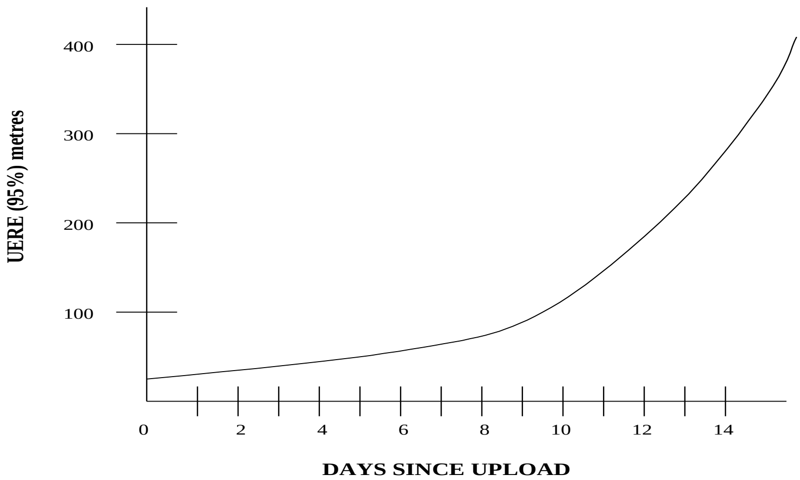

Figure 1. UERE Graceful Degradation

7. SYSTEM AVAILABILITY AND SIGNAL-IN-SPACE INTEGRITY

7.1 General

The user of any system demands not only that it should have adequate basic performance, but that the service offered should be available whenever required, and that no incorrect or misleading information should be given that could adversely affect the user's operations or affect safety. A system is defined to have high availability and integrity when there is:

a. A high probability that service to the full specification will be available whenever required;
b. A very low probability that undetected errors are present in the system, causing misleading information to be given to the user.

7.2 System Availability

System availability is defined as the probability that 21 or more satellites will be in their assigned orbital slots and operating within specifications as specified in this STANAG. In addition, the system will meet the SS and CS segment errors listed in the UERE budget shown in Tables IV and V. The GPS has a system availability of at least 98% for users.

7.3 Availability of Accuracy

The availability of accuracy from GPS is limited by the constellation geometry. The constellation geometry, in turn, is limited by the number of healthy and operating satellites in the constellation slots. When multiple satellites fail, there are times and places on the globe where there are not enough healthy and operating satellites visible to allow users to compute a position-time solution. In these cases, the GDOP, HDOP, VDOP, etcetera become infinite and GPS accuracy is defined to be unavailable.

The bound on the probability of GPS accuracy becoming unavailable is the 99% availability of accuracy constraint which appears in Tables VI and VII. Accuracy is specified at the 99th percentile worst-case geometry.

7.4 Signal-in-Space (SIS) Integrity

The overall mission integrity requirement is a 0.9979 probability (averaged over any one-year interval) of no unalerted misleading signal information (UMSI) from anywhere in the entire constellation. This requirement is allocated entirely to the signal-in-space (SIS) provided by the SS and CS. Since there are 8760 hours in a year, this mean that UMSI from anywhere in the constellation shall occur no more than 18 hours out of a year.

UMSI occurs when the SIS from a satellite marked as healthy is affected by an unexpected soft failure and the SIS URE grows to become greater than 4.42 times the upper bound on the user range accuracy (URA) value corresponding to the URA index ‘‘N’’ currently broadcast by the satellite for the PPS user.

The overall mission integrity requirement assumes the mean time between loss of integrity (MTBLOI) for the entire constellation is greater than or equal to 0.33 years. The overall mission integrity requirement also assumes the mean maximum time to restore integrity (MaxTTRI) is less than or equal to 6 hours.) The allocation between the MTBLOI for the GPS satellite signals and the MaxTTRI for the CS response is unconstrained, provided that the overall mission integrity requirement above is satisfied.

A user at a single location, which sees an affected satellite signal for the maximum duration of all UMSI events, will experience mission integrity of greater than or equal to 99.79%. On a global average, under the minimum

MTBLOI and the maximum MaxTTRI, a user with equipment which only processes 4 satellite signals at a time will experience an average mission integrity of 99.97% since that user's equipment only has a 4-in-24 chance of using a satellite signal affected by UMSI. Similarly, since the global average number of satellites in view is 8, a user with equipment which processes all satellite signals in view will experience an average mission integrity of 99.94% since that equipment has an 8-in-24 chance of using a satellite signal affected by UMSI.

8. WIDE AREA GPS ENHANCEMENT (WAGE)

GPS has a built-in wide area differential GPS (DGPS) service for PPS users. This DGPS service is called the Wide Area GPS Enhancement (WAGE). The DGPS corrections are broadcast in a Navigation Message Correction Table (NMCT) as part of each satellite's navigation (NAV) message. The NMCT is currently encrypted and is available only to PPS users.

Unclassified details regarding WAGE are given in IS-GPS-200. Classified details, particularly how to decrypt the NMCT, are given in ICD-GPS-224 (SECRET) and/or in ICD-GPS-225 (SECRET) and/or in ICD-GPS-227 (SECRET).

Use of WAGE significantly improves SIS accuracy, but does not do anything for SIS integrity. The NMCT is only broadcast once every 12.5 minutes, which is too slow to impact integrity.

The specified accuracy for dual-frequency PPS with WAGE is a SIS URE of 4.4 m 95%, which is roughly a 25% improvement compared to the SIS URE of 5.9 m 95% for dual-frequency PPS with WAGE. Actual accuracy improvement with WAGE in 2006 has typically been observed to be the 50% range for dual-frequency PPS.

9. STANDARD ALGORITHMS

Standard receiver algorithms are defined in Appendix 6.

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APPENDIX 1 –– DEFINITIONS AND ABBREVIATIONS

1. DEFINITIONS

Authorized User - A user whose GPS receiver contains both current valid PPS keys and has the requisite hardware/software capabilities to be able to properly use those PPS keys. Also known as a PPS user.

Baseline Constellation - The defined orbital slots for the deployment of Navstar satellites. An orbital slot is characterized by a near one-half sidereal day period such that the orbit ground trace repeats each sidereal day. The orbital slots are organized into an orbit plane. Each orbit plane has multiple slots with each slot having a unique orbital ground trace. There are six orbit planes, each with four slots, in the baseline 24-satellite constellation.

Block II Satellites - The first block of full scale operational satellites developed by Rockwell International are designated as satellite vehicle numbers (SVNs) 13 through 21 and are termed "Block II" satellites. These satellites were designed to provide 14 days of positioning service without contact from the Control Segment.

Block IIA Satellites - The second block of full scale operational satellites developed by Rockwell International are designated as SVNs 22 through 40 and are termed "Block IIA" satellites. These satellites were designed to provide 60 days of positioning service without contact from the Control Segment, but are only guaranteed for the first 14 days after an upload.

Block IIR Satellites - The block of operational replenishment satellites developed by Martin Marietta are designated as SVNs 41 through 61 and are termed "Block IIR" satellites. These satellites will provide at least 14 days of positioning service without contact from the Control Segment when the satellites are operating in the Block IIA mode.

Block IIR-M Satellites - The subset of operational replenishment satellites developed by Martin Marietta, which are ‘‘Modernized’’ configuration of ‘‘Block IIR’’ satellites. The first block of operational satellites that transmit M-code.

Block IIF Satellites - The block of operational replenishment satellites developed by Boeing are designed as SVNs 62-73 and are termed ‘‘Block IIF’’ satellites. These satellites will provide at least 14 days of positioning service without contact from the Control Segment when the satellites are operating in the Block IIA mode

Constellation Value —— The fraction of the Earth's surface, averaged over time, where PDOP for the best four satellites above a 5° elevation does not exceed six.

Control Segment —— The ground-based segment of the GPS, consisting of four major components: Monitor Stations, a Master Control Station (MCS), Backup Master Control Station (BMCS) and Ground Antennas.

Developmental Satellites - The original concept validation satellites developed by Rockwell International and designated as SVNs 1 through 11 were termed "Block I" satellites. These satellites were designed to provide 3 to 4 days of positioning service without contact from the Control Segment. These satellites transmitted a configuration code of 000. There are no longer any active Block I satellites in the GPS Constellation. The last Block I satellites was decommissioned in 1995.

Geometric Dilution of Precision (GDOP) —— A factor used to account for the specific constellation geometry in the estimation of a navigation error. GDOP depends only on the geometry of the satellites in view.

Horizontal Dilution of Precision (HDOP) —— The horizontal position component of GDOP.

Horizontal 95% —— The radius of the smallest horizontal circle, centered at the true position point, that encompasses 95% of the measurements.

Long-term Extended Operations - The satellite is in long-term extended operations whenever the fit interval flag is one and the IODE is in the range 240-255. Note: The DoD Navigation User Segment and Time Transfer User have no requirement to operate, and may not operate properly, whenever any satellite is operating in long-term extended operations.

M-Code - provides the ranging code for Military-Unique (MU) Signal in Space (SIS) on both the L1 M and L2 M RF links as defined in ICD-GPS-700.

Normal Operations - The satellite is undergoing normal operations whenever the fit interval flag is zero.

Operational Satellites - The operational satellites are designated Block II, Block IIA,Block IIR, Block IIR-M and Block IIF satellites. These satellites transmit configuration codes. The navigation signal provides no direct indication of the type of the transmitting satellite.

Position Dilution of Precision (PDOP) —— The position component of GDOP.

Precise Positioning Service (PPS) —— The GPS broadcast signals based on the L1 P(Y)-codes, L1 C/A-codes, and L2 P(Y)-codes, as defined in IS-GPS-200, ICD-GPS-224, ICD-GPS-225, and ICD-GPS-227, provided to authorized users. The PPS performance is defined in the *PPS Performance Standard (PPS PS)* in accordance with U.S. Government policy.

Short-term Extended Operations - The satellite is in short-term extended operations whenever the fit interval flag is one and the IODE is less than 240. This is approximately for days 2 through 14 after an upload.

Space Segment —— The GPS segment consisting of the satellites on orbit.

Standard Positioning Service (SPS) — The GPS broadcast signals based on the L1 C/A-codes, as defined in IS-GPS-200, provided to peaceful civil, commercial, and scientific users. SPS performance is defined in the *SPS Performance Standard (SPS PS)* in accordance with U.S. Government policy.

Three-Dimensional (3-D) 95% —— The radius of the smallest sphere, centered at the true position point that encompasses 95% of the measurements.

Time 95% —— The smallest resultant magnitude, centered at truth, which would encompass 95% of the observations.

Time Dilution of Precision (TDOP) —— The time component of GDOP.

Unauthorized User - A user whose GPS receiver: (1) does not contain current valid PPS keys, or (2) does not have the requisite hardware/software capabilities to be able to use PPS keys.

User Equipment (UE) —— UE includes antennas, receivers, control/displays, etcetera.

User Equipment Error (UEE) —— The portion of the ranging error component for the satellite along the line of sight between the user and the satellite being evaluated which is the responsibility of the User Segment.

User Equivalent Range Error (UERE) —— The component of system accuracy, which is independent of location and time, that represents the receiver and satellite ranging errors found in the measured ranging data.

User Range Accuracy (URA) —— URA is a statistical indicator of the ranging accuracies obtainable with a specific satellite. URA is a one-sigma estimate of the user range errors in the navigation data for the transmitting satellite. It includes all errors for which the Space and Control Segments are responsible. It does not include any errors introduced in the user set or the transmitting media. While the URA may vary over a given subframe fit interval, the URA index (N) reported in the NAV message corresponds to the maximum value of URA anticipated for the fit interval.

User Range Error (URE) —— The portion of the ranging error component for the satellite along the line of sight between the user and the satellite being evaluated which is the responsibility of the SS and CS.

User Segment —— The GPS segment consisting of the users with user equipment (UE), peculiar support equipment, etcetera.

Velocity 95% Per Axis —— The smallest resultant magnitude, centered at truth, which would encompass 95% of the observations.

Vertical 95% —— The smallest resultant magnitude, centered at truth, which would encompass 95% of the observations.

2. ABBREVIATIONS

AIV	All-in-view (e.g., at least able to track 12 satellites)
A-S	Anti-spoofing
AOD	Age of data (e.g., time since last upload)
AODA	Age of data, almanac
ASCII	American Standard Code for Information Interchange
BIH	Bureau International de L'Heure
BOC	Binary Offset Carrier
bps	Bits per second
BPSK	Bi-phase shift keying
C/A	Coarse/acquisition code
CIO	Conventional International Origin
COMSEC	Communications security
CONUS	Continental United States
cov	Covariance
CS	Control Segment
dB	Decibel
dBic	Decibels above isotropic circular
dBW	Decibels referenced to one watt
DEC	Declination
DGPS	Differential GPS (e.g., Wide Area GPS Enhancement)
DIP	Inclination
DMA	U.S. Defense Mapping Agency
DOD	U.S. Department of Defense
E, exp	Exponent
GDOP	Geometric dilution of precision
GPS	Global Positioning System
HDOP	Horizontal dilution of precision
HOW	Handover word
Hz	Hertz

ICD	Interface control document
ID	Identification
IODC	Issue of data, clock
IODE	Issue of data, ephemeris
IS	Interface Specification
kbps	Kilobits per second (10^3 bps)
kHz	Kilohertz (10^3 Hz)
km	Kilometre (10^3 m)
LSB	Least significant bit
L1	D-band carrier (1575.42 MHz)
L2	D-band carrier (1227.6 MHz)
m	Metre
MAGVAR	Magnetic variation
MAS	Military Agency for Standardization
Mbps	Megabits per second (10^6 bps)
MHz	Megahertz (10^6 Hz)
MNAV	Military navigation
ms	Milliseconds (10^{-3} s)
MSB	Most significant bit
MSL	Mean sea level
m/s	Metres per second
MU	Military unique
NA	Not Available
NATO	North Atlantic Treaty Organization
NAV	Navigation
NMCT	Nav Message Correction Table (part of WAGE)
ns	Nanoseconds (10^{-9} s)
NS	NATO Secret
NSC	Nonstandard C/A code
NSY	Nonstandard Y-code
NU	NATO unclassified

N/A	Not Applicable
P	Precision code
PA	Puncture Acquisition code
PDOP	Position dilution of precision
PPS	Precise Positioning Service
PRN	Pseudorandom noise
P(Y)	P or Y -code
rms	Root-mean-square
s, sec	Second
SA	Selective availability
SC	Semicircles
SD	Special datum
SEP	Spherical Error Probable
sigma	Standard deviation
SIS	Signal in space
SPS	Standard Positioning Service
STANAG	Standardization Agreement
SV	Space vehicle
SVN	Space vehicle number
SYNCH	Synchronization signal
TBS	To be supplied
TDOP	Time dilution of precision
TLM	Telemetry word
TOW	Time of week
TRANSEC	Transmission security
TTDOP	Time transfer dilution of precision
U	Unclassified
UERE	User equivalent range error
UMSI	Unalerted misleading signal information
URA	User range accuracy
URE	User range error
US	United States of America
USNO	United States Naval Observatory

UTC	Coordinated Universal Time
VDOP	Vertical dilution of precision
WAGE	Wide Area GPS Enhancement
WMM-90	World Magnetic Model 1990
WMM-95	World Magnetic Model 1995
WGS 72	World Geodetic System 1972
WGS 84	World Geodetic System 1984
Y	Precision code, A-S mode
3-D	Three-dimensional
*	When used in equations, the asterisk indicates multiplication. When used in text or tables it indicates a footnote.
%	Percent
°	Degrees of arc
µs	Microseconds (10^{-6} s)

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APPENDIX 2

P(Y)-CODE AND C/A-CODE CHARACTERISTICS

For Annex A Appendix 2 information regarding P-code, C/A-code, P(Y)-code and C/A-code navigation data characteristics, and P(Y)-code and C/A-code electrical characteristics, refer to IS-GPS-200. For Annex A Appendix 2 information regarding Y-code, selective availabilty, and anti-spoofing, refer to ICD-GPS-224 and/or ICD-GPS-225 and/or ICD-GPS-227.

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APPENDIX 3

M-CODE CHARACTERISTICS

M-code provides the ranging code for Military-Unique (MU) Signal in Space (SIS) on both the L1 M and L2 M RF links as defined in ICD-GPS-700. The ranging code is formed by a modulo-2 addition of a Transmission Security (TRANSEC) derived spreading sequence, also known as the M-code Pseudorandom (PRN) spreading sequence, at a chipping rate of 5.115 MHz and a 10.23 MHz square wave that are synchronized in time. The resultant digital bitstream, along with Military Navigation Data (MNAV), is used to modulate the respective carrier frequency. This technique is known at Binary Offset Carrier (BOC) Modulation. Puncture Acquisition (PA) code provides a secure aid acquisition of M-code. PA-code is a TRANSEC-controlled operation that replaces portions of the M-code PRN spreading sequence. TRANSEC is provided by the Modernized Navstar Security Algorithm (MNSA) which is defined in IS-GPS-703.

Military Navigation Data (MNAV) includes the system data defined in IS-GPS-200, as well as additional data unique to the GPS military signal architecture. The data stream consists of two operational data rates: 25-bps (low data rate) and 100-bps (high data rate), respectively. The MNAV is modulo-2 added to the M-code which is used to modulate the L1 M and L2 M RF carriers. Subject to the CS control, the nominal configurations for L1 M and L2 M are as follows: (1) MNAV data stream may be present on both links, (2) be transmitted at high data rate (100-bps), and (3) contain identical data content on both links.

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APPENDIX 5 —— GEOMETRIC DILUTION OF PRECISION (GDOP)

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APPENDIX 5 —— GEOMETRIC DILUTION OF PRECISION*

1. EXACTLY-DETERMINED SOLUTIONS

GDOP relates estimated position and time solution accuracy with pseudorange measurement accuracy. The basic pseudorange measurement equations using four satellites are as follows:

$$\sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + ct = R_1 \tag{1}$$
$$\sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + ct = R_2 \tag{2}$$
$$\sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + ct = R_3 \tag{3}$$
$$\sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + ct = R_4 \tag{4}$$

where (x, y, z) is the user position (unknown) and t is the user clock bias (unknown); (x_i, y_i, z_i) is the position of the ith satellite for i = 1, 2, 3, 4 (knowns); R_i is the pseudorange measurement to the ith satellite; and c is the speed of light. Here the quantities R_1, R_2, R_3 and R_4 are "pseudo-ranges" in that they are the sum of the actual range displacements plus the offset due to user clock bias. In the equations shown here the four pseudoranges are the measured quantities. The satellite positions are

*GDOP's derivation is explained in terms of error. GDOP is not an error, but an approximation of geometry's impact to error.

known, and the four unknowns are the user position coordinates and the user clock bias.

This situation with ''four equations and four unknowns'' leads to an exactly-determined solution. So long as the four equations are mutually independent, the four unknowns can be solved for. Instead, if there were only three equations with the four unknowns, then it would be an under-determined situation and no solution would be possible without additional assumptions. If there were five equations (all mutually independent) and the same four unknowns, then an over-determined solution would be possible as described in a following section.

The above four equations are nonlinear. While it is possible to solve these equations in their non-linear form, receivers employ a much simpler linear version of these equations. Linear versions of these basic navigation equations can be achieved by employing incremental relationships as follows:

Let:

x_n, y_n, z_n, t_n be nominal (a priori best estimate) values of x, y, z, t;

Δx, Δy, Δz, Δt be the positive or negative corrections to these nominal values;

R_{ni} be the nominal pseudorange measurements from the ith satellite;

and

ΔR_i be the difference between the actual and nominal measurements.

Therefore:

$$
\begin{aligned}
x &= x_n + \Delta x \\
y &= y_n + \Delta y \\
z &= z_n + \Delta z \\
t &= t_n + \Delta t \\
R_i &= R_{ni} + \Delta R_i
\end{aligned}
\tag{5}
$$

and

$$R_{ni} = \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} + ct_n \tag{6}$$

Substituting the incremental expressions into the basic equations (1) through (4) yields:

$$\sqrt{(x_n + \Delta x - x_i)^2 + (y_n + \Delta y - y_i)^2 + (z_n + \Delta z - z_i)^2} = R_{ni} + \Delta R_i - ct_n - c\Delta t \tag{7}$$

$i = 1, 2, 3, 4$

By ignoring second-order error terms, equations (7) can be written as:

$$\sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} + \frac{(x_n - x_i)\Delta x + (y_n - y_i)\Delta y + (z_n - z_i)\Delta z}{\sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2}} \tag{8}$$

$$= R_{ni} + \Delta R_i - ct_n - c\Delta t$$

By substitution:

$$\frac{(x_n - x_i)}{R_{ni} - ct_n}\Delta x + \frac{(y_n - y_i)}{R_{ni} - ct_n}\Delta y + \frac{(z_n - z_i)}{R_{ni} - ct_n}\Delta z + c\Delta t = \Delta R_i \qquad (9)$$

The four equations (9), for i = 1, 2, 3, 4, are the linearized equations that relate pseudorange measurements to the desired user's position solution as well as the user's clock bias. The known quantities of the right-hand side of the equation are the differences between the actual measured pseudoranges and the measurements predicted by the GPS receiver's computer based on the knowledge of satellite position and the receiver's most current estimate of position and clock bias. The quantities to be computed, Δx, Δy, Δz and Δt, are corrections that the receiver will make to its current estimate of position and clock bias. The coefficients of these quantities on the left-hand side are the direction cosines of the line-of-sight from the user to the satellite as projected along the x, y and z coordinates. These linear equations can be conveniently expressed in matrix notation and appear as follows:

$$\begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & 1 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & 1 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 1 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & 1 \end{bmatrix} * \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ c\Delta t \end{bmatrix} = \begin{bmatrix} \Delta R_1 \\ \Delta R_2 \\ \Delta R_3 \\ \Delta R_4 \end{bmatrix} \qquad (10)$$

where α_{ij} is the direction cosine of the angle between the range to the ith satellite and the jth coordinate.

