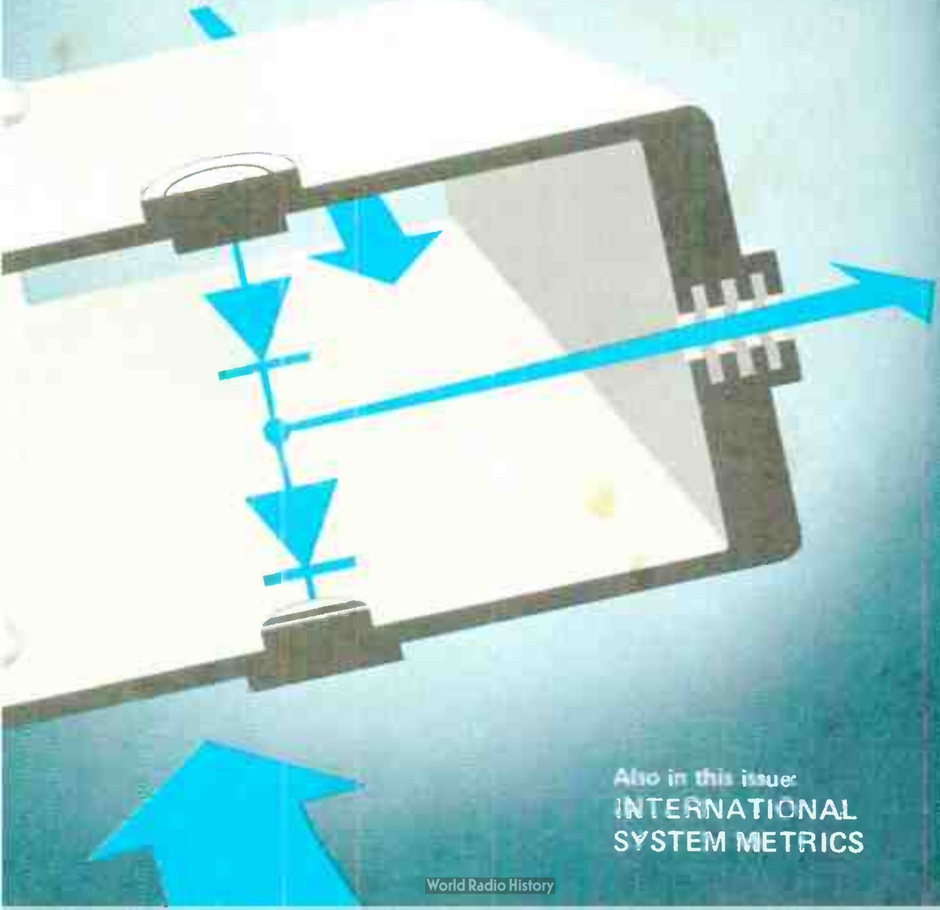
GTE LENKURT
DEMODULATOR
NOVEMBER/DECEMBER 1976

Microwave Mixers



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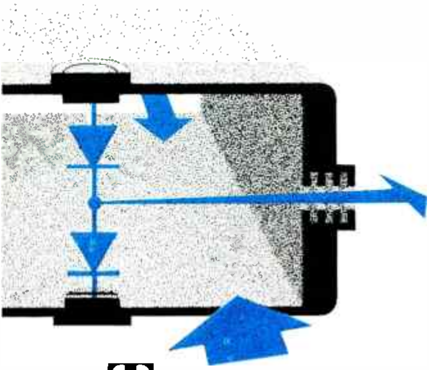

Frequency converters have been used for decades to up- and down-convert portions of the frequency spectrum. They can be defined as circuits whose input and output signals have the same phase and amplitude relationships among their components, but have different center frequencies.

The mixer stage in a heterodyne radio receiver is a frequency converter that, in most cases, is intended to change the frequency of a received radio frequency (rf) signal to a lower, or intermediate, frequency (IF) that can then be amplified to a level suitable for detection. Within a mixer, the conversion from rf to IF is accomplished by using the rf signal to modulate the continuous-wave output of a local oscillator (LO). The output of the mixer contains components representing the original and local oscillator frequencies, and the sum, difference, and other combinations of the fundamentals and harmonics of the signal and oscillator frequencies. The difference frequency is normally utilized as the IF, and the others treated as spurious interfering products.

The received rf signals are essentially the information-bearing components of an electromagnetic wave, and are invariably associated with some type of noise. At microwave frequencies random, or white, noise is usually of greatest concern.

Noise Figure

Not only is white noise present in a received rf signal, but operation of the receiver itself contributes additional noise. The amount of noise added by a receiver is indicated by the "noise figure," which is usually expressed in decibels (dB's). The noise figure represents the relationship between the signal-to-noise ratio at the input and the signal-to-noise ratio at the output; a noise figure of unity (zero dB) would indicate that the receiver generated no noise at all. This, of course, is true in ideal circuits only. In practical applications, the goal is to keep the noise figure as low as possible. The mixer stage, including the local oscillator, is a major potential source of noise in a receiver, and reducing its contribution to the noise figure has been the subject of much research.

