Applied Technology Institute (ATIcourses.com)

Stay Current In Your Field • Broaden Your Knowledge • Increase Productivity

349 Berkshire Drive • Riva, Maryland 21140
888-501-2100 • 410-956-8805
Website: www.ATIcourses.com • Email: ATI@ATIcourses.com

Boost Your Skills With ATIcourses.com!

ATI Provides Training In:

- Acoustic, Noise & Sonar Engineering
- Communications and Networking
- Engineering & Data Analysis
- Information Technology
- Radar, Missiles & Combat Systems
- Remote Sensing
- Signal Processing
- Space, Satellite & Aerospace Engineering
- Systems Engineering & Professional Development

Check Our Schedule & Register Today!

The Applied Technology Institute (ATIcourses.com) specializes in training programs for technical professionals. Our courses keep you current in state-of-the-art technology that is essential to keep your company on the cutting edge in today's highly competitive marketplace. Since 1984, ATI has earned the trust of training departments nationwide, and has presented On-site training at the major Navy, Air Force and NASA centers, and for a large number of contractors. Our training increases effectiveness and productivity.

Learn From The Proven Best!

Satellite Communication Systems Engineering

A comprehensive, quantitative tutorial designed for satellite professionals

March 16-18, 2009

Boulder, Colorado

June 15-17, 2009

Beltsville, Maryland

$1740 (8:30am - 4:30pm)

"Register 3 or More & Receive $\$100^{00}$ each Off The Course Tuition."

Instructor

Dr. Robert A. Nelson is president of Satellite Engineering Research Corporation, a consulting firm in Bethesda, Maryland, with clients in both commercial industry and government. Dr. Nelson holds the degree of Ph.D. in physics from the University of Maryland and is a licensed Professional Engineer. He is coauthor of the textbook *Satellite Communication Systems Engineering, 2nd ed.* (Prentice Hall, 1993) and is Technical Editor of *Via Satellite magazine.* He is a member of IEEE, AIAA, APS, AAPT, AAS, IAU, and ION.

Additional Materials

In addition to the course notes, each participant will receive a book of collected tutorial articles written by the instructor and soft copies of the link budgets discussed in the course.

Testimonials

"Great handouts. Great presentation. Great real-life course note examples and cd. The instructor made good use of student's experiences."

"Very well prepared and presented. The instructor has an excellent grasp of material and articulates it well"

"Outstanding at explaining and defining quantifiably the theory underlying the concepts."

"Fantastic! It couldn't have been more relevant to my work."

"Very well organized. Excellent reference equations and theory. Good examples."

"Good broad general coverage of a complex subject."

Course Outline

1. **Mission Analysis.** Kepler's laws. Circular and elliptical satellite orbits. Altitude regimes. Period of revolution. Geostationary Orbit. Orbital elements. Ground trace.

2. **Earth-Satellite Geometry.** Azimuth and elevation. Slant range. Coverage area.

3. **Signals and Spectra.** Properties of a sinusoidal wave. Synthesis and analysis of an arbitrary waveform. Fourier Principle. Harmonics. Fourier series and Fourier transform. Frequency spectrum.

4. **Methods of Modulation.** Overview of modulation. Carrier. Sidebands. Analog and digital modulation. Need for RF frequencies.

5. **Analog Modulation.** Amplitude Modulation (AM). Frequency Modulation (FM).

6. **Digital Modulation.** Analog to digital conversion. BPSK, QPSK, 8PSK FSK, QAM. Coherent detection and carrier recovery. NRZ and RZ pulse shapes. Power spectral density. ISI. Nyquist pulse shaping. Raised cosine filtering.

7. **Bit Error Rate.** Performance objectives. Eb/No. Relationship between BER and Eb/No. Constellation diagrams. Why do BPSK and QPSK require the same power?

8. **Coding.** Shannon's theorem. Code rate. Coding gain. Methods of FEC coding. Hamming, BCH, and Reed-Solomon block codes. Convolutional codes. Viterbi and sequential decoding. Hard and soft decisions. Concatenated coding. Turbo coding. Trellis coding.

9. **Bandwidth.** Equivalent (noise) bandwidth. Occupied bandwidth. Allocated bandwidth. Relationship between bandwidth and data rate. Dependence of bandwidth on methods of modulation and coding. Tradeoff between bandwidth and power. Emerging trends for bandwidth efficient modulation.

10. **The Electromagnetic Spectrum.** Frequency bands used for satellite communication. ITU regulations. Fixed Satellite Service. Direct Broadcast Service. Digital Audio Radio Service. Mobile Satellite Service.

11. **Earth Stations.** Facility layout. RF components. Network Operations Center. Data displays.

12. **Antennas.** Antenna patterns. Gain. Half power beamwidth. Efficiency. Sidelobes.

13. **System Temperature.** Antenna temperature. LNA. Noise figure. Total system noise temperature.

14. **Satellite Transponders.** Satellite communications payload architecture. Frequency plan. Transponder gain. TWTA and SSPA. Amplifier characteristics. Nonlinearity. Intermodulation products. SFD. Backoff.

15. **The RF Link.** Decibel (dB) notation. Equivalent isotropic radiated power (EIRP). Figure of Merit (G/T). Free space loss. WhyPower flux density. Carrier to noise ratio. The RF link equation.

16. **Link Budgets.** Communications link calculations. Uplink, downlink, and composite performance. Link budgets for single carrier and multiple carrier operation. Detailed worked examples.

17. **Performance Measurements.** Satellite modem. Use of a spectrum analyzer to measure bandwidth, C/N, and Eb/No. Comparison of actual measurements with theory using a mobile antenna and a geostationary satellite.

18. **Multiple Access Techniques.** Frequency division multiple access (FDMA). Time division multiple access (TDMA). Code division multiple access (CDMA) or spread spectrum. Capacity estimates.

19. **Polarization.** Linear and circular polarization. Misalignment angle.

20. **Rain Loss.** Rain attenuation. Crane rain model. Effect on G/T.

Via Satellite, February 2000

The International System of Units (SI)

Its History and Use in Science and Industry

by Robert A. Nelson

On September 23, 1999 the Mars Climate Orbiter was lost during an orbit injection maneuver when the spacecraft crashed onto the surface of Mars. The principal cause of the mishap was traced to a thruster calibration table, in which British units instead of metric units were used. The software for celestial navigation at the Jet Propulsion Laboratory expected the thruster impulse data to be expressed in newton seconds, but Lockheed Martin Astronautics in Denver, which built the orbiter, provided the values in pound-force seconds, causing the impulse to be interpreted as roughly one-fourth its actual value. The failure was magnified by the loss of the companion spacecraft Mars Polar Lander due to an unknown cause on December 3.

The incident renews a controversy that has existed in the United States since the beginning of the space program regarding the use of metric or British units of measurement. To put the issue into perspective, this article reviews the history of the metric system and its modern version, the International System of Units (SI). The origin and evolution of the metric units, and the role they have played in the United States, will be summarized. Technical details and definitions will be provided for reference. Finally, the use of metric units in the satellite industry will be examined.

ORIGIN OF THE METRIC SYSTEM

The metric system was one of many reforms introduced in France during the period between 1789 and 1799, known as the French Revolution. The need for reform in the system of weights and measures, as in other affairs, had long been recognized. No other aspect of applied science affects the course of human activity so directly and universally.

Prior to the metric system, there had existed in France a disorderly variety of measures, such as for length, volume, or mass, that were arbitrary in size and variable from one town to the next. In Paris the unit of length was the *Pied de Roi* and the unit of mass was the *Livre poids de marc*. These units could be traced back to Charlemagne. However, all attempts to impose the “Parisian” units on the whole country were fruitless, as they were opposed by the guilds and nobles who benefited from the confusion.

The advocates of reform sought to guarantee the uniformity and permanence of the units of measure by taking them from properties derived from nature. In 1670, the abbe Gabriel Mouton of Lyons proposed a unit of length equal to one minute of arc on the earth’s surface, which he divided into decimal fractions. He suggested a pendulum of specified period as a means of preserving one of these submultiples.

The conditions required for the creation of a new measurement system were made possible by the French Revolution, an event that was initially provoked by a national financial crisis. In 1787 King Louis XVI convened the Estates General, an institution that had last met in 1614, for the purpose of imposing new taxes to avert a state of bankruptcy. As they assembled in 1789, the commoners, representing the Third Estate, declared themselves to be the only legitimate representatives of the people, and succeeded in having the clergy and nobility join them in the formation of the National Assembly. Over the next two years, they drafted a new constitution.

In 1790, Charles-Maurice de Talleyrand, Bishop of Autun, presented to the National Assembly a plan to devise a system of units based on the length of a pendulum beating seconds at latitude 45°. The new order was envisioned as an “enterprise whose result should belong some day to the whole world.” He sought, but failed to obtain, the collaboration of England, which was concurrently considering a similar proposal by Sir John Riggs Miller.

The two founding principles were that the system would be based on scientific observation and that it would be a decimal system. A distinguished commission of the French Academy of Sciences, including J. L. Lagrange and Pierre Simon Laplace, considered the unit of length. Rejecting the seconds pendulum as insufficiently precise, the commission defined the unit, given the name *metre* in 1793, as one ten millionth of a quarter of the earth’s meridian passing through Paris. The proposal was accepted by the National Assembly on March 26, 1791.

The definition of the meter reflected the extensive interest of French scientists in the figure of the earth. Surveys in Lapland by Pierre Louis Maupertuis in 1736 and in France by Nicolas Lacaille in 1740 had refined the value of the earth’s radius and established definitively that the shape of the earth is oblate. Additional meridian arcs were measured in Peru in 1735 – 1743 and at the Cape of Good Hope in 1751.

To determine the length of the meter, a new survey was conducted by the astronomers Jean Baptiste Delambre and P.F.A. Mechain between Dunkirk, in France on the English Channel, and Barcelona, Spain, on the coast of the Mediterranean Sea. This work was begun in 1792 and completed in 1798, enduring the hardships of the “reign of terror” and the turmoil of revolution. We now know that the quadrant of the earth is 10 001 966 meters (in the WGS 84 model) instead of exactly 10 000 000 meters as originally planned. The principal source of error was the assumed value of the earth’s flattening used in correcting for oblateness.

The unit of volume, the *pinte* (later renamed the *litre*), was defined as the volume of a cube having a side equal to one-tenth of a meter. The unit of mass, the *grave* (later renamed the *kilogramme*), was defined as the mass of one pinte of distilled water at the temperature of melting ice. In addition, the centigrade scale for temperature was adopted, with fixed points at 0 °C and 100 °C representing the freezing and boiling points of water (now replaced by the Celsius scale).

The work to determine the unit of mass was assigned to Antoine-Laurent Lavoisier, the father of modern chemistry, and Rene-Just Hauy. In a tragedy symbolic of the period, Lavoisier was guillotined by a revolutionary tribunal in 1794. The measurements were completed by Louis Lefevre-Gineau and Giovanni Fabbroni in 1799. However, they found that they could not cool liquid water to exactly 0 °C and that the maximum density occurs at 4 °C, not at 0 °C as had been supposed. Therefore, the definition of the kilogram was amended to specify the temperature of maximum density. We now know that the intended mass was 0.999 972 kg, i.e., 1000.028 cm^3 instead of exactly 1000 cm^3 for the volume of 1 kilogram of pure water at 4 °C.