By the use of matrix notation, the above equations can be expressed very compactly as follows:

Let:

r = the four-element pseudorange measurement difference vector

x = the user position and time correction vector

A = the 4 by 4 observation matrix

$$A \equiv \begin{bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & 1 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & 1 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 1 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & 1 \end{bmatrix}$$

$$\mathbf{X} = [\Delta x \quad \Delta y \quad \Delta z \quad c\Delta t]^T \qquad (11)$$

$$\mathbf{r} = [\Delta R_1 \quad \Delta R_2 \quad \Delta R_3 \quad \Delta R_4]^T$$

Therefore:

$$\mathbf{A}\,\mathbf{x} = \mathbf{r} \quad \text{or} \quad \mathbf{x} = \mathbf{A}^{-1}\,\mathbf{r} \qquad (12)$$

The last equation presented compactly expresses the relationship between pseudorange measurements and user position and clock bias. Since this relationship is linear, it can be used to express the relationship between the errors in pseudorange measurements and the errors in the user position solution quantities. This relationship is therefore as follows:

$$\boldsymbol{\varepsilon}_x = \mathbf{A}^{-1}\;\boldsymbol{\varepsilon}_r \qquad (13)$$

where $\boldsymbol{\varepsilon}_r$ represents the pseudorange measurement errors, and $\boldsymbol{\varepsilon}_x$ represents the corresponding errors in user position and clock bias.

Let us now consider the covariance matrix of the expected errors in pseudorange measurements and the covariance matrix of the user quantities. The first covariance matrix is a 4 by 4 array composed of the expected values of the squares and products of the errors in the pseudorange measurements. The diagonal terms in the matrix, namely the squares of the expected errors, are the variances, i.e., the squares of the expected one-sigma values of the pseudorange measurement errors. The off-diagonal terms are the covariance between the pseudorange measurements and reflect the correlations to be expected in these measurements. Likewise, the covariance matrix for the user quantities is composed of the expected values of the squares and products of the errors in the user quantities. The diagonal terms are the variance or the squares of the one-sigma errors in user position and time, while the off-diagonal terms reflect the correlations in these errors. These covariance matrices are given by:

$$\mathrm{cov}\,(\mathrm{r}) = \mathrm{E}\{\ \varepsilon_{\mathrm{r}}\, \varepsilon_{\mathrm{r}}^{\mathrm{T}}\}$$

$$\mathrm{cov}\,(\mathrm{x}) = \mathrm{E}\{\ \varepsilon_{\mathrm{x}}\, \varepsilon_{\mathrm{x}}^{\mathrm{T}}\} \qquad (14)$$

where the symbol E { } designates "expected value" of the quantity inside the braces.

Upon substitution, the matrix relationship between the two covariance matrices becomes:

$$\text{cov}(\mathbf{x}) = \mathbf{A}^{-1}\ \text{cov}(\mathbf{r})\ \mathbf{A}^{-T} \tag{15}$$

An alternate formulation for this relationship based on a straightforward matrix algebra manipulation is as follows:

$$\text{cov}(\mathbf{x}) = [\mathbf{A}^{T}\ \text{cov}(\mathbf{r})^{-1}\ \mathbf{A}]^{-1} \tag{16}$$

From the relationship between covariance matrices just developed, it should be noted that the relationship between the pseudorange measurement errors and the user's position and clock bias errors is a function only of the solution matrix, **A**. This matrix is a function only of the direction cosines of the lines-of-sight from the user to the satellites along the coordinate system being employed. In other words, the error relationships are a function only of satellite geometry. Therefore, an important consideration in the proper use of GPS is that the four satellites used for the position solution should be arranged in a "good" geometric relationship. In this context "good" means that small errors in pseudorange measurements (UERE) result in small user position and clock bias errors. This qualitative explanation leads to the concept of GDOP, which is a measure of how satellite geometry affects positioning accuracy.

The following assumption regarding pseudorange measurement errors provides a method for quantitatively determining whether a particular four-satellite geometry is good or bad. Assume that each individual pseudorange measurement has an one-sigma error of unity where the expected mean is zero and the correlation of errors between satellites is also zero. With these assumptions, the covariance matrix for the errors in the pseudorange measurements becomes a 4 by 4 identity matrix. Thus, for this case, the covariance matrix for user position and clock bias errors is given by the following:

$$\mathrm{cov}(\mathbf{x}) = (\mathbf{A}^T \ \mathbf{A})^{-1} \qquad (17)$$

GDOP is defined as the square root of the trace of cov(**x**) when cov(**r**) is an identity matrix. Therefore:

$$\mathrm{GDOP} = \sqrt{\mathrm{TRACE}[(A^T A)^{-1}]} \qquad (18)$$

Equivalently, define:

$$\mathbf{K} = \mathbf{A}^{-1} \qquad (19)$$

such that **K** is the 4 by 4 solution matrix in

$$\mathbf{x} = \mathbf{A}^{-1}\ \mathbf{r} \quad \text{or} \quad \mathbf{x} = \mathbf{K}\ \mathbf{r} \qquad (20)$$

GDOP is then given by:

$$\mathrm{GDOP} = ((K_{11})^2+(K_{12})^2+(K_{13})^2+(K_{14})^2+ (K_{21})^2+(K_{22})^2+(K_{23})^2+(K_{14})^2+ (K_{31})^2+(K_{32})^2+(K_{33})^2+(K_{34})^2+ (K_{41})^2+(K_{42})^2+(K_{43})^2+(K_{44})^2)^{1/2} \qquad (21)$$

Some properties of this quantity can be summarized as follows. GDOP is:

a. In effect, the amplification factor of pseudorange measurement errors into user errors due to the effect of satellite geometry.

b. Independent of the coordinate system employed.

c. A criterion for designing satellite constellations.

d. A means for user selection of the four best satellites from those which are visible.

As an alternative to GDOP as a criterion for selecting satellites or evaluating satellite constellations, only some of the variances of user position and time might be used. These are defined as follows:

a. Position Dilution of Precision (PDOP) —— The square root of the sum of the squares of the three components of position error.

b. Horizontal Dilution of Precision (HDOP) —— The square root of the sum of the squares of the horizontal components of the position error. Note: HDOP depends on the coordinate frame.

c. Vertical Dilution of Precision (VDOP) —— The altitude error.
Note: $PDOP^2 = HDOP^2 + VDOP^2$

d. Time Dilution of Precision (TDOP) —— The error in the user clock bias multiplied by the velocity of light.

Note: $GDOP^2 = PDOP^2 + TDOP^2$

The alternative criterion most frequently employed is PDOP, which is used to determine position accuracy. Another alternative is HDOP, which is most meaningful for users interested only in horizontal position accuracy.

2. OVER-DETERMINED SOLUTIONS

In an over-determined situation, there are more equations available than there are unknowns. This situation is the rule rather than the exception with modern all-in-view (AIV) GPS receivers. A common way to take advantage of the redundant information available is to perform an over-determined solution using weighted least-squares.

The formulation of an over-determined weighted least-squares solution is an extension of the preceding equation (11). Assume there be ''N'' pseudorange measurements from ''N'' satellites. Then, in parallel with equation (11), let:

r = the N-element pseudorange measurement difference vector
x = the user position and time correction vector
A = the N by 4 observation matrix

$$A = \begin{bmatrix} \alpha_{11} & \alpha_{12} & a_{13} & 1 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & 1 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 1 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ \alpha_{N1} & \alpha_{N2} & \alpha_{N3} & 1 \end{bmatrix}$$

$$\mathbf{X} = [\Delta x \quad \Delta y \quad \Delta z \quad c\Delta t]^T \qquad (22)$$

$$\mathbf{r} = [\Delta R_1 \quad \Delta R_2 \quad \Delta R_3 \quad \Delta R_4 \quad \ldots \quad \Delta R_N]^T$$

Without weighting the measurements to allow for accounting of potentially variable measurement accuracy, the analogue of equation (12) is still true:

$$\mathbf{A}\ \mathbf{x} = \mathbf{r} \qquad \text{or} \qquad \mathbf{x} = \mathbf{A}^{-1}\ \mathbf{r} \qquad (23)$$

As before, this relationship is linear and it is used to express the relationship between the errors in the pseudorange measurements and the errors in the user position solution quantities.

The weighted version of the right-hand version of equation (23) is:

$$\mathbf{x} = (\mathbf{A}^T \mathbf{W} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{W} \mathbf{r} \tag{24}$$

Where the inverse of the weighting matrix W is given by:

$$W^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_N^2 \end{bmatrix}$$

The weighting matrix **W** is diagonal based on the standard assumption that the pseudorange measurement errors for each satellite are uncorrelated with the errors affecting any other satellite. In this case, the weighted least-squares solution is also a minimum variance solution.

In parallel with equation (19) earlier, define:

$$\mathbf{K} = (\mathbf{A}^T \mathbf{W} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{W} \tag{25}$$

such that **K** is the 4 by N solution matrix in

$$\mathbf{x} = (\mathbf{A}^T \mathbf{W} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{W} \mathbf{r} \quad \text{or} \quad \mathbf{x} = \mathbf{K} \mathbf{r} \tag{26}$$

If the weighting matrix **W** is the identity matrix or a scalar multiple of the identity matrix such that the weighted least-squares solution is equal to the unweighted least-squares solution, then GDOP is given by:

$$\text{GDOP} = \left((K_{11})^2 + (K_{12})^2 + (K_{13})^2 + (K_{14})^2 + \cdots + (K_{1N})^2 + (K_{21})^2 + (K_{22})^2 + (K_{23})^2 + (K_{14})^2 + \cdots + (K_{2N})^2 + (K_{31})^2 + (K_{32})^2 + (K_{33})^2 + (K_{34})^2 + \cdots + (K_{3N})^2 + (K_{41})^2 + (K_{42})^2 + (K_{43})^2 + (K_{44})^2 + \cdots + (K_{4N})^2 \right)^{1/2} \quad (27)$$

Comparing equation (27) to equation (21) reveals that the nature of GDOP is unchanged for over-determined solutions. GDOP is still an amplification factor of pseudorange measurement errors into user position errors due to the effect of satellite geometry, independent of the coordinate system, and a criterion for designing satellite constellations. If the GPS receiver tracks fewer than all satellites in view, then GDOP is still a means for user selection of the ‘‘N’’ best satellites from those which are visible.

If the weighting matrix **W** is not a scalar multiple of the identity matrix, then the solution matrix **K** becomes a function of both the geometry and the weighting matrix. The root-sum-square of the elements of the weighted **K** matrix are not equal to the GDOP as they are in equation (27). Instead, the root-sum-square of the elements of the weighted **K** matrix are equal to the weighted GDOP (KGDOP) as in equation (28):

$$\text{KGDOP} = \left((K_{11})^2 + (K_{12})^2 + (K_{13})^2 + (K_{14})^2 + \cdots + (K_{1N})^2 + (K_{21})^2 + (K_{22})^2 + (K_{23})^2 + (K_{14})^2 + \cdots + (K_{2N})^2 + (K_{31})^2 + (K_{32})^2 + (K_{33})^2 + (K_{34})^2 + \cdots + (K_{3N})^2 + (K_{41})^2 + (K_{42})^2 + (K_{43})^2 + (K_{44})^2 + \cdots + (K_{4N})^2 \right)^{1/2} \quad (28)$$

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1. STANDARD MEAN SEA LEVEL ALGORITHM

1.1 Algorithm Formulation

The weighting function approach for modelling irregular surfaces* provides a simple procedure for approximating an irregular surface from regularly spaced data. This approach will be used in GPS receivers to provide the standard mean-sea-level (MSL) algorithm. The obtained MSL value is a first order approximation to the WGS 84 geoid surface. The mathematical formulation for interpolated geoid height (approximately MSL) $N_p(\varphi,\lambda)$ is:

$$N_p = \sum_{i=1}^{4} W_i(x, y) N_i \quad (1)$$

where the general equation for the weighting function is:

$$W(x,y) = x^2y^2 (9 - 6x - 6y + 4xy) \quad (2)$$

and N_i are geoid height values at the four corners of a square or rectangle, as shown in Figure 1. In particular,

N_p = Interpolated geoid height at desired point P, whose geographic coordinates are φ and λ

$W_1(x,y) = W(x,y)$

$W_2(x,y) = W(1 - x, y)$

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*Junkins, Miller, and Jancaitis; "A Weighting Function Approach to Modeling of Irregular Surfaces"; Journal of Geophysical Research; Volume 78, No. 110, April 1973.

$W_3(x,y) = W(1 - x,\ 1 - y)$

$W_4(x,y) = W(x,\ 1 - y)$

$\Delta\lambda = \lambda - \lambda_1$

$\Delta\varphi = \varphi - \varphi_1$

$$x = \frac{\Delta\lambda}{\text{grid interval}} = \frac{\Delta\lambda}{\lambda_2 - \lambda_1}$$

$$y = \frac{\Delta\phi}{\text{grid interval}} = \frac{\Delta\phi}{\phi_2 - \phi_1}$$

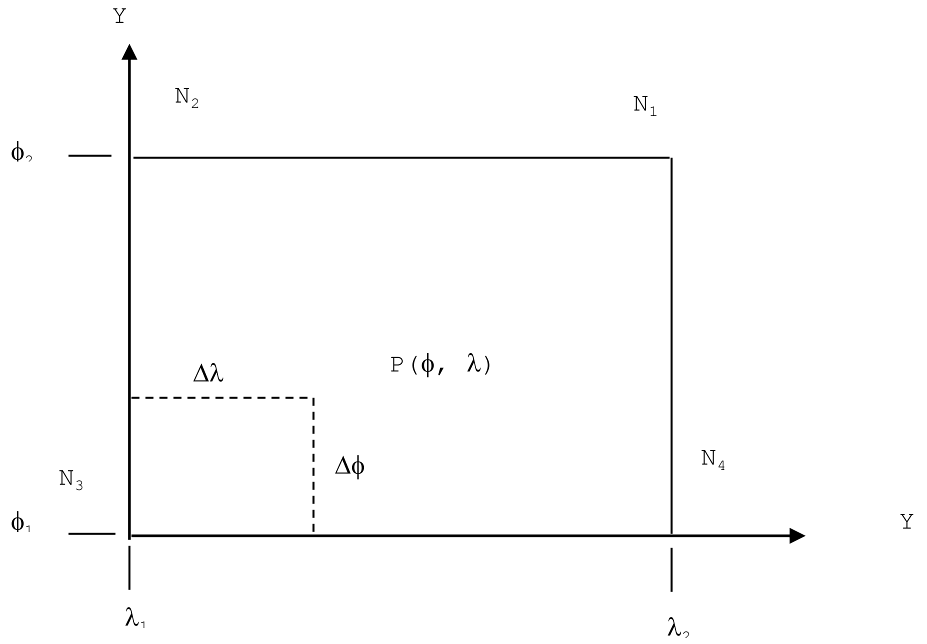

Figure 1. Interpolation Algorithm

As seen from equations (1) and (2), this interpolation technique involves simple algebra and provides a continuous, regular surface.

1.2 Algorithm Data Base

A matrix of gridded geoid height values is calculated using the full WGS 84 coefficient set. This matrix, consisting of worldwide geoid height values at a 10° spacing, has been adjusted in a least-squares sense to minimize residuals between interpolated geoid height values and those calculated from the full coefficient set.

The adjusted matrix of geoid height values is given in Table I, and will be used with the standard MSL algorithm for GPS.

1.3 Remarks

A comparison was made between geoid height values calculated at the center of 1° by 1° squares from the full WGS 84 coefficient set, and values estimated from the data base given in Table I using the above algorithms. Results from this comparison are shown in Table II, and are summarized below:

a. Number of 1° by 1° values compared: 64800
b. Average difference, metres: 0.3 m
c. Root-mean-square difference: ±3.4 m
d. Largest positive difference: 23.6 m
(at φ = 36°N, λ = 49°E)
e. Largest negative difference: −28.0 m
(at φ = 35°N, λ = 27°E)

Table I. Data Base of Adjusted Geoid Height Values (Sheet 1 of 2)

(Units = Metres)

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

Table I. Data Base of Adjusted Geoid Height Values (Sheet 2 of 2)

(Units = Metres)

φ|λ	180°	190°	200°	210°	220°	230°	240°	250°	260°	270°	280°	290°	300°	310°	320°	330°	340°	350°
90°	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
80°	3	1	—2	—3	—3	—3	—1	3	1	5	9	11	19	27	31	34	33	34
70°	2	2	1	—1	—3	—7	—14	—24	—27	—25	—19	3	24	37	47	60	61	58
60°	2	9	17	10	13	1	—14	—30	—39	—46	—42	—21	6	29	49	65	60	57
50°	—8	8	8	1	—11	—19	—16	—18	—22	—35	—40	—26	—12	24	45	63	62	59
40°	—12	—10	—13	—20	—31	—34	—21	—16	—26	—34	—33	—35	—26	2	33	59	52	51
30°	—7	—5	—8	—15	—28	—40	—42	—29	—22	—26	—32	—51	—40	—17	17	31	34	44
20°	5	10	7	—7	—23	—39	—47	—34	—9	—10	—20	—45	—48	—32	—9	17	25	31
10°	13	12	11	2	—11	—28	—38	—29	—10	3	1	—11	—41	—42	—16	3	17	33
0°	22	16	17	13	1	—12	—23	—20	—14	—3	14	10	—15	—27	—18	3	12	20
—10°	36	22	11	6	—1	—8	—10	—8	—11	—9	1	32	4	—18	—13	—9	4	14
—20°	51	27	10	0	—9	—11	—5	—2	—3	—1	9	35	20	—5	—6	—5	0	13
—30°	46	22	5	—2	—8	—13	—10	—7	—4	1	9	32	16	4	—8	—4	12	15
—40°	21	6	1	—7	—12	—12	—12	—10	—7	—1	8	23	15	—2	—6	6	21	24
—50°	—15	—18	—18	—16	—17	—15	—108	—10	—8	—2	6	14	13	3	3	10	20	27
—60°	—45	—43	—37	—32	—30	—26	—23	—22	—16	—10	—2	10	20	20	21	24	22	17
—70°	—61	—60	—61	—55	—49	—44	—38	—31	—25	—16	—6	1	4	5	4	2	6	12
—80°	—53	—54	—55	—52	—48	—42	—38	—38	—29	—26	—26	—24	—23	—21	—19	—16	—12	—8
—90°	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30	—30

Table II. Range of Geoid Height Differences

Range (metres)		Percent of Cumulative Differences
From	To	
—1	1	32.06
—2	2	55.72
—3	3	71.17
—4	4	81.48
—5	5	88.29
—6	6	92.68
—7	7	95.23
—8	8	97.79
—9	9	98.43
—10	10	99.68
—15	15	99.68
<—15	>15	100.00

2. STANDARD MAGNETIC VARIATION ALGORITHM

2.1 Introduction

The magnetic variation algorithm (MAGVAR) is based on a spherical harmonic expansion representing the Earth's magnetic field, the coefficients of which comprise the World Magnetic Model (WMM). These coefficients are produced jointly by the U.S. National Geophysical Data Center (NGDC) and the British Geological Survey (BGS) and are distributed by the NGDC, BGS and the National Geospatial-Intelligence Agency (NGA). The World Magnetic Models are usually produced at 5-year intervals and are composed of two parts: a main field model, which describes the Earth's magnetic field at some base epoch, and a secular variation model, which accounts for the slow temporal variations in the main geomagnetic field from the base epoch to a maximum of 5 years beyond the base epoch. For example, the base epoch of the WMM2000 magnetic field model is 2000.0. This model is therefore considered valid between 2000.0 and 2005.0 and will subsequently be replaced at 2005.0 by the WMM2005 magnetic field model. The WMM2005 and future model coefficients will be available from:

National Geophysical Data Center
NOAA Geomagnetic Data Group EGC1
325 Broadway
Boulder, CO 80303
URL: www.ngdc.noaa.gov/seg/WMM/DoDWMM.shtml

In addition, a sample computer program, which implements the MAGVAR calculations and associated documentation, is available from the same address. The program was developed by the U.S. Naval Oceanographic Office for the GPS and is compatible with Fortran 77.

It is extremely important to recognize that the WMM series of geo-magnetic models characterize primarily that portion of the Earth's magnetic field, which is generated by the Earth's conducting fluid outer core. The portions of the geomagnetic field generated by the Earth's crust, mantle, ionosphere and magnetosphere are for the most part not represented in these models. Consequently, a magnetic sensor such as a compass or magnetometer may observe spatial and temporal magnetic anomalies when referenced to the appropriate World Magnetic Model. In particular, certain local, regional and temporal magnetic declination anomalies can exceed 10 degrees. Anomalies of this magnitude are not common, but they do exist. Declination anomalies on the order of 3 or 4 degrees are not uncommon, but are of small spatial extent (< 50km) and relatively isolated. On land, spatial anomalies are produced by mountain ranges, ore deposits, ground that has been struck by lightning, geological faults and man-made objects such as trains, planes, tanks, rail-road tracks and power lines. In ocean areas, spatial anomalies are produced by continental margins, seamounts, oceanic ridges, trenches and fault zones and by ships and submarines. Temporal anomalies in either ocean or land areas can last from a few minutes to several days and are produced by ionospheric and magnetospheric processes which are driven by the solar wind. Magnetic storms in particular can cause severe and persistent magnetic anomalies. Even in periods of quiet solar activity, significant spatial and temporal magnetic anomalies are found in the polar and equatorial regions of the Earth where magnetic fields produced by ionospheric current systems such as the auroral electrojets and the equatorial electroject are always present. Most of the possible sources of magnetic anomalies are comparatively isolated in either space or time. Therefore, from a global perspective, the root-mean-square (rms) declination (DEC) and inclination (DIP) errors of the World Magnetic Model at sea level are estimated to be less than 1.0 degrees over the entire 5-year life of a particular model. Similarly, the rms horizontal and vertical intensity errors are estimated to be less than 200 nanoteslas over the life of the model.

2.2 The Mathematical Model

The Earth's magnetic field has associated with it a geomagnetic potential $V(r,\theta,\varphi,\tau)$, which can be expressed in spherical coordinates in terms of a spherical harmonic expansion of the following form:

$$V(r,\theta,\phi,\tau) = R_E \sum_{n=1}^{N} \left(\frac{R_E}{r} \right)^{n+1} \sum_{m=0}^{n} \{ g_n^m(\tau) \cos m\phi + h_n^m(\tau) \sin m\phi \} P_n^m(\theta)$$

where the spherical coordinates (r,θ,φ) correspond to the radius from the center of the earth, the colatitude (i.e., 90° — latitude) and the longitude. R_E is the mean radius of the earth. $g_n^m(\tau)$ and $h_n^m(\tau)$ are referred to as the Gauss coefficients at time τ, where τ is the time in years (e.g., 1987.312). $P_n^m(\theta)$ represents a particular associated Legendre polynomial of degree n and order m. These polynomials are functions of the colatitude θ. The Gauss coefficients are slowly varying functions of time and are expressed in the form:

$$g_n^m(\tau) = g_n^m(T_{EPOCH}) + \dot{g}_n^m(\tau - T_{EPOCH})$$

$$h_n^m(\tau) = h_n^m(T_{EPOCH}) + \dot{h}_n^m(\tau - T_{EPOCH})$$

where T_{EPOCH} is the base epoch of the model, which for WMM2000 is 2000.0.

Thus, $g_n^m(T_{EPOCH})$ and $h_n^m(T_{EPOCH})$ are the Gauss coefficients of the World Magnetic Model at the base epoch, while $\dot{g}_n^m$ and $\dot{h}_n^m$ (pronounced g_n^m dot and h_n^m dot) are the annual rates of change of the Gauss coefficients. The Gauss coefficients $g_n^m(T_{EPOCH})$ and $h_n^m(T_{EPOCH})$ and their annual rates of change are spherical harmonic coefficients. The Gauss coefficients $g_n^m(T_{EPOCH})$ and $h_n^m(T_{EPOCH})$ characterize the Earth's main magnetic field at the base epoch of the model=, T_{EPOCH}, while $\dot{g}_n^m$ and $\dot{h}_n^m$ characterize the secular change of the Earth's main magnetic field during the 5-year life of the model. These coefficients, up to degree and order 12 for the main field and up to degree and order 8 for the secular variation of the main field, comprise the World Magnetic Model and are presented in Table 3.

Table III. WMM2000 Schmidt Normalized Gauss Coefficients
(Sheet 1 of 3)

n	m	g_n^m	h_n^m	$\dot{g}_n^m$	$\dot{h}_n^m$
1	0	-29616.0	0.0	14.7	0.0
1	1	-1722.7	5194.5	11.1	-20.4
2	0	-2266.7	0.0	-13.6	0.0
2	1	3070.2	-2484.8	-0.7	-21.5
2	2	1677.6	-467.9	-1.8	-9.6
3	0	1322.4	0.0	0.3	0.0
3	1	-2291.5	-224.7	-4.3	6.4
3	2	1255.9	293.0	0.9	-1.3
3	3	724.8	-486.5	-8.4	-13.3
4	0	932.1	0.0	-1.6	0.0
4	1	786.3	273.3	0.9	2.3
4	2	250.6	-227.9	-7.6	0.7
4	3	-401.5	120.9	2.2	3.7
4	4	106.2	-302.7	-3.2	-0.5
5	0	-211.9	0.0	-0.9	0.0
5	1	351.6	42.0	-0.2	0.0
5	2	220.8	173.8	-2.5	2.1
5	3	-134.5	-135.0	-2.7	2.3
5	4	-168.8	-38.6	-0.9	3.1
5	5	-13.3	105.2	1.7	0.0
6	0	73.8	0.0	1.2	0.0
6	1	68.2	-17.4	0.2	-0.3
6	2	74.1	61.2	1.7	-1.7
6	3	-163.5	63.2	1.6	-0.9
6	4	-3.8	-62.9	-0.1	-1.0
6	5	17.1	0.2	-0.3	-0.1
6	6	-85.1	43.0	0.8	1.9
7	0	77.4	0.0	-0.4	0.0
7	1	-73.9	-62.3	-0.8	1.4
7	2	2.2	-24.5	-0.2	0.2
7	3	35.7	8.9	1.1	0.7
7	4	7.3	23.4	0.4	0.4
7	5	5.2	15.0	0.0	-0.3
7	6	8.4	-27.6	-0.2	-0.8
7	7	-1.5	-7.8	-0.2	-0.1

Table III. WMM2000 Schmidt Normalized Gauss Coefficients (Sheet 2 of 3)					
8	0	23.3	0.0	-0.3	0.0
8	1	7.3	12.4	0.6	-0.5
8	2	-8.5	-20.8	-0.8	0.1
8	3	-6.6	8.4	0.3	-0.2
8	4	-16.9	-21.2	-0.2	0.0
8	5	8.6	15.5	0.5	0.1
8	6	4.9	9.1	0.0	-0.1
8	7	-7.8	-15.5	-0.6	0.3
8	8	-7.6	-5.4	0.1	0.2
9	0	5.7	0.0	0.0	0.0
9	1	8.5	-20.4	0.0	0.0
9	2	2.0	13.9	0.0	0.0
9	3	-9.8	12.0	0.0	0.0
9	4	7.6	-6.2	0.0	0.0
9	5	-7.0	-8.6	0.0	0.0
9	6	-2.0	9.4	0.0	0.0
9	7	9.2	5.0	0.0	0.0
9	8	-2.2	-8.4	0.0	0.0
9	9	-6.6	3.2	0.0	0.0
10	0	-2.2	0.0	0.0	0.0
10	1	-5.7	0.9	0.0	0.0
10	2	1.6	-0.7	0.0	0.0
10	3	-3.7	3.9	0.0	0.0
10	4	-0.6	4.8	0.0	0.0
10	5	4.1	-5.3	0.0	0.0
10	6	2.2	-1.0	0.0	0.0
10	7	2.2	-2.4	0.0	0.0
10	8	4.6	1.3	0.0	0.0
10	9	2.3	-2.3	0.0	0.0
10	10	0.1	-6.4	0.0	0.0
11	0	3.3	0.0	0.0	0.0
11	1	-1.1	-1.5	0.0	0.0
11	2	-2.4	0.7	0.0	0.0
11	3	2.6	-1.1	0.0	0.0
11	4	-1.3	-2.3	0.0	0.0
11	5	-1.7	1.3	0.0	0.0
11	6	-0.6	-0.6	0.0	0.0
11	7	0.4	-2.8	0.0	0.0
11	8	0.7	-1.6	0.0	0.0
11	9	-0.3	-0.1	0.0	0.0

Table III. WMM2000 Schmidt Normalized Gauss Coefficients (Sheet 3 of 3)

11	10	2.3	-1.9	0.0	0.0
11	11	4.2	1.4	0.0	0.0
12	0	-1.5	0.0	0.0	0.0
12	1	-0.2	-1.0	0.0	0.0
12	2	-0.3	0.7	0.0	0.0
12	3	0.5	2.2	0.0	0.0
12	4	0.2	-2.5	0.0	0.0
12	5	0.9	-0.2	0.0	0.0
12	6	-1.4	0.0	0.0	0.0
12	7	0.6	-0.2	0.0	0.0
12	8	-0.6	0.0	0.0	0.0
12	9	-1.0	0.2	0.0	0.0
12	10	-0.3	-0.9	0.0	0.0
12	11	0.3	-0.2	0.0	0.0
12	12	0.4	1.0	0.0	0.0

The Earth's magnetic field $\vec{B}(r,\theta,\varphi,\tau)$ is a vector quantity having three components, which correspond to the projection of the magnetic field vector onto the three coordinate axes. Thus, $B_r(r,\theta,\varphi,\tau)$ is that portion of the field pointing in the radial direction (i.e., perpendicular to the surface of the earth), $B_\theta(r,\theta,\varphi,\tau)$ is that portion of the field pointing locally due South and $B_\varphi(r,\theta,\varphi,\tau)$ is that portion of the field pointing locally due East. The magnetic field vector can be computed from the geomagnetic potential by taking its gradient thus:

$$\vec{B}(r,\theta,\phi,\tau) = -\vec{\nabla}V(r,\theta,\phi,\tau)$$

Consequently, the magnetic field components are related to the geomagnetic potential as follows:

$$B_r(r,\theta,\phi,\tau) = -\frac{\partial V(r,\theta,\phi,\tau)}{\partial r}$$

$$B_\theta(r,\theta,\phi,\tau) = -\frac{1}{r}\frac{\partial V(r,\theta,\phi,\tau)}{\partial \theta}$$

$$B_\phi(r,\theta,\phi,\tau) = -\frac{1}{r\sin\theta}\frac{\partial V(r,\theta,\phi,\tau)}{\partial \phi}$$

which yield the following spherical harmonic expansions:

$$B_r(r,\theta,\phi,\tau) = \sum_{n=1}^{N}(n+1)\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n}\{\, g_n^m(\tau)\cos m\phi + h_n^m(\tau)\sin m\phi \,\}\, P_n^m(\theta)$$

$$B_\theta(r,\theta,\phi,\tau) = -\sum_{n=1}^{N}\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n}\{\, g_n^m(\tau)\cos m\phi + h_n^m(\tau)\sin m\phi \,\}\frac{d\,P_n^m(\theta)}{d\theta}$$

$$B_\phi(r,\theta,\phi,\tau) = \frac{1}{\sin\theta}\sum_{n=1}^{N}\left(\frac{R_E}{r}\right)^{n+2}\sum_{m=0}^{n} m\{\, g_n^m(\tau)\sin m\phi - h_n^m(\tau)\cos m\phi \,\}\, P_n^m(\theta)$$

It must be noted that the Gauss coefficients $g_n^m(\tau)$ and $h_n^m(\tau)$, as well as the associated Legendre polynomials and their derivatives, are Schmidt normalized by an international agreement (circa 1930) of the International Union of Geodesy and Geophysics. This particular normalization allows one to determine which terms of the spherical harmonic model are the most significant simply by a cursory inspection of the model coefficients. The Schmidt normalized associated Legendre polynomials $P_n^m(\theta)$
are related to the unnormalized associated Legendre Polynomials $P^{nm}(\theta)$ (note position of indices) by the following relation:

$$P_n^m(\theta) = S^{nm}P^{nm}(\theta)$$

The Schmidt normalization factors S^{nm} and the unnormalized associated Legendre Polynomials $P^{nm}(\theta)$ are computed via recurrence relationships as follows:

$$P^{\infty}(\theta) = 1$$

$$P^{nm}(\theta) = (\sin\theta)P^{n-1,m-1}(\theta), \quad \text{for } m = n \neq 0$$

$$P^{nm}(\theta) = (\cos\theta)P^{n-1,m}(\theta) - \kappa^{nm}P^{n-2,m}(\theta), \quad \text{for } m < n,\ n \geq 1$$

$$\frac{d\,P^{\infty}(\theta)}{d\,\theta} = 0$$

$$\frac{d\,P^{nm}(\theta)}{d\,\theta} = (\sin\theta)\frac{d\,P^{n-1,m}(\theta)}{d\,\theta} + (\cos\theta)P^{n-1,m-1}(\theta) \quad , \quad \text{for } m = n \neq 0$$

$$\frac{d\,P^{nm}(\theta)}{d\,\theta} = (\cos\theta)\frac{d\,P^{n-1,m}(\theta)}{d\,\theta} - (\sin\theta)P^{n-1,m}(\theta) - \kappa^{nm}\frac{d\,P^{n-2,m}(\theta)}{d\,\theta} \quad , \quad m \neq n\ , \quad n \geq 1$$

where

$$\kappa^{nm} = \frac{(n-1)^2 - m^2}{(2n-1)(2n-3)}$$

and where it is understood that the undefined polynomials $P^{-1,0}(\theta)$ and $\frac{d\,P^{-1,0}}{d\theta}(\theta)$ are to be set equal to zero. Similarly,

$$S^{\infty} = 1$$

$$S^{\infty} = \left(\frac{2n-1}{n}\right) S^{n-1,0} \text{ , for } n > 0$$

$$S^{nm} = \sqrt{\frac{(n-m+1)J}{n+m}}\ S^{n,m-1} \ , \qquad \left\{ \begin{array}{l} J = 2 \text{ for } m = 1 \\ J = 1 \text{ for } m > 1 \end{array} \right\}$$

Also computed via recursion relations are the longitudinally dependent functions cos $m\varphi$ and sin $m\varphi$, which are computed as follows:

$$\sin m\varphi = 0, \quad \text{for } m = 0$$

$$\cos m\varphi = 1, \quad \text{for } m = 0$$

$$\sin m\varphi = \sin\varphi \cos((m - 1)\varphi) + \cos\varphi \sin((m - 1)\varphi), \quad \text{for } m > 0$$

$$\cos m\varphi = \cos\varphi \cos((m - 1)\varphi) - \sin\varphi \sin((m - 1)\varphi), \quad \text{for } m > 0$$

2.3 Coordinate Transformations

MAGVAR is intended to compute various components of the geomagnetic field in a geodetic coordinate system that uses the WGS 84 ellipsoid as the reference ellipsoid. However, the mathematical analysis in the previous section is based on spherical coordinates. Consequently, some coordinate transformations are necessary. A three-step procedure is required.

1. Convert the geodetic latitude, longitude and altitude (λ,φ,h) to spherical coordinates (r,θ,φ).

2. Compute the magnetic field components $B_r(r,\theta,\varphi,\tau)$, $B_\theta(r,\theta,\varphi,\tau\}$ and $B_\varphi(r,\theta,\varphi,\tau)$

3. Rotate the magnetic field components from spherical coordinates to geodetic coordinates yielding the magnetic field components $B_X(\lambda,\varphi,h,\tau)$, $B_Y(\lambda,\varphi,h,\tau)$ and $B_Z(\lambda,\varphi,h,\tau)$ which are the projections of the magnetic field vector $\vec{B}(\lambda,\varphi,h,\tau)$ onto the X-North, Y-East, Z-vertically down coordinates of a local rectangular coordinate system defined by the tangent plane to the ellipsoid which is concentric about the WGS 84 reference ellipsoid but which encompasses the point (λ,φ,h).

The transformations in step one are as follows:

$$\cos\theta = \frac{\sin\lambda}{\sqrt{Q^2\cos^2\lambda + \sin^2\lambda}}$$

$$\sin\theta = \sqrt{1 - \cos^2\theta}$$

where, if a and b are respectively the semimajor and semiminor axes of the WGS 84 ellipsoid:

$$Q = \frac{h\sqrt{a^2 - (a^2 - b^2)\sin^2\lambda} + a^2}{h\sqrt{a^2 - (a^2 - b^2)\sin^2\lambda} + b^2}$$

Furthermore:

$$r^2 = h^2 + 2h\sqrt{a^2(a^2 - b^2)\sin^2\lambda} + \frac{a^4 - (a^4 - b^4)\sin^2\lambda}{a^2 - (a^2 - b^2)\sin^2\lambda}$$

The transformation in step 3 depends on the rotation angle α through which the magnetic field vector must be rotated in going from spherical to geodetic coordinates. The following relations define this rotation angle:

$$\cos\alpha = \frac{h + \sqrt{a^2\cos^2\lambda + b^2\sin^2\lambda}}{r}$$

$$\sin\alpha = \frac{(a^2 - b^2)\cos\lambda\sin\lambda}{r\sqrt{a^2\cos^2\lambda + b^2\sin^2\lambda}}$$

$$\alpha = \lambda - \frac{\pi}{2} + \theta$$

Consequently, the components of the magnetic field vector in geodetic coordinates may be computed as follows:

$$B_X(\lambda,\varphi,h,\tau) = -\cos\alpha\; B_\theta(r,\theta,\varphi,\tau) - \sin\alpha\; B_r(r,\theta,\varphi,\tau)$$

$$B_Y(\lambda,\varphi,h,\tau) = B_\varphi(r,\theta,\varphi,\tau)$$

$$B_Z(\lambda,\varphi,h,\tau) = \sin\alpha\, B_\theta(r,\theta,\varphi,\tau) - \cos\alpha\, B_r(r,\theta,\varphi,\tau)$$

From these rectangular components of the geomagnetic field, it is possible to construct all others. In particular, the following parameters may be computed:

$$B_H(\lambda,\phi,h,\tau) = \sqrt{B_X^2(\lambda,\phi,h,\tau) + B_Y^2(\lambda,\phi,h,\tau)} \quad \text{(Horizontal Intensity)}$$

$$B_F(\lambda,\phi,h,\tau) = \sqrt{B_H^2(\lambda,\phi,h,\tau) + B_Z^2(\lambda,\phi,h,\tau)} \quad \text{(Total Intensity)}$$

$$B_D(\lambda,\phi,h,\tau) = \tan^{-1}\left\{\frac{B_Y(\lambda,\phi,h,\tau)}{B_X(\lambda,\phi,h,\tau)}\right\} \quad \text{(Declination)}$$

$$B_I(\lambda,\phi,h,\tau) = \tan^{-1}\left\{\frac{B_Z(\lambda,\phi,h,\tau)}{B_H(\lambda,\phi,h,\tau)}\right\} \quad \text{(Inclination)}$$

3. GEODETIC DATUM CONVERSION

3.1 WGS 84 Defining Parameters

All GPS navigation parameters are referenced to the ellipsoid defined in WGS 84. The four defining parameters of the WGS 84 ellipsoid are as follows:

a	=	Semimajor Axis	
$\bar{C}_{2,0}$	=	Normalized Second Degree Zonal Harmonic Coefficient of the Gravitational Potential	(3)
ω	=	Angular Velocity of the Earth	
GM	=	The Earth's Gravitational Constant (Mass of the Earth's Atmosphere included)*	

The values and estimated one-sigma accuracies of the WGS 84 defining parameters are given in Table IV.

*GM as defined in DMA TR 8350.2 is the same as μ in Appendix 3 to Annex A.

Table IV. WGS 84 Defining Parameters

Parameter	Magnitude	Accuracy	Units
a	6378137	± 2	metres
$\bar{C}_{2,0}$	$-484.16685 \times 10^{-6}$	$\pm 1.30 \times 10^{-9}$	dimensionless
ω	7292115×10^{-11}	$\pm 0.1500 \times 10^{-11}$	rad/s
GM	$3986005 \times 10^{+8}$	$\pm 0.6 \times 10^{+8}$	m^3/s^2

In addition, an important derived geometric constant is the flattening (ellipticity) constant (f) given below.

$f = 1/298.257223563 = 0.00335281066474$

3.2 WGS 84 Datum Shift Values

Datum shift values necessary for parameter conversion referenced to other geodetic datums are given in Table V. The table lists geodetic datums by name, number and reference ellipsoid, and gives datum shift constants for conversion from WGS 84. The constants are defined below:

ΔX = X-axis offset of local datum from WGS 84 ellipsoid
ΔY = Y-axis offset of local datum from WGS 84 ellipsoid
ΔZ = Z-axis offset of local datum from WGS 84 ellipsoid (4)
Δa = Local datum semi-major axis shift from WGS 84 ellipsoid
Δf = Local datum flattening shift from WGS 84 ellipsoid

NOTE: Datum shift values given in Table V are the best that are currently available. The use of WGS 84 is encouraged since it enables more precise positioning and weapon delivery.

Table V. Standardized Datum List (Sheet 1 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	$\Delta f \times 10^4$	ΔX(m)	ΔY(m)	ΔZ(m)
ARC 1950 01. Mean Value (Botswana, Lesotho, Malawi, Swaziland, Zaire, Zambia and Zimbabwe)	Clarke 1880	112.145	0.54750714	143	90	294
ARC 1960 02. Mean Value (Kenya and Tanzania)	Clarke 1880	112.145	0.54750714	160	8	300
AUSTRALIAN GEODETIC 1966 03. Australia and Tasmania Island	Australian National	23	0.00081204	133	48	-148
AUSTRALIAN GEODETIC 1984 04. Australia and Tasmania Island	Australian National	23	0.00081204	134	48	-149
BOGOTA OBSERVATORY 05. Columbia	International	251	0.14192702	-307	-304	318
CAMPO INCHAUSPE 06. Argentina	International	251	0.14192702	148	-136	-90
CAPE 07. South Africa	Clarke 1880	112.145	0.54750714	136	108	292

(See notes at the end of the table.)

Table V. Standardized Datum List (Sheet 2 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	Δf x 10^4	ΔX(m)	ΔY(m)	ΔZ(m)
CARTHAGE	Clarke 1880	112.145	0.54750714			
08. Tunisia				263	-6	-431
CHATHAM 1971	International	251	0.14192702			
09. Chatham Island (New Zealand)				-175	38	-113
CHUA ASTRO	International	251	0.14192702			
10. Paraguay				134	-229	29
CORREGO ALEGRE	International	251	0.14192702			
11. Brazil				206	-172	6
EUROPEAN 1950	International	251	0.14192702			
12. Western Europe (Limited to Austria, Denmark, France, Federal Republic of Germany, Netherlands and Switzerland)				87	96	120
13. Cyprus				104	101	140
14. Egypt				130	117	151
15. Iran				117	132	164
16. Sicily				97	88	135

(See notes at the end of the table.)

Table V. Standardized Datum List (Sheet 3 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	Δf x 10^4	ΔX(m)	ΔY(m)	ΔZ(m)
EUROPEAN 1979 17. Mean Value (Austria, Finland, Netherlands, Norway, Spain, Sweden, and Switzerland)	International	251	0.14192702	86	98	119
GANDAJIKA BASE 18. Republic of Maldives	International	251	0.14192702	133	321	-50
GEODETIC DATUM 1949 19. New Zealand	International	251	0.14192702	-84	22	-209
HJORSEY 1955 20. Iceland	International	251	0.14192702	73	-46	86
INDIAN 21. Thailand and Vietnam	Everest	-860.655	-0.28361368	-214	-836	-303
22. Bangladesh, India and Nepal				-289	-734	-257
IRELAND 1965 23. Ireland	Modified Airy	-796.811	-0.11960023	-506	122	-611
KERTAU 1948 24. West Malaysia and Singapore	Modified Everest	-832.937	-0.28361368	11	-851	-5
LIBERIA 1964 25. Liberia	Clarke 1880	112.145	0.54750714	90	-40	-88
LUZON 26. Philippines (Excluding Mindanao Island)	Clarke 1866	69.4	0.37264639	133	77	51

(See notes at the end of the table.)

Table V. Standardized Datum List (Sheet 4 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	Δf x 10⁴	ΔX(m)	ΔY(m)	ΔZ(m)
MASSAWA 27. Eritrea (Ethiopia)	Bessel 1841	-739.845	-0.10037483	-639	-405	-60
MERCHICH 28. Morocco	Clarke 1880	112.145	0.54750714	-31	-146	-47
MINNA 29. Nigeria	Clarke 1880	112.145	0.54750714	92	93	-122
NAHRWAN 30. Saudi Arabia	Clarke 1880	112.145	0.54750714	231	196	-482
NORTH AMERICAN 31. Mean Value (CONUS)	Clarke 1880	69.4	0.54750714	8	-160	-176
32. Mean Value (Alaska)				5	-135	-172
33. Mean value (Canada including Newfoundland Island)				10	-158	-187
34. Mean Value [Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua) and Mexico]				6	-127	-192
NORTH AMERICAN 1983 35. Alaska, Canada, Central America, CONUS, and Mexico	GRS 80	0	0.00000016	0	0	0
OLD EGYPTIAN 36. Egypt	Helmert 1906	63	-0.00480795	130	-110	13
OLD HAWAIIAN 37. Mean Value	Clarke 1866	69.4	0.37264639	-61	285	181

(See notes at the end of the table.)

Table V. Standardized Datum List (Sheet 5 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	Δf x 10⁴	ΔX(m)	ΔY(m)	ΔZ(m)
OMAN 38. Oman	Clarke 1880	112.145	0.54750714	345	1	-224
ORDNANCE SURVEY OF GREAT BRITAIN 1936 39. Mean Value (England, Isle of Man, Scotland, Shetland Islands, and Wales)	Airy	-573.604	-0.11960023	-375	111	-431
PITCAIRN ASTRO 1967 40. Pitcairn Island	International	251	0.14192702	-185	-165	-42
QATAR NATIONAL 41. Qatar	International	251	0.14192702	128	283	-22
QORNOQ 42. South Greenland	International	251	0.14192702	-164	-138	189
SCHWARZECK 43. Namibia	Bessel 1841	-653.135 [3]	-0.10037483	-616	-97	251
SOUTH AMERICA 1969 44.Mean Value (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Venezuela, Trinidad, and Tobago)	South American 1969	23	0.00081204	57	-1	41
TIMBALAI 1948 45. Brunei and East Malaysia (Sarawak and Sabah)	Everest	-860.655	-0.28361368	689	-691	46

(See notes at the end of the table.)

Table V. Standardized Datum List (Sheet 7 of 7)

Local Geodetic Systems[1]	Reference Ellipsoids and Parameter Differences[2]			Transformation Parameters		
	Name	Δa(m)	Δf x 10⁴	ΔX(m)	ΔY(m)	ΔZ(m)
TOKYO	Bessel 1841	-739.845	-0.10037483			
46. Mean Value (Japan, Korea, and Okinawa)				128	-481	-664
ZANDERIJ	International	251	0.14192702			
47. Surinam				265	-120	358
48. WGS 1972	WGS 72[4]	2.0	0.3121057 $x10^{-3}$	0.0	0.0	4.5
49. USER ENTERED[5]						

[1] Geoid heights computed using spherical harmonic expansion and WGS 84 EGM coefficient set (n=m=180), then referenced to the ellipsoid and orientation associated with each of the local geodetic systems.
[2] Ellipsoid parameters given in Table 7.4, DMA TR 8350.2.
[3] This a-value reflects an a-value of 6377483.865 metres for the Bessel 1841 Ellipsoid in Namibia.
[4] The transformation achieved using these parameters is not precise and is an approximation, a precise transformation is provided in Appendix 6, paragraph 3.3.
[5] User entered allows for operator entering of the 5 parameters for any of the other datums that are listed in Tables 7.5 and 10.1 of DMA TR 8350.2 and DMA TR 8350.2B respectively. The GPS receiver then operates in the local datum entered.

3.3 Precise Transformation Between WGS 84 and WGS 72 Coordinates

A precise transformation between WGS 84 and WGS 72 coordinates may be performed with formulas and parameters provided in Table VI and the equations listed below.

The geodetic latitude ($\Delta\varphi$), longitude ($\Delta\lambda$), and height (ΔH) formulas given in Table VI are designed to provide input values for the following equations:

$$\begin{aligned} \varphi_{WGS\ 72} &= \varphi_{WGS\ 84} - \Delta\varphi \\ \lambda_{WGS\ 72} &= \lambda_{WGS\ 84} - \Delta\lambda \\ H_{WGS\ 72} &= H_{WGS\ 84} - \Delta H \end{aligned} \tag{5}$$

Table VI. Formulas and Parameters for Transforming
WGS 72 Coordinates to WGS 84 Coordinates

Formulas	$\Delta\varphi'' = (4.5 \cos\varphi \,/\, a \sin 1'') + (\Delta f \sin 2\varphi \,/\, \sin 1'')$ $\Delta\lambda'' = 0.554$ $\Delta H_m = 4.5 \sin\varphi + a\Delta f \sin^2\varphi - a + r$
Parameters	$\Delta f = 0.3121057 \times 10^{-7}$ $a = 6378135$ metres $\Delta a = 2.0$ metres $\Delta r = 1.4$ metres
Note: Latitude is positive north and longitude positive east (0° to 360°).	

4. IONOSPHERIC CORRECTION MODEL

4.1 Model Description

The ionospheric correction model for single frequency users is given by

$$T_{iono} = \left\{ \begin{array}{ll} F\left[5*10^{-9} + AMP\left(1 - \frac{x^2}{2} + \frac{x^4}{24}\right)\right] & , \quad |x| < 1.57 \\ F\,(5*10^{-9}) & , \quad |x| \geq 1.57 \end{array} \right\} \text{seconds} \qquad (6)$$

where T_{iono} is referenced to the L1 frequency. If the user is operating on the L2 frequency, the correction term must be multiplied by γ (reference Appendix 3, paragraph 3.4.4.3).

The obliquity factor (F) in the model is given by:

$$F = 1 + 16(0.53 - E)^3 \text{ (dimensionless)} \qquad (7)$$

where

E = Elevation angle between the user and satellite (semicircles)

The vertical delay amplitude (AMP) in the model is given by:

$$AMP = \left\{ \begin{array}{ll} \sum_{n=0}^{3} \alpha_n \phi_m^n & , \quad AMP \geq 0 \\ \text{if } AMP < 0 & , \quad AMP = 0 \end{array} \right\} \text{seconds} \qquad (8)$$

where

α_n = The satellite-transmitted coefficients of a cubic equation representing the amplitude of the vertical delay with n = 0, 1, 2 and 3 (four coefficients, eight bits each)

φ_m = Geomagnetic latitude of the earth projection of the ionospheric intersection point. The mean ionospheric height is assumed to be 350 km.

= $\varphi_i + 0.064 \cos(\lambda_i - 1.617)$ semicircles (9)

φ_i = Geodetic latitude of the earth projection of the ionospheric intersection point

= $\varphi_u + \psi \cos A$ semicircles,

for $|\varphi_i| \leq 0.416$ semicircles (10)

if $\varphi_i > 0.416$, then $\varphi_i = +0.416$

if $\varphi_i < -0.416$, then $\varphi_i = -0.416$

φ_u = User WGS 84 geodetic latitude (semicircles)

ψ = Earth's central angle between user position and Earth projection of the ionospheric intersection point

$$= \frac{0.0137}{E + 0.11} - 0.022 \text{ semicircles} \quad (11)$$

A = Azimuth angle between the user and satellite, measured clockwise positive from true north (semicircles)

λ_i = Geodetic longitude of the earth projection of the ionospheric intersection point

$$= \lambda_u + \frac{\psi \sin A}{\cos \phi_i} \text{ semicircles} \qquad (12)$$

λ_u = User WGS 84 geodetic longitude (semicircles)

The phase (X) in the model is given by:

$$X = \frac{2\pi\,(t - 50400)}{PER} \text{ radians} \qquad (13)$$

where

t = Local time = $(4.32 * 10^4)\lambda_i$ + GPS time (seconds)
for $0 \le t \le 86400$ seconds (14)
if $t \ge 86400$ seconds, subtract 86400 seconds
if $t < 0$ seconds, add 86400 seconds

GPS time = Receiver-computed system time

$$PER = \text{Period of the model} = \left\{ \begin{array}{ll} \sum_{n=o}^{3} \beta_n \phi_m^n & , PER \ge 72000 \\ \text{if } PER < 72000 & , PER = 72000 \end{array} \right\} \text{seconds} \qquad (15)$$

β_n = The satellite-transmitted coefficients of a cubic equation representing the period of the model with n = 0, 1, 2 and 3 (four coefficients, eight bits each)

4.2 Typical Satellite-Transmitted Terms

Typical satellite-transmitted seasonal ionospheric model terms are listed in Table VII to assist in ionospheric model implementation. The associated values are during a period of minimum solar flux activity.