In one typical balanced microwave mixer, for example, a hybrid-T is used, with mixer diodes terminating two of the ports (see Figure 1). In a hybrid-T, energy introduced into port 1 divides equally between the port 2 and port 3 arms, but does not couple into port 4. Energy fed into port 4 similarly couples into the port 2 and 3 arms, but not into port 1. The received signal is fed into port 1, where it divides between the two arms in such a way that the resulting signal components have opposite phases. The local oscillator energy, and any noise that might be associated with it, divides into two in-phase components when applied to port 4. The IF signals resulting from the mixing in each arm are out of phase, while the noise elements contributed by the local oscillator are in phase. By feeding the diode outputs through filters that suppress spurious

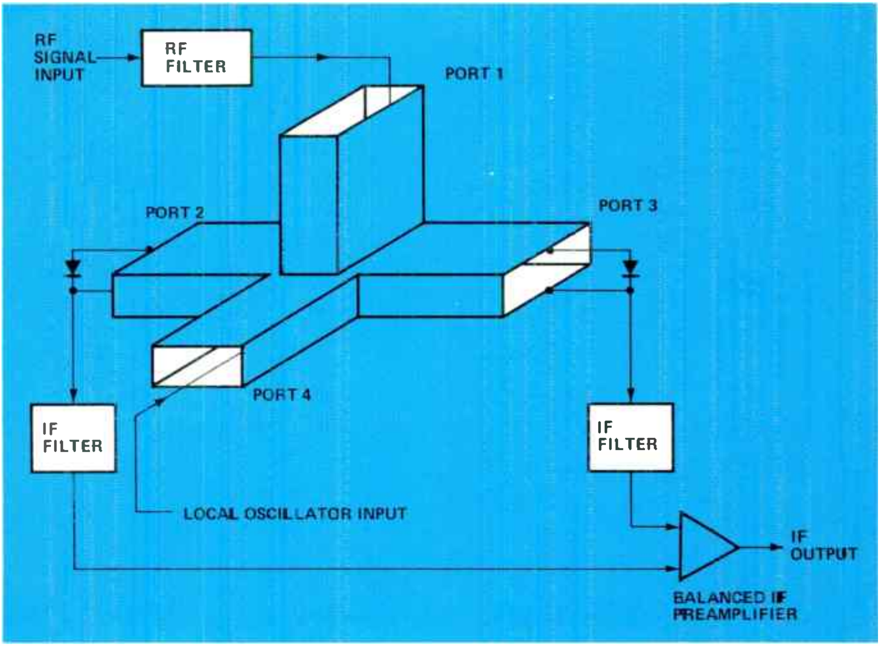

Figure 1. A four-port hybrid-T can be used as a mixer to provide cancellation of local oscillator noise contributions.

frequency products into a balanced IF preamplifier, the oscillator noise can be cancelled and the IF signals made to add in phase to produce the desired output.

Image Frequency

For any given local oscillator frequency, there are two radio frequency signals, one higher and one lower than the LO frequency, that will produce the desired IF:

$$f_{rf} = f_{LO} + f_{IF}$$
$$f_{rf'} = f_{LO} - f_{IF}$$

where f_{rf} and $f_{rf'}$ are the received rf signals, f_{LO} is the local oscillator frequency, and f_{IF} is the desired intermediate frequency product. For example, an rf input signal of 2.175 GHz and an LO frequency of 2.245 GHz will generate a difference IF of 70 MHz, which is the most commonly used IF in the telecommunications industry. It is also possible to obtain a 70-MHz IF with the same local oscillator frequency and an rf input of 2.315 GHz. Of these two, only one is normally desired; the other is the "image" frequency. The ratio of mixer output power derived from the desired signal to output power derived from the image frequency is the "signal-to-image" ratio or, more simply, the "image" ratio. In most microwave receivers, filtering in the pre-mixer portion of the receiver keeps the image frequency input small. However, the non-linear characteristics of the mixer components can cause the image to be generated within the mixer itself, causing interference with the desired signal.

Conversion Efficiency

Modulation of the LO output by an rf input signal is due to the action of the LO energy on the transconductance of the various detector-type devices used in mixers. The "conversion efficiency" of a mixer is a measure of how much energy is lost from the signal during its passage through the varying transconductance. Conversion gain is the ratio of IF output power to rf input power; conversion loss, normally expressed in dB's, is the reciprocal of conversion gain.

Conversion efficiency is a dominant factor in determining the noise figure of a mixer since losing a great deal of power in the conversion process decreases the available IF output power. While part of the conversion loss is resistive, causing a portion of the power to be irrevocably lost, a significant amount of the energy is contained in the spurious and image frequency products, which have historically been absorbed by circuit components to reduce their impact on the IF output.

Mixer Types

There are many types of mixers, with the simplest being a diode into which the rf and LO signals are fed (see Figure 2). In such a single-ended mixer, the transconductance of the diode varies at a rate determined by the LO frequency, so that it behaves like an on-off switch. When an rf input is applied to this time-varying conductance, the intermittent interruption generates the output spectrum, which contains the desired IF as well as all of the spurious frequency products that must be suppressed by external circuitry.

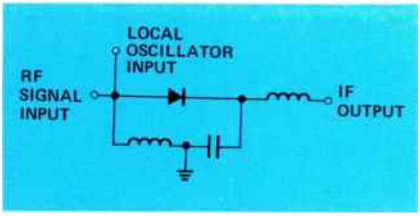

Figure 2. Equivalent circuit of a single-ended mixer. The local oscillator varies the transconductance of the diode to produce the mixing effect.

When two single-ended mixers are operated in parallel and 180° out of phase, they form a single-balanced mixer (see Figure 3) which reduces the even-order harmonics generated by one of the inputs (usually the local oscillator). By placing two single-balanced mixers in parallel and 180° out of phase (see Figure 4), the spurious signals caused by both inputs can be suppressed; in such a double-balanced mixer the four diodes alternately reverse the input-to-output connection on each half-cycle of the LO input. Filtering circuits are generally provided to reduce the effects of any undesired frequency components that might still remain in the output.

The physical realization of microