STANDARD 156-10

DATA SCIENCES GROUP

PHYSICAL CONSTANTS, UNITS, AND UNCERTAINTY STANDARD

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PHYSICAL CONSTANTS, UNITS, AND UNCERTAINTY STANDARD

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PREFACE

This standard presents the work performed by the Data Sciences Group (DSG) of the Range Commanders Council (RCC) under RCC Task DS-006. This standard replaces the Inter-range Instrumentation Group (IRIG) Standard 156-73, Physical Constants and Conversion Factors. Contained herein are changes in conversion methods and new reference datum. The following information has also been added:

a. Naming and abbreviation standards for units used in technical documents and programming codes.
b. A standard for expressing measurement uncertainty in technical documents.

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ACRONYMS

AFFTC	Air Force Flight Test Center
ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
CODATA	Committee on Data for Science and Technology
DMA	Defense Mapping Agency
GUM	Guide to the Expression of Uncertainty in Measurement
IAUWG	International Astronomical Union Working Group
IEEE	Institute of Electric and Electronic Engineers
IERS	International Earth Rotation and Reference Systems Service
ISO	International Organization for Standardization
NCSL	National Conference of Standards Laboratories
NIMA	National Imagery and Mapping Agency
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NSFA	Numerical Standards for Fundamental Astronomy
RCC	Range Commanders Council
SI	International System of Units
SL	sea level
U.S.	United States
USCS	United States Customary System (of units)

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CONSTANTS, UNITS, AND UNCERTAINTY

1 Introduction

This standard provides basic information and a collection of references for mathematical and physical constants, units, and uncertainty. The contents are for use in data processing and analysis activities by the Range Commanders Council (RCC) organizations. Contained herein are overviews of selected constants, units, and measurement uncertainty issues. The overviews are given for explanatory purposes. Additionally, reference material is identified for use in gaining a comprehensive understanding of the information being discussed.

For consistency, the following conventions are used.

a. Publication References. The title of a referenced publication is shown in italic font enclosed with double quotes, and is followed by the hyperlinked reference number enclosed in square brackets.

Example: "*Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*" [1]

b. Website References. The title of a referenced website is shown in normal font and underlined, and is followed by the hyperlinked reference number enclosed in square brackets, with the number prefixed with the letter w.

Example: Digital Library of Mathematical Functions [w1]

2 Constants

This section presents a few of the more commonly used constants, along with references to a wide variety of other constants. Where possible, the name and/or symbol associated with the constant are given. If known, an exact or defining value is given. Reference numbers corresponding to the source material in the references at paragraph 5 and paragraph 6 are given for each constant listed.

2.1 Mathematical.

Table 1 provides two key constants of Pi and Euler's Number. The National Institute of Standards and Technology (NIST) has the Digital Library of Mathematical Functions [w1] website, which is a complete rewrite of the "*Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*" [1]. This digital library contains a full list of mathematical constants and functions.

TABLE 1. MATHEMATICAL CONSTANTS				
Quantity	**Symbol**	**Value**	**Units**	**Ref**
Pi	π	3.141592653589793238462643*	nd**	[1]
Euler's Number	e	2.718281828459045235360287*	nd**	[1]

* This value is an irrational number, and therefore it cannot be represented exactly with a finite number of decimal positions. Consequently, this value is the best approximation available for an Institute of Electric and Electronic Engineers (IEEE) 64-bit double precision floating point number. Additionally, most computer languages will have function to return this value to machine precision.
** nd = non-dimensional

2.2 Universal.

Table 2 shows the exact value of the speed of light in a vacuum. For a full list of universal constants, visit the NIST website [w2].

TABLE 2. UNIVERSAL CONSTANTS				
Quantity	**Symbol**	**Value**	**Units**	**Ref**
Speed of light (vacuum)	c, c_0	299792458*	m/s	[2]

* Exact value

2.3 Electromagnetic.

For a full list of electromagnetic constants, visit the NIST website [w2].

2.4 Atomic and Nuclear.

For a full list of atomic and nuclear constants, visit the NIST website [w2].

2.5 Physico-chemical.

For a full list of physico-chemical constants, visit the NIST website [w2].