On August 1, 1793 the National Convention, which by then ruled France, issued a decree adopting the preliminary definitions and terms. The "methodical" nomenclature, specifying multiples and fractions of the units by Greek and Latin prefixes, was chosen in favor of the "common" nomenclature, involving separate names.

A new calendar was established by a law of October 5, 1793. Its origin was designated retroactively as September 22, 1792 to commemorate the overthrow of the monarchy and the inception of the Republic of France. The French Revolutionary Calendar consisted of twelve months of thirty days each, concluded by a five or six day holiday. The months were given poetic names that suggested the prevailing seasons. Each month was divided into three ten-day weeks, or decades. The day itself was divided into decimal fractions, with 10 hours per day, 100 minutes per hour, and 100 seconds per minute. The calendar was politically, rather than scientifically, motivated, since it was intended to weaken the influence of Christianity. It was abolished by Napoleon in 1806 in return for recognition by the Church of his authority as emperor of France. Although the calendar reform remained in effect for twelve years, the new method of keeping the time of day required the replacement of valued clocks and timepieces and was never actually used in practice.

The metric system was officially adopted on April 7, 1795. The government issued a decree (*Loi du 18 germinal, an III*) formalizing the adoption of the definitions and terms that are in use today. A brass bar was made to represent the provisional meter, obtained from the survey of Lacaille, and a provisional standard for the kilogram was derived.

A scientific conference was held from 1798 to 1799 that included representatives of the Netherlands, Switzerland, Denmark, Spain, and the Italian states, as well as France, to validate the computations and design prototype standards. Permanent standards for the meter and kilogram made from platinum were constructed. The full length of the meter bar represented the unit. These standards were deposited in the Archives of the Republic. They became official by an act of December 10, 1799.

During the Napoleonic era, several regressive acts were passed that temporarily revived old traditions. Thus in spite of its auspicious beginning, the metric system was not quickly adopted in France. Although the system continued to be taught in the schools, lack of funds prevented the distribution of secondary standards. Finally, after a three year transition period, the metric system became compulsory throughout France as of January 1, 1840.

REACTION IN THE UNITED STATES

The importance of a uniform system of weights and measures was recognized in the United States, as in France. Article I, Section 8, of the U.S. Constitution provides that Congress shall have the power "to coin money ... and fix the standard of weights and measures." However, although the progressive concept of decimal coinage was introduced, the early American settlers both retained and cultivated the customs and tools of their British heritage, including the measures of length and mass. In contrast to the French Revolution, the "American Revolution" was not a revolution at all, but was rather a war of independence.

In 1790, the same year that Talleyrand proposed metric reform in France, President George Washington referred the subject of weights and measures to his Secretary of State, Thomas Jefferson. In a report submitted to the House of Representatives, Jefferson considered two alternatives: if the existing measures were retained they could be rendered more simple and uniform, or if a new system were adopted, he favored a decimal system based on the principle of the seconds pendulum. As it was eventually formulated, Jefferson did not endorse the metric system, primarily because the metric unit of length could not be checked without a sizable scientific operation on European soil.

The political situation at the turn of the eighteenth century also made consideration of the metric system impractical. Although France under Louis XVI had supported the colonies in the war with England, by 1797 there was manifest hostility. The revolutionary climate in France was viewed by the external world with a mixture of curiosity and alarm. The National Convention had been replaced by the Directory, and French officials who had been sympathetic to the United States either had been executed or were in exile. In addition, a treaty negotiated with England by John Jay in 1795 regarding settlement of the Northwest Territories and trade with the British West Indies was interpreted by France as evidence of an Anglo-American alliance. France retaliated by permitting her ships to prey upon American merchant vessels and Federalist President John Adams prepared for a French invasion. Thus in 1798, when dignitaries from foreign countries were assembled in Paris to learn of France's progress with metrological reform, the United States was not invited.

A definitive investigation was prepared in 1821 by Secretary of State John Quincy Adams that was to remove the issue from further consideration for the next 45 years. He found that the standards of length, volume, and mass used throughout the 22 states of the Union were already substantially uniform, unlike the disparate measures that had existed in France prior to the French Revolution. Moreover, it was not at all evident that the metric system would be permanent, since even in France its use was sporadic and, in fact, the consistent terminology had been repealed in 1812 by Napoleon. Therefore, if the metric system failed to win support in early America, it was not for want of recognition.

Serious consideration of the metric system did not occur again until after the Civil War. In 1866, upon the advice of the National Academy of Sciences, the metric system was made legal by the Thirty-Ninth Congress. The Act was signed into law on July 28 by President Andrew Johnson.

TREATY OF THE METER

A series of international expositions in the middle of the nineteenth century enabled the French government to promote the metric system for world use. Between 1870 and 1872, with an interruption caused by the Franco-Prussian War, an international meeting of scientists was held to consider the design of new international metric standards that would replace the meter and kilogram of the French Archives. A Diplomatic Conference on the Meter was convened to ratify the scientific decisions. Formal international approval was secured by the Treaty of the Meter, signed in Paris by the delegates of 17 countries, including the United States, on May 20, 1875.

The treaty established the International Bureau of Weights and Measures (BIPM). It also provided for the creation of an International Committee for Weights and Measures (CIPM) to run the Bureau and the General Conference on Weights and Measures (CGPM) as the formal diplomatic body that would ratify changes as the need arose. The French government offered the Pavillon de Breteuil, once a small royal palace, to serve as headquarters for the Bureau in Sevres, France near Paris. The grounds of the estate form a tiny international enclave within French territory.

The first three kilograms were made in 1880 and one was chosen as the international prototype. In 1884 an additional 40 kilograms and 30 meter bars were obtained. They were all manufactured from a an alloy of 90 percent platinum and 10 percent iridium by Johnson, Mathey and Company of London. The original meter and kilogram of the French Archives in their existing states were taken as the points of departure. The standards were intercompared at the International Bureau. A particular meter bar, number 6, became the international prototype. The remaining standards were distributed to the signatories. The work was approved by the First General Conference on Weights and Measures in 1889.