Table VII. Typical Ionospheric Model Terms and Values

Term	Units*	Winter	Spring	Summer	Fall
α_0	sec	7.9E—9	9.2E—9	4.3E—9	1.2E—8
α_1	sec/SC	—8.9E—9	1.8E—8	1.2E—8	—2.3E—9
α_2	sec/SC^2	—6.2E—8	—7.2E—8	—3.4E—8	—9.2E—8
α_3	sec/SC^3	7.0E—8	—1.2E—7	—8.8E—8	2.1E—8
β_0	sec	8.8E+4	8.7E+4	8.0E+4	9.3E+4
β_1	sec/SC	—2.7E+4	5.0E+4	6.3E+4	—1.5E+3
β_2	sec/SC^2	—1.7E+5	—1.6E+5	—8.3E+4	—2.2E+5
β_3	sec/SC^3	1.9E+5	—3.3E+5	—4.1E+5	1.5E+4
* sec = seconds, SC = semicircles (1 SC = 180 degrees), E = exponent					

5. TROPOSPHERIC CORRECTION REFERENCE MODEL

Tropospheric time delay is caused by two effects: angular bending of the radiowaves, which increases the path length over what it would be in free space; and a decrease in the propagation velocity. Both effects result from a change in the index of refraction as a function of altitude, N(h), of the troposphere, which varies with temperature, pressure, and humidity. However, the index generally decreases approximately linearly from mean sea level up to 1 km in altitude and exponentially thereafter.

N(h) is essentially independent of frequency to 30 GHz. Of interest to the user is the range error associated with tropospheric time delay. Because path length is also related to elevation angle, a correction must be made to compensate for the increased oblique travel through the troposphere. The range error can be defined by:

R(h,θ) = f(θ) * _R(h) (16)

where

R(h,θ) = Total range error (metres)

ΔR(h) = Range error as a function of altitude (metres)

h = Altitude above mean sea level (metres)

and

f(θ) = Range error factor (mapping function) as a function of elevation angle

$$f(\theta) = \frac{1}{\sin\theta + \dfrac{0.00143}{\tan\theta + 0.0455}}, \quad \text{for } \theta < 90°$$

(17)

$$f(\theta) = 1, \quad \text{for } \theta = 90°$$

and

θ = Elevation angle between GPS receiver and satellite

$\Delta R(h) = \Delta R_1(h) + \Delta R_2(h) + \Delta R_3(h)$ metres (18)

where

$\Delta R_1(h)$ = Range error for altitude 0 km ≤ h ≤ 1 km

$\Delta R_2(h)$ = Range error for altitude 1 km ≤ h ≤ 9 km

$\Delta R_3(h)$ = Range error for altitude 9 km ≤ h ≤ h_{sv}

h_{sv} = Altitude of satellites (kilometres)

Note: All altitudes are referenced to mean sea level.

For: $0 \text{ km} \leq h_u \leq 1 \text{ km}$

$\Delta R_2(h) = 1430 * 10^{-3}$ metres (19)

$$\Delta R_1(h) = \int_{h=h_u}^{h=1km} (N_s + h\,\Delta N)\,dh = \left[N_s\,h + 0.5\,\Delta N\,h^2 \Big|_{h_u}^{1km} \right] * 10^{-3} \text{ metres}$$

$\Delta R_3(h) = 732 * 10^{-3}$ metres

where

h_u = Altitude of GPS receiver (kilometres)

N_s = Surface refractivity index at mean sea level

$\Delta N = -7.32 \exp(0.005577\ N_s)$

and

Note: The global mean value of N_s at mean sea level is 324.8 with a standard deviation of 25.98. The equations are presented in terms of N_s to allow a measured value to be used if desired.

$$\Delta R(h) = \left[\left(N_s\,h + 0.5\,\Delta N\,h^2 \Big|_{h_u}^{1km} \right) + 1430 + 732 \right] * 10^{-3} \text{ metres} \quad (20)$$

For: $1 \text{ km} < h_u \leq 9 \text{ km}$

$\Delta R_1(h) = 0$

$$\Delta R_2(h) = \int_{h=h_u}^{h=9\,km} N_1 \exp[-C(h-1)]\,dh$$

$$= \left[\left[\frac{-8\,N_1}{\ln\left(\frac{N_1}{105}\right)} \exp\left[0.125\,(1-h)\ln\left(\frac{N_1}{105}\right)\right]\right]_{h_u}^{9\,km} \right] * 10^{-3} \text{ metres}$$

$\Delta R_3(h) = 732 * 10^{-3}$ metres

where

N_1 = Refractivity index at h = 1 km

$N_1 = N_s + \_N$

$$C = \frac{1}{8}\ln\left(\frac{N_1}{105}\right)$$

and

$$\Delta R(h) = \left[0 + \left(\left(\frac{-8\,N_1}{\ln\left(\frac{N_1}{105}\right)} \exp\left[0.125\,(1-h)\ln\left(\frac{N_1}{105}\right)\right]\right)_{h_u}^{9\,km} \right) + 732 \right] * 10^{-3} \text{ metres} \qquad (22)$$

For: $9\ km < h_u \leq h_{sv}$

$\Delta R_1(h) = 0$

$\Delta R_2(h) = 0$

(23)

$$\Delta R_3(h) = \int_{h=h_u}^{h=h_{sv}} 105 \exp[-0.1424(h-9)]\,dh$$

$$= \left[\frac{-105}{0.1424}\exp[-0.1424(h-9)]\right]_{h_u}^{20186.8\,km} * 10^{-3} \text{ metres}$$

and

$$\Delta R(h) = \left[0 + 0 + \left(\frac{-105}{0.1424}\exp[-0.1424(h-9)]\right)_{h_u}^{20186.8\,km}\right] * 10^{-3} \text{ metres} \qquad (24)$$

There are other troposphere correction models available, some of which offer better accuracy at the expense of more complexity. One such model is given in paragraph A.4.2.4 of RTCA/DO-229C. This RTCA/DO-229C troposphere correction model has recently been validated for satellite elevation angles down to 2 degrees above the horizon.

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Part I - SYSTEM CHARACTERISTICS

ANNEX A: GENERAL SYSTEM CHARACTERISTICS

APPENDIX 7 —— SUMMARY OF PERFORMANCE REQUIREMENTS

1. GPS PERFORMANCE CHARACTERISTICS

This appendix contains a summary of PPS and SPS performance characteristics for the Navstar Global Positioning System (GPS), for the operational constellation of 24 satellites.

Unless otherwise noted, the 95th percentile values presented in the following tables are based on accuracy distributions which are cumulative over 24 hours, worldwide, for a mask angle of 5 degrees, with receivers that track and use all in-view (AIV) satellites. These values may be used for planning purposes and are derived using the following factors and assumptions in computer simulations:

a. Single-frequency ionospheric delay model errors are assumed to be from 9.8 metres to 19.6 metres 95%

b. User correctly implements IS-GPS-200 and if PPS, also correctly implements ICD-GPS-224 or ICD-GPS-225 or ICD-GPS-227.

c. The URE distribution is assumed to be Gaussian and the age of the data (AOD) broadcast by the satellites during normal operations is assumed to be uniformly distributed between 0 and 24 hours.

d. The dual-frequency PPS User Equipment Error (UEE) is assumed to be Gaussian with an accuracy of 7.1 m 95%, and the single-frequency SPS UEE is also assumed to be Gaussian with an accuracy of 7.1 m 95%

e. Unless otherwise noted, users track and use all satellites from the 24-slot constellation in view at their location above a mask angle of 5 degrees.

f. Performance is calculated at sites uniformly distributed in time and space over the surface of the earth.

GPS 3-D 95% positioning accuracies shall be as presented in Table I. GPS satellite 95% time transfer accuracies shall be as presented in Table II. GPS 95% velocity accuracies shall be as presented in Table III.

Table I. 3-D Positioning Accuracies* (Metres, 95%)

Operating Mode		Dual Frequency		Single Frequency****	
SA	A-S	PPS	SPS	PPS	SPS
DISCONTINUED	OFF	25	25	29	29
NORMAL PEACETIME	OFF	25	170**	29	174**
TBS*****	OFF	25	TBS*****	29	TBS*****
DISCONTINUED	ON	25	NA***	29	29
NORMAL PEACETIME	ON	25	NA***	29	174**
TBS**	ON	25	NA***	29	TBS*****

* Worldwide, 99% availability, minimum satellite elevation 5° unless otherwise noted.
** Commitment for receivers which only track the ‘‘best 4’’ subset of satellites, independent of constellation slot occupancy state, minimum satellite elevation 7.5°, includes single-frequency ionospheric delay model errors.
*** NA indicates not available with A-S on.
**** Ignores single-frequency ionospheric delay model errors unless otherwise noted.
***** TBS indicates a data element to be supplied. This table is classified NATO SECRET when TBS is replaced with actual data.

Table II. Satellite Time Transfer Accuracies* (Nsec, 95%)

Operating Mode		Dual Frequency		Single Frequency****	
SA	A-S	PPS	SPS	PPS	SPS
DISCONTINUED	OFF	72	72	80	80
NORMAL PEACETIME	OFF	72	335**	80	340**
TBS*****	OFF	72	TBS*****	80	TBS*****
DISCONTINUED	ON	72	NA***	80	80
NORMAL PEACETIME	ON	72	NA***	80	340**
TBS*****	ON	72	NA***	80	TBS*****

* Worldwide, 99% availability, minimum satellite elevation 5° unless otherwise noted.
** Commitment for receivers which only track the ‘‘best 4’’ subset of satellites, independent of constellation slot occupancy state, minimum satellite elevation 7.5°, includes single-frequency ionospheric delay model errors.
*** NA indicates not available with A-S on.
**** Ignores single-frequency ionospheric delay model errors unless otherwise noted.
***** TBS indicates a data element to be supplied. This table is classified NATO SECRET when TBS is replaced with actual data.

Table III. Velocity Accuracies (Metres per Second per Axis, 95%)

Operating Mode*	Dual Frequency		Single Frequency	
SA	PPS	SPS	PPS	SPS
DISCONTINUED	0.2	0.2	0.2	0.2
NORMAL PEACETIME	0.2	TBS**	0.2	TBS**
TBS**	0.2	TBS**	0.2	TBS**

* Independent of A-S.
** TBS indicates a data element to be supplied. This table is classified NATO SECRET when TBS is replaced with actual data.

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