2.6 Geodetic.

Table 3 provides ellipsoid values from the years 1972 and 1984. For other ellipsoid data, refer to the "Defense Mapping Agency (*DMA) Technical Manual: Datums, Ellipsoids, Grids, and Grid Reference Systems*" [3]. Also found in this reference are reference datums and datum shift constants. Additionally, the "National Imagery and Mapping Agency (NIMA) *Technical Report: Department of Defense World Geodetic System 1984*" [4] defines the Department of Defense World Geodetic System 1984.

TABLE 3. GEODETIC CONSTANTS				
Ellipsoid	**Semi-Major Axis (a)**	**Semi-Minor Axis (b)**	**1/f [(a-b)/a]**	**Ref**
World Geodetic System 1972	6,378,135 m	6,356,750.5 m	298.26	[3]
World Geodetic System 1984	6,378,137 m	6,356,752.3142 m	298.257223563	[3]

2.7 Atmospheric.

Table 4 shows values for several atmospheric constants. For additional information on the standard atmospheres, visit the National Oceanic and Atmospheric Administration (NOAA) website [w3].

TABLE 4. ATMOSPHERIC CONSTANTS				
Quantity	**Symbol**	**Value**	**Units**	**Ref**
Standard sea level (SL) pressure	P_0	1.013250×10^5	N/m^2	[5]
Standard SL temperature	T_0	288.15	K	[5]
Standard SL density	ρ_0	1.225	Kg/m^3	[5]
Speed of sound*	a_0	340.292046	m/s	[5]

* The speed of sound is given for standard sea level (SL) pressure, density, and temperature.

2.8 Astronomical.

TABLE 5. ASTRONOMICAL CONSTANTS

Definition	Symbol	Value	Units	Ref
Mean Angular Velocity of the Earth	ω	7.292115×10^{-5}	rad/s	[6]
Nominal Angular Velocity of the Earth (epoch 1820)	ω_N	$7.2921151467064 \times 10^{-5}$*	rad/s	**
Newtonian Constant of Gravitation (CODATA-06)***	G	$(6.674\ 28 \pm .00067) \times 10^{-11}$	$m^3/(kg*s^2)$	[2]

* Exact value.
** Current value from the epoch 1820 reference point can be obtained from [w5]. The International Astronomical Union Working Group (IAUWG) on Numerical Standards for Fundamental Astronomy (NSFA)[w5].
*** CODATA = Committee on Data for Science and Technology.

For a full list of astronomical constants, see The Astronomical Almanac website [w4] from the United States (U.S.) Nautical Almanac Office.

For the current best estimates of astronomical constants, see the IAUWG on the NSFA website [w5].

Current values related to earth's rotation and reference system may be obtained from the International Earth Rotation and Reference Systems Service (IERS) website [w6].

2.9 Oceanographic.

The NOAA website [w3] contains information and publications related to the world's oceans, including historical oceanographic databases and models.

3 Units

A unit is a specific physical quantity that is defined and adopted by convention, and which other quantities of the same kind are compared with to express their value.

3.1 International System of Units (SI).

The NIST website [w7] maintains an archive of information on the International System of Units (SI), which is the modern form of the metric system.

Additional information may be found in the following NIST special publications:

a. NIST Special Publication 330: "*The International System of Units (SI)*" [7].
b. NIST Special Publication 811: "*Guide for the use of the International System of Units*" [8].
c. NIST Special Publication 447: "*Weights and Measures Standards of the United States: A Brief History*" [9].

3.2 United States Customary System (USCS) of Units.

The history and tables of units for the USCS may be found in the "*Specification, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices"* [10].

3.3 Notation for Technical Documents.

A complete explanation of expressing units in the SI format may be found in the NIST Special Publication 811: "*Guide for the use of the International System of Units*" [8]. This guide provides the necessary information required to print unit symbols within technical documents. This may also be used as a guide to print the equivalent set of units found within the USCS document.