The United States received meters 21 and 27 and kilograms 4 and 20. On January 2, 1890 the seals to the shipping cases for meter 27 and kilogram 20 were broken in an official ceremony at the White House with President Benjamin Harrison presiding. The standards were deposited in the Office of Weights and Measures of the U.S. Coast and Geodetic Survey.

U.S. CUSTOMARY UNITS

The U.S. customary units were tied to the British and French units by a variety of indirect comparisons.

Troy weight was the standard for the minting of coins. Congress could be ambivalent about nonuniformity in standards for trade, but it could not tolerate nonuniformity in its standards for money. Therefore, in 1827 a brass copy of the British troy pound of 1758 was secured by Ambassador to England and former Secretary of the Treasury, Albert Gallatin. This standard was kept in the Philadelphia mint and lesser copies were made and distributed to other mints. The troy pound of the Philadelphia mint was virtually the primary standard for commercial transactions until 1857 and remained the standard for coins until 1911.

The semi-official standards used in commerce for a quarter century may be attributed to Ferdinand Hassler, who was appointed superintendent of the newly organized Coast Survey in 1807. In 1832 the Treasury Department directed Hassler to construct and distribute to the states standards of length, mass, and volume, and balances by which masses might be compared. As the standard of length, Hassler adopted the Troughton scale, an 82-inch brass bar made by Troughton of London for the Coast Survey that Hassler had brought back from Europe in 1815. The distance between the 27th and 63rd engraved lines on a silver inlay scale down the center of the bar was taken to be equal to the British yard. The standard of mass was the avoirdupois pound, derived from the troy pound of the Philadelphia mint by the ratio 7000 grains to 5760 grains. It was represented by a brass knob weight that Hassler constructed and marked with a star. Thus it has come to be known as the “star” pound.

The system of weights and measures in Great Britain had been in use since the reign of Queen Elizabeth I. Following a reform begun in 1824, the imperial standard avoirdupois pound was made the standard of mass in 1844 and the imperial standard yard was adopted in 1855. The imperial standards were made legal by an Act of Parliament in 1855 and are preserved in the Board of Trade in London. The United States received copies of the British imperial pound and yard, which became the official U.S. standards from 1857 until 1893.

When the metric system was made lawful in the United States in 1866, a companion resolution was passed to distribute metric standards to the states. The Treasury Department had in its possession several copies derived from the meter and kilogram of the French Archives. These included the “Committee” meter and kilogram, which were an iron end standard and a brass cylinder with knob copied from the French prototypes, that Hassler had brought with him when he immigrated to the United States in 1805. He had received them as a gift from his friend, J.G. Tralles, who was the Swiss representative to the French metric convocation in 1798 and a member of its committee on weights and measures. Also available were the “Arago” meter and kilogram, named after the French physicist who certified them. They were purchased by the United States in 1821 through Albert Gallatin, then minister to France. The Committee meter and the Arago kilogram were used as the prototypes for brass metric standards that were distributed to the states.

In 1893, under a directive from Thomas C. Mendenhall, Superintendent of Standard Weights and Measures of the Coast and Geodetic Survey, the U.S. customary units were redefined in terms of the metric units. The primary standards of length and mass adopted were prototype meter No. 27 and prototype kilogram No. 20 that the United States had received in 1889 as a signatory to the Treaty of the Meter. The yard was defined as 3600/3937 meter and the avoirdupois pound-mass was defined as 0.453 592 427 7 kilogram. The conversion for mass was based on a comparison between the British imperial standard pound and the international prototype kilogram performed in 1883. These definitions were used by the National Bureau of Standards (now the National Institute of Standards and Technology) from its founding in 1901 until 1959. On July 1, 1959 the definitions were fixed by international agreement among the English-speaking countries to be 1 yard = 0.9144 meter and 1 pound-mass = 0.453 592 37 kilogram exactly. The definition of the yard is equivalent to the relations 1 foot = 0.3048 meter and 1 inch = 2.54 centimeters exactly.

The derived unit of force in the British system is the pound-force (lbf), which is defined as the weight of one pound-mass (lbm) at a hypothetical location where the acceleration of gravity has the standard value 9.806 65 m/s^2 exactly. Thus, 1 lbf = 0.453 592 37 kg x 9.806 65 m/s^2 = 4.448 N approximately. The slug (sl) is the mass that receives an acceleration of one foot per second squared under a force of one pound-force. Thus 1 sl = (1 lbf)/(1 ft/s^2) = (4.448 N)/(0.3048 m/s^2) = 14.59 kg = 32.17 lbm approximately.

ELECTROMAGNETISM

The theories of electricity and magnetism developed and matured during the early 1800s as fundamental discoveries were made by Hans Christian Oersted, Andre-Marie Ampere, Michael Faraday, and many others. The possibility of making measurements of terrestrial magnetism in terms of mechanical units, that is, in “absolute measure,” was first pointed out by Karl Friedrich Gauss in 1833. His analysis was carried further to cover all electromagnetic phenomena by Wilhelm Weber, who in 1851 discussed a method by which a complete set of absolute units might be developed.

In 1861 a committee of the British Association for the Advancement of Science, that included William Thomson (later Lord Kelvin), James Clerk Maxwell, and James Prescott Joule, undertook a comprehensive study of electrical measurements. This committee introduced the concept of a *system* of units. Four equations were sufficient to determine the units of charge q, current I, voltage V, and resistance R. These were either Coulomb’s force law for charges or Ampere’s force law for currents, the relation between charge and current $q = I\,t$, Ohm’s law $V = I\,R$, and the equation for electrical work $W = V\,q = I^2\,R\,t$, where t is time.

A fundamental principle was that the system should be coherent. That is, the system is founded upon certain base units for length, mass, and time, and derived units are obtained as products or quotients without requiring numerical factors. The meter, gram, and mean solar second were selected as base units. In 1873 a second committee recommended a centimeter-gram-second (CGS) system of units because in this system the density of water is unity.

Two parallel systems of units were devised, the electrostatic and electromagnetic subsystems, depending on whether the law of force for electric charges or for electric currents was taken as fundamental. The ratio of the electrostatic to the electromagnetic unit of charge or current was a fundamental experimental constant c.

The committee also conducted research on electrical standards. It issued a wire resistance standard, the “B.A. unit,” which soon became known as the “ohm.” The idea of naming units after eminent scientists was due to Sir Charles Bright and Latimer Clark.

At the time, electricity and magnetism were essentially two distinct branches of experimental physics. However, in a series of papers published between 1856 and 1865, Maxwell created a unified theory based on the field concept introduced by Faraday. He predicted the existence of electromagnetic waves and identified the "ratio of the units" c with the speed of light.

In 1888, Heinrich Hertz verified Maxwell's prediction by generating and detecting electromagnetic waves at microwave frequencies in the laboratory. He also greatly simplified the theory by eliminating unnecessary physical assumptions. Thus the form of Maxwell's equations as they are known to physicists and engineers today is due to Hertz. (Oliver Heaviside made similar modifications and introduced the use of vectors.) In addition, Hertz combined the electrostatic and electromagnetic CGS units into a single system related by the speed of light c, which he called the "Gaussian" system of units.

The recommendations of the B.A. committees were adopted by the First International Electrical Congress in Paris in 1881. Five "practical" electrical units were defined as certain powers of 10 of the CGS units: the ohm, farad, volt, ampere, and coulomb. In 1889, the Second Congress added the joule, watt, and a unit of inductance, later given the name henry.

In 1901, the Italian engineer Giovanni Giorgi demonstrated that the practical electrical units and the MKS mechanical units could be incorporated into a single coherent system by (1) selecting the meter, kilogram, and second as the base units for mechanical quantities; (2) expanding the number of base units to four, including one of an electrical nature; and (3) assigning physical dimensions to the permeability of free space μ_0, with a numerical value of $4\pi \times 10^{-7}$ in a "rationalized" system or 10^{-7} in an "unrationalized" system. (The term "rationalized," due to Heaviside, concerned where factors of 4π should logically appear in the equations based on symmetry.) The last assumption implied that the magnetic flux density B and magnetic field H, which are related in vacuum by the equation $B = \mu_0 H$, are physically distinct with different units, whereas in the Gaussian system they are of the same character and are dimensionally equivalent. An analogous situation occurs for the electric fields D and E that are related by $D = \varepsilon_0 E$, where ε_0 is the permittivity of free space given by $c^2 = 1 / \mu_0 \varepsilon_0$.

In 1908, an International Conference on Electrical Units and Standards held in London adopted independent, easily reproducible primary electrical standards for resistance and current, represented by a column of mercury and a silver coulombmeter, respectively. These so-called "international" units went into effect in 1911, but they soon became obsolete with the growth of the national standards laboratories and the increased application of electrical measurements to other fields of science.

With the recognition of the need for further international cooperation, the 6th CGPM amended the Treaty of the Meter in 1921 to cover the units of electricity and photometry and the 7th CGPM created the Consultative Committee for Electricity (CCE) in 1927. By the 8th CGPM in 1933 there was a universal desire to replace the "international" electrical units with "absolute" units. Therefore, the International Electrotechnical Commission (IEC) recommended to the CCE an absolute system of units based on Giorgi's proposals, with the practical electrical units incorporated into a comprehensive MKS system. The choice of the fourth unit was left undecided.

At the meeting of the CCE in September 1935, the delegate from England, J.E. Sears, presented a note that set the course for future action. He proposed that the ampere be selected as the base unit for electricity, defined in terms of the force per unit length between two long parallel wires. The unit could be preserved in the form of wire coils for resistance and Weston cells for voltage by calibration with a current balance. This recommendation was unanimously accepted by the CCE and was adopted by the CIPM.

Further progress was halted by the intervention of World War II. Finally, in 1946, by authority given to it by the CGPM in 1933, the CIPM officially adopted the MKS practical system of absolute electrical units to take effect January 1, 1948.

TEMPERATURE

The concepts of temperature and its measurement have evolved along two parallel paths. On one hand, there has been the steady advance since the early eighteenth century of mercury, alcohol, and resistance thermometers and the development of practical scales of temperature based on arbitrary fixed points. On the other hand, there has been the growth of gas thermometry and the definition of an absolute measure of temperature based on its interpretation in terms of thermodynamic processes.

The first reliable mercury-in-glass thermometers were constructed by the German instrument maker Gabriel Daniel Fahrenheit in the period between 1708 and 1724. He defined the Fahrenheit scale by taking as fixed points the freezing point of water mixed with salt at 0 °F and the normal temperature of the human body at 96 °F (now known to be nearly 3° higher). The resulting freezing and boiling points of pure water were 32 °F and 212 °F , with 180° between them. In 1730, R.A.F. de Reaumer proposed dividing the same interval into 80° using an alcohol thermometer. This scale was widely used in France until the Revolution.

Another mercury thermometer scale was invented by Joseph Delisle in 1732. Delisle took the boiling point of water as 0° and worked downward to 150° as the freezing point. In 1741 the Swedish astronomer Anders Celsius recalibrated the Delisle thermometer with a centigrade temperature scale, having an interval of 100° between the fixed points, again with the boiling point at 0 °C but with the freezing point defined as 100 °C. By 1745, the botanist Carl Linnaeus, a colleague of Celsius, adopted a similar scale, but inverted it so that the freezing and boiling points are at 0 °C and 100 °C, respectively, as is customary today. This centigrade scale of temperature was adopted in France in 1794 during the creation of the metric system.