3.4 Notation for Computer Code.

The notation used for computer code printing should be equivalent to the notation used for technical documents. However, not all print symbol units in technical documents have equivalent representations in American Standard Code for Information Interchange (ASCII) (or Unicode). When a print symbol unit has no equivalent representation in ASCII (or Unicode), a surrogate representation is used:

Print Symbol Unit	Surrogate for ASCII (or Unicode)	Example
Subscript:	Underscore "_"	A_1 → A_1
Superscript:	Caret or double asterisk "^" or "**"	ft^2 → ft^2 or ft**2

3.5 Conversion Factors.

TABLE 6. GENERAL CONVERSION FACTORS

To Convert From:	Multiply by (Exact Value)*	Multiply by (Approximate Value)	Units	Ref
Feet to meters	0.3048	-	m/ft	[8]
Inches to meters	0.0254	-	m/in	[8]
Inches to feet	1 / 12	0.083333333333333	ft/in	[10]
Nautical miles to meters	1852	-	m/nmi	[8]
Nautical miles to feet	1852 / 0.3048	6076.115485564304	ft/nmi	[8]
Statute miles to meters	1609.344	-	m/mi	[8]
Statute miles to feet	5280	-	ft/mi	[10]
Astronomical units to meters	149597871464	-	m/AU	[10]
Astronomical units to feet	149597871464 / 0.3048	4.908066649081365e+011	ft/AU	[10]
Knots to meters per second	1852 / 3600	0.514444444444444	(m/s)/kt	[8]
Knots to feet per second	1852 / (0.3048 * 3600)	1.687809857101196	(ft/s)/kt	[8]
Average mean gravity field	9.80665	-	m/s^2	[8]
Pounds (mass) to kilograms	0.45359237	-	kg/lbm	[10]
Pounds (force) to newtons	4.4482216152605	-	N/lbf	[8]
Radians to degrees	180/Pi	-	deg/rad	-
Mils to degrees	0.05625	-	deg/mil	[8]
Gallons (U.S.) to liters	-	3.785412	L/gal	[10]

* With the exception of Pi, these values are exact. For maximum accuracy, recommend using the exact value column rather than the Approximate Value column where possible.

TABLE 7. TEMPERATURE CONVERSION FACTORS

To Convert From	Formula	Ref
Fahrenheit to Celsius	(5/9)*(Tf-32)	[8]
Celsius to Fahrenheit	(9/5)*Tc+32	[8]
Fahrenheit to Rankine	Tf + 459.67	[8]
Celsius to Kelvin	Tc+273.15	[8]

4 Uncertainty

All measured quantities contain some level of measurement uncertainty, and most physical (i.e., non-mathematical) constants are measured quantities. The primary guidance for expressing measurement uncertainty is the International Organization for Standardization (ISO) publication "*Guide to the Expression of Uncertainty in Measurement*"(*GUM*) [11]. The U.S. version of this guide is the American National Standards Institute (ANSI) publication "*American National Standard for Calibration--U.S. Guide to the Expression of Uncertainty in Measurement*" [12]. The following subparagraphs present a very brief summary of the GUM [11].

Further clarification on expressing uncertainty can be found in the following publications:

a. Range Commanders Council (RCC) Document 122-07: "*Uncertainty Analysis Principles and Methods*" [13].
b. NIST Technical Note 1297: "*Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*" [14].
c. National Conference of Standards Laboratories (NCSL) Recommended Practice RP-12: "*Determining and Reporting Measurement Uncertainties*" [15].

Additionally, the NIST website [w8] maintains a section on uncertainty of measurement results.

4.1 Evaluating Standard Uncertainty.

In general, the best estimate x_i of the expected value of a measured quantity X_i that varies randomly, and for which n independent observations $X_{i,k}$ have been obtained under the same conditions of measurement, is the arithmetic mean $\overline{X_i}$:

$$x_i = \overline{X_i} = \frac{1}{n}\sum_{k=1}^{n} X_{i,k} \qquad \text{(Eq. 1)}$$

The standard uncertainty $u(x_i)$ of the estimate x_i is equivalent to the experimental standard deviation of the estimate x_i, which is equivalent to the experimental standard deviation of the arithmetic mean $\overline{X_i}$:

$$u(x_i) = s(x_i) = s(\overline{X_i}) = \sqrt{\frac{1}{n(n-1)}\sum_{k=1}^{n}(X_{i,k} - \overline{X_i})^2} \qquad \text{(Eq. 2)}$$