The notion of an absolute temperature scale based on a thermodynamic process is due to the French physicist Guillaume Amontons, who is credited with the invention of the air thermometer in 1699. According to Amontons, the temperature could be defined as proportional to the pressure of the air.

In 1854 William Thomson (Lord Kelvin) proposed a definition of temperature in terms of the macroscopic notion of heat or work according to the theory of an ideal reversible heat engine, derived by the French engineer Sadi Carnot. The ratio of the thermodynamic temperatures can be defined as the ratio of the heat taken in to that given out by a reversible heat engine operating in a Carnot cyle, so that $T_1/T_2 = Q_1/Q_2$. The definition of thermodynamic temperature is thus independent of the working substance. The research of James Clerk Maxwell, Ludwig Boltzmann, and J. Willard Gibbs provided an equally valid microscopic interpretation of temperature as a measure of the energy distribution of the particles in the system.

The Carnot cycle defines only the ratio of temperatures; to determine the unit of temperature it is also necessary to specify the temperature difference between two fixed points. Historically, these fixed points have been either the freezing and boiling points of water in a relative scale, or the triple point of water with respect to absolute zero in a thermodynamic scale. Such a temperature scale can be realized by means of an ideal gas, whose equation of state is given by $p\ V = n\ R\ T = N\ k\ T$, where p is the pressure, V is the volume, T is the thermodynamic temperature, and R is the universal gas constant. The number of moles is $n = m/M = N/N_0$, where m is the mass, M is the molar mass, N is the number of particles, and N_0 is Avogadro's number. The connection between the macroscopic and microscopic viewpoints is thus made by Boltzmann's constant through the relation $k = R/N_0$.

The First General Conference of Weights and Measures in 1889 adopted the constant volume hydrogen scale based on fixed points at the freezing point (0 °C) and the boiling point (100 °C) of water at standard pressure. The temperature derived from the measured pressure was corrected to thermodynamic temperature by a Joule-Thomson pourous-plug experiment. By extrapolation of the data, it was found that the thermodynamic temperature T, defined by the ideal gas equation of state, was related to the centigrade temperature t_C by the approximate relation $T = t_C + 273$.

The mercury thermometer was selected as a secondary standard. Mercury-in-glass thermometers, made by Tonnelot of Paris of lead-free hard glass and carefully annealed, were distributed to the participants. The United States received six of these thermometers as temperature standards for the range 0 °C to 100 °C to accompany prototype meters 21 and 27 and prototype kilograms 4 and 20. In 1948 the Ninth General Conference on Weights and Measures renamed the centigrade scale as the Celsius scale, with the unit degree Celsius.

INTERNATIONAL SYSTEM OF UNITS (SI)

By 1948 the General Conference on Weights and Measures was responsible for the units and standards of length, mass, electricity, photometry, temperature, and ionizing radiation. At this time, the next major phase in the evolution of the metric system was begun. It was initiated by a request of the International Union of Pure and Applied Physics "to adopt for international use a practical international system of units." Thus the 9th CGPM decided to define a complete list of derived units. Derived units had not been considered previously because they do not require independent standards. Also, the CGPM brought within its province the unit of time, which had been the prerogative of astronomers.

The work was started by the 10th CGPM in 1954 and was completed by the 11th CGPM in 1960. During this period there was an extensive revision and simplification of the metric unit definitions, symbols, and terminology. The kelvin and candela were added as base units for thermodynamic temperature and luminous intensity, and in 1971 the mole was added as a seventh base unit for amount of substance.

The modern metric system is known as the International System of Units, with the international abbreviation SI. It is founded on the seven base units, summarized in Table 1, that by convention are regarded as dimensionally independent. All other units are derived units, formed coherently by multiplying and dividing units within the system without the use of numerical factors. Some derived units, including those with special names, are listed in Table 2. For example, the unit of force is the newton, which is equal to a kilogram meter per second squared, and the unit of energy is the joule, equal to a newton meter. The expression of multiples and submultiples of SI units is facilitated by the use of prefixes, listed in Table 3. (Additional information is available on the Internet at the websites of the International Bureau of Weights and Measures at http//www.bipm.fr and the National Institute of Standards and Technology at http://physics.nist.gov/cuu.)

METRIC STANDARDS

One must distinguish a unit, which is an abstract idealization, and a standard, which is the physical embodiment of the unit. Since the origin of the metric system, the standards have undergone several revisions to reflect increased precision as the science of metrology has advanced.

The meter. The international prototype meter standard of 1889 was a platinum-iridium bar with an X-shaped cross section. The meter was defined by the distance between two engraved lines on the top surface of the bridge instead of the distance between the end faces. The meter was derived from the meter of the French Archives in its existing state and reference to the earth was abandoned.

The permanence of the international prototype was verified by comparison with three companion bars, called "check standards." In addition, there were nine measurements in terms of the red line of cadmium between 1892 and 1942. The first of these measurements was carried out by A. A. Michelson using the interferometer which he invented. For this work, Michelson received the Nobel Prize in physics in 1907.

Improvements in monochromatic light sources resulted in a new standard based on a well-defined wavelength of light. A single atomic isotope with an even atomic number and an even mass number is an ideal spectral standard because it eliminates complexity and hyperfine structure. Also, Doppler broadening is minimized by using a gas of heavy atoms in a lamp operated at a low temperature. Thus a particular red-orange krypton-86 line was chosen, whose wavelength was obtained by direct comparison with the cadmium wavelength. In 1960, the 11th CGPM defined the meter as the length equal to 1 650 763.73 wavelengths of this spectral line.

Research on lasers at the Boulder, CO laboratory of the National Bureau of Standards contributed to another revision of the meter. The wavelength and frequency of a stabilized helium-neon laser beam were measured independently to determine the speed of light. The wavelength was obtained by comparison with the krypton wavelength and the frequency was determined by a series of measurements traceable to the cesium atomic standard for the second. The principal source of error was in the profile of the krypton spectral line representing the meter itself. Consequently, in 1983 the 17th CGPM adopted a new definition of the meter based on this measurement as "the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second." The effect of this definition is to fix the speed of light at exactly 299 792 458 m/s. Thus experimental methods previously interpreted as measurements of the speed of light c (or equivalently, the permittivity of free space ε_0) have become calibrations of length.

The kilogram. In 1889 the international prototype kilogram was adopted as the standard for mass. The prototype kilogram is a platinum-iridium cylinder with equal height and diameter of 3.9 cm and slightly rounded edges. For a cylinder, these dimensions present the smallest surface area to volume ratio to minimize wear. The standard is carefully preserved in a vault at the International Bureau of Weights and Measures and is used only on rare occasions. It remains the standard today. The kilogram is the only unit still defined in terms of an arbitrary artifact instead of a natural phenomenon.

The second. Historically, the unit of time, the second, was defined in terms of the period of rotation of the earth on its axis as 1/86 400 of a mean solar day. Meaning "second minute," it was first applied to timekeeping in about the seventeenth century when pendulum clocks were invented that could maintain time to this precision.

By the twentieth century, astronomers realized that the rotation of the earth is not constant. Due to gravitational tidal forces produced by the moon on the shallow seas, the length of the day is increasing by about 1.4 milliseconds per century. The effect can be measured by comparing the computed paths of ancient solar eclipses on the assumption of uniform rotation with the recorded locations on earth where they were actually observed. Consequently, in 1956 the second was redefined in terms of the period of revolution of the earth about the sun, as represented by the *Tables of the Sun* computed at the end of the nineteenth century by the astronomer Simon Newcomb of the U.S. Naval Observatory in Washington, DC. The second was defined to be 1/31 556 925.974 7 of the tropical year 1900. The operational significance of this definition was to adopt the linear coefficient in Newcomb's formula for the mean longitude of the sun to determine the unit of time.

The rapid development of atomic clocks soon permitted yet another definition. Accordingly, in 1967 the 13th CGPM defined the second as "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two ground states of the cesium-133 atom." This definition was based on observations of the moon, whose ephemeris is tied indirectly to the apparent motion of the sun, and was equivalent to the previous definition within the limits of experimental uncertainty.

The ampere. The unit of electric current, the ampere, is defined as that constant current which, if maintained in each of two parallel, infinitely long wires with a separation of 1 meter in vacuum, would produce a force per unit length between them equal to 2 x 10^{-7} N/m. This formal definition serves to establish the value of the constant μ_0 as 4π x 10^{-7} N/A^2 exactly. Although the base unit for electricity is the ampere, the electrical units are maintained through the volt and the ohm.

In the past, the practical representation of the volt was a group of Weston saturated cadmium-sulfate electrochemical standard cells. A primary calibration experiment involved the measurement of the force between two coils of an "ampere balance" to determine the current, while the cell voltage was compared to the potential difference across a known resistance.

The ohm was represented by a wire-wound standard resistor. Its resistance was measured against the impedance of an inductor or a capacitor at a known frequency. The inductance can be calculated from the geometrical dimensions alone. From about 1960, a so-called Thompson-Lampard calculable capacitor has been used, in which only a single measurement of length is required.

Since the early 1970s, the volt has been maintained by means of the Josephson effect, a quantum mechanical tunneling phenomenon discovered by Brian Josephson in 1962. A Josephson junction may be formed by two superconducting niobium films separated by an oxide insulating layer. If the Josephson junction is irradiated by microwaves at frequency f and the bias current is progressively increased, the current-voltage characteristic is a step function, in which the dc bias voltage increases discontinuously at discrete voltage intervals equal to f / K_J , where $K_J = 2e/h$ is the Josephson constant, h is Planck's constant, and e is the elementary charge.

The ohm is now realized by the quantum Hall effect, a characteristic of a two-dimensional electron gas discovered by Klaus von Klitzing in 1980. In a device such as a silicon metal-oxide-semiconductor field-effect transistor (MOSFET), the Hall voltage V_H for a fixed current I increases in discrete steps as the gate voltage is increased. The Hall resistance, or $R_H = V_H / I$, is equal to an integral fraction of the von Klitzing constant, given by $R_K = h / e^2 = \mu_0 c / 2\alpha$, where α is the fine structure constant. In practice, R_K can be measured in terms of a laboratory resistance standard, whose resistance is obtained by comparison with the impedance of a calculable capacitor, or it can be obtained indirectly from α.

A new method to determine the relation between the mechanical and electromagnetic units that has shown much promise is by means of a "watt balance," which has greater precision than an ordinary ampere balance. In this experiment, a current I is passed through a test coil suspended in the magnetic field of a larger coil so that the force F balances a known weight mg. Next the test coil is moved axially through the magnetic field and the velocity v and induced voltage V are measured. By the equivalence of mechanical and electrical power, $F v = V I$. The magnetic field and apparatus geometry drop out of the calculation. The voltage V is measured in terms of the Josephson constant K_J while the current I is calibrated by the voltage across a resistance known in terms of the von Klitzing constant R_K. The experiment determines $K_J{}^2 R_K$ (and thus h), which yields K_J if R_K is assumed to be known in terms of the SI ohm.