4.2 Combining Standard Uncertainty.

A derived quantity Y is not measured directly, but is determined from N other measured quantities $X_1, X_2, \ldots, X_N$ through a functional relationship f:

$$Y = f(X_1, X_2, \ldots, X_N) \qquad \text{(Eq. 3)}$$

If the function f is linear, then the estimate y of the expected value of a quantity Y is given by:

$$y = f(x_1, x_2, \dots, x_n) = f(\overline{X_1}, \overline{X_2}, \dots, \overline{X_N}) \quad \text{(Eq. 4)}$$

If the measured quantities $X_1, X_2, \dots, X_N$ are independent and the function f is linear, then the standard uncertainty of the estimate y is obtained by appropriately combining the standard uncertainties of the estimates $x_1, x_2, \dots, x_n$. This combined standard uncertainty $u_c(y)$ of the estimate y is given by:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)} \quad \text{(Eq. 5)}$$

If the measured quantities $X_1, X_2, \dots, X_N$ are dependent and the function f is linear, then the combined standard uncertainty $u_c(y)$ of the estimate y is given by:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=1}^{N} \frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} u(x_i, x_j)} \quad \text{(Eq. 6)}$$

Where $u(x_i, x_j)$ is the covariance associated with x_i and x_j and is given by:

$$u(x_i, x_j) = s(x_i, x_j) = s(\overline{X}_\iota, \overline{X}_J) = \frac{1}{n(n-1)} \sum_{k=1}^{n} (X_{i,k} - \overline{X}_\iota)(X_{j,k} - \overline{X}_J) \quad \text{(Eq. 7)}$$

Note. If function f is nonlinear, then the estimate y and the combined standard uncertainty $u_c(y)$ need to be determined by more sophisticated methods. See the *GUM* [11] for details.

4.3 Determining Expanded Uncertainty.

The expanded uncertainty U is obtained by multiplying the combined standard uncertainty $u_c(y)$ by a coverage factor k:

$$\mathrm{U = ku_c(y)} \quad \text{(Eq. 8)}$$

The result of a measurement is then expressed as:

$$\mathrm{Y = y \pm U} \quad \text{(Eq. 9)}$$

which means that the best estimate of the quantity Y is y, and that the interval $[\mathrm{y - U}$ to $\mathrm{y + U}]$ is expected to contain a significant percentage of the values that could reasonably be attributed to Y.

Ideally, one would choose a specific value of k that corresponds to a specific statistical confidence level, such as 95 percent or 99 percent. However, this can be difficult to do in practice because it requires knowledge of the probability distribution of y and $u_c(y)$. In general, k is selected to be in the range of 2 to 3.

4.4 Reporting Uncertainty.

When reporting a measurement result and its uncertainty, it is better to provide too much information rather than too little information. The methods used to calculate the measurement result and its uncertainty should be fully described so that the calculation of the reported result can be independently repeated if necessary. Two examples are provided below.

a. Combined Standard of Uncertainty, $u_c(y)$. When the measure of uncertainty is the combined standard uncertainty $u_c(y)$, it is preferable to state the numerical in a similar manner as shown below. If u_c is defined elsewhere in the document reporting the result, then the words in parentheses may be omitted for conciseness.

"m = (100.021 47 ± 0.000 35) g, where the number following the symbol ± is the numerical value of (the combined standard uncertainty) u_c, and does not represent a confidence interval."

b. Expanded Uncertainty, U. When the measure of uncertainty is the expanded uncertainty U, it is preferable to state the numerical result in a similar manner as shown below. If U, u_c, and k are defined elsewhere in the document reporting the result, then the words in parentheses may be omitted for conciseness.

"m = (100.021 47 ± 0.000 79) g, where the number following the symbol ± is the numerical value of the expanded uncertainty $U = ku_c$, with U determined from (the combined standard uncertainty) u_c = 0.35 mg and (the coverage factor) k = 2.26 based upon the t-distribution for v = 9 degrees of freedom, and represents a confidence interval estimated to have a confidence level of 95 percent."

5 Publication References

The following list includes references to various publications that contain specific information related to constants, units, and uncertainty. If available, internet links are provided so the reader can access and download relevant publications.

5.1 Constants.

[1] Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, Tenth Printing, National Bureau of Standards, Applied Mathematics Series 55, December 1972.
(http://www.convertit.com/Go/ConvertIt/Reference/AMS55.ASP)

[2] Mohr, Peter J.; Taylor, Barry N.; Newell, David B., *CODATA Recommended Values of the Fundamental Physical Constants: 2006*, National Institute of Standards and Technology, Gaithersburg, MD, December 2007.