The Josephson and quantum Hall effects provide highly uniform and conveniently reproducible quantum mechanical standards for the volt and the ohm. For the purpose of practical engineering metrology, conventional values for the Josephson constant and the von Klitzing constant were adopted by international agreement starting January 1, 1990. These values are $K_{J\text{-}90}$ = 483 597.9 GHz/V and $R_{K\text{-}90}$ = 25 812.807 Ω exactly. The best experimental SI values, obtained as part of an overall least squares adjustment of the fundamental constants completed in 1998, differ only slightly from these conventional values.

The kelvin. From 1889 until 1927, the national reference standard of temperature for the United States comprised a set of sixteen mercury-in-glass thermometers. In 1927, the CIPM adopted an International Temperature Scale (ITS-27) based on six reproducible equilibrium states that agreed with thermodynamic temperatures within the limits of measurement. The platinum resistance thermometer, the platinum rhodium/platinum thermocouple, and the optical pyrometer were used for interpolation over three temperature ranges. This scale was modified in 1948 and clarified in 1960.

The Tenth General Conference on Weights and Measures in 1954 adopted the absolute temperature scale with a single fixed point, where the three phases of water (solid, liquid, and gas) coexist, with the unit "degree Kelvin," later renamed simply kelvin. The unit of thermodynamic temperature, the kelvin, is defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The effect of this definition is to make the temperature of the triple point to be 273.16 K, which corresponds to 0.01 °C. The Celsius scale is defined by the relation $t_C = T - 273.15$ exactly. Although the values of the thermodynamic and Celsius temperatures differ, the units are equivalent. Thus the degree Celsius, with symbol °C, is equal to the kelvin, with symbol K.

A new International Practical Temperature Scale (IPTS-68) with 13 equilibrium states was adopted in 1968 and was amended in 1975. This scale, however, was found to deviate from the thermodynamic temperature in certain regions and thus was replaced by the International Temperature Scale of 1990 (ITS-90).

By implication, the interval between the freezing and boiling boiling points of water at standard pressure is no longer rigorously 100 °C, since thermodynamic temperature is defined by a single fixed point. Since 1968, when the revised International Practical Temperature Scale was adopted, evidence has indicated that the definition of the kelvin leads to the value 99.975 °C for the boiling point, instead of exactly 100 °C as originally intended. The correct value for the triple point would have been 273.22 K.

METRIC UNITS IN INDUSTRY

The International System of Units (SI) has become the fundamental basis of scientific measurement worldwide. It is also used for everyday commerce in virtually every country of the world but the United States. Congress has passed legislation to encourage use of the metric system, including the Metric Conversion Act of 1975 and the Omnibus Trade and Competitiveness Act of 1988, but progress has been slow.

The space program should have been the leader in the use of metric units in the United States and would have been an excellent model for education. Burt Edelson, Director of the Institute for Applied Space Research at George Washington University and former Associate Administrator of NASA, recalls that “in the mid-‘80s, NASA made a valiant attempt to convert to the metric system” in the initial phase of the international space station program. However, he continued, “when the time came to issue production contracts, the contractors raised such a hue cry over the costs and difficulties of conversion that the initiative was dropped. The international partners were unhappy, but their concerns were shunted aside. No one ever suspected that a measurement conversion error could cause a failure in a future space project.”

Economic pressure to compete in an international environment is a strong motive for contractors to use metric units. Barry Taylor, head of the Fundamental Constants Data Center of the National Institute of Standards and Technology and U.S. representative to the Consultative Committee on Units of the CIPM, expects that the greatest stimulus for metrication will come from industries with global markets. “Manufacturers are moving steadily ahead on SI for foreign markets,” he says. Indeed, most satellite design technical literature does use metric units, including meters for length, kilograms for mass, and newtons for force, because of the influence of international partners, suppliers, and customers.

CONCLUSION

As we begin the new millennium, there should be a renewed national effort to promote the use of SI metric units throughout industry, and to assist the general public in becoming familiar with the system and using it regularly. The schools have taught the metric system in science classes for decades. It is time to put aside the customary units of the industrial revolution and to adopt the measures of precise science in all aspects of modern engineering and commerce, including the United States space program and the satellite industry.

Dr. Robert A. Nelson, P.E. is president of Satellite Engineering Research Corporation, a satellite engineering consulting firm in Bethesda, Maryland. He is *Via Satellite*’s Technical Editor.

Table 1. SI Base Units

Quantity	*Unit*	
	Name	*Symbol*
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 2. Examples of SI Derived Units

Quantity	*Unit*		
	Special Name	*Symbol*	*Equivalent*
plane angle	radian	rad	1
solid angle	steradian	sr	1
angular velocity			rad/s
angular acceleration			rad/s^2
frequency	hertz	Hz	s^{-1}
speed, velocity			m/s
acceleration			m/s^2
force	newton	N	kg m/s^2
pressure, stress	pascal	Pa	N/m^2
energy, work, heat	joule	J	kg m^2/s^2, N m
power	watt	W	kg m^2/s^3, J/s
power flux density			W/m^2
linear momentum, impulse			kg m/s, N s
angular momentum			kg m^2/s, N m s
electric charge	coulomb	C	A s
electric potential, emf	volt	V	W/A, J/C
magnetic flux	weber	Wb	V s
resistance	ohm	Ω	V/A
conductance	siemens	S	A/V, Ω^{-1}
inductance	henry	H	Wb/A
capacitance	farad	F	C/V
electric field strength			V/m, N/C
electric displacement			C/m^2
magnetic field strength			A/m
magnetic flux density	tesla	T	Wb/m^2, N/(A m)
Celsius temperature	degree Celsius	°C	K
luminous flux	lumen	lm	cd sr
illuminance	lux	lx	lm/m^2
radioactivity	becquerel	Bq	s^{-1}

Table 3. SI Prefixes

Factor	*Prefix*	*Symbol*	*Factor*	*Prefix*	*Symbol*
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y