(http://physics.nist.gov/cuu/Constants/codata.pdf)

[3] *Datums, Ellipsoids, Grids, and Grid Reference Systems*, Defense Mapping Agency Technical Manual 8358.1, Hydrographic/Topographic Center, Washington, D.C., September 1990. (http://earth-info.nga.mil/GandG/publications/tm8358.1/pdf/TM8358_1.pdf)

[4] *Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems*, Third Edition, National Imagery and Mapping Agency Technical Report 8350.2, Geodesy and Geophysics Department, St. Louis, MO, 2004. (http://earth-info.nga.mil/GandG/publications/tr8350.2/wgs84fin.pdf)

[5] *U.S. Standard Atmosphere, 1976*, National Oceanic and Atmospheric Administration, Washington, D.C., October 1976.

[6] *The Astronomical Almanac for the Year 2010*, Defense Dept., Naval Observatory, Nautical Almanac Office, Washington, D.C., 2008. (http://asa.usno.navy.mil/SecK/2010/Astronomical_Constants_2010.pdf)

5.2 Units.

[7] *The International System of Units (SI)*, National Institute of Standards and Technology Special Publication 330, March 2008. (http://physics.nist.gov/Pubs/SP330/sp330.pdf)

[8] *Guide for the use of the International System of Units*, National Institute of Standards and Technology Special Publication 811, March 2008. (http://physics.nist.gov/cuu/pdf/sp811.pdf)

[9] *Weights and Measures Standards of the United States: A brief history*, National Institute of Standards and Technology Special Publication 447, March 1976. (http://physics.nist.gov/Pubs/SP447/contents.html)

[10] *Specification, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices*, National Institute of Standards and Technology Handbook 44, Weights and Measures Division, Gaithersburg, MD, 2010. (http://ts.nist.gov/WeightsAndMeasures/Publications/h44-10.cfm)

5.3 Uncertainty.

[11] Guide to the Expression of Uncertainty in Measurement, ISO/IEC Guide 98-3:2008. (http://www.iso.org/sites/JCGM/GUM-JCGM100.htm)

[12] American National Standard for Calibration--U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540.2-1997 (R2002). (http://store.ncsli.org/ANSI_NCSL_Z540_2-1997_R2002__P118.cfm)

[13] *Uncertainty Analysis Principles and Methods*, Range Commanders Council Document 122-07, Telemetry Group, September 2007. (https://wsmrc2vger.wsmr.army.mil/rcc/manuals/122-07/122-07.pdf)

[14] *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, National Institute of Standards and Technology Technical Note 1297, September 1994. (http://physics.nist.gov/Pubs/guidelines/TN1297/tn1297s.pdf)

[15] *Determining and Reporting Measurement Uncertainties*, NCSL International Recommended Practice RP-12, April 1995. (https://wsmrc2vger.wsmr.army.mil/rcc/manuals/122-07/122-07.pdf)

6 Website References

The following list includes references to various websites that contain general information related to constants, units, and uncertainty.

6.1 Constants.

[w1] The Digital Library of Mathematical Functions.
http://dlmf.nist.gov/

[w2] The NIST Reference on Constants, Units, and Uncertainty, National Institute of Standards and Technology (Constants page).
http://physics.nist.gov/cuu/Constants

[w3] The National Oceanic and Atmospheric Administration.
http://www.noaa.gov

[w4] The Astronomical Almanac, U.S. Nautical Almanac Office (Astronomical Constants page).
http://asa.usno.navy.mil/SecK/Constants.html

[w5] The International Astronomical Union Working Group on Numerical Standards for Fundamental Astronomy (Current Best Estimates page).
http://maia.usno.navy.mil/NSFA/CBE.html

[w6] The International Earth Rotation and Reference Systems Service.
http://www.iers.org

6.2 Units.

[w7] The NIST Reference on Constants, Units, and Uncertainty, National Institute of Standards and Technology (Units page). http://physics.nist.gov/cuu/Units/index.html

6.3 Uncertainty.

[w8] The NIST Reference on Constants, Units, and Uncertainty, National Institute of Standards and Technology (Uncertainty page). http://physics.nist.gov/cuu/Uncertainty/index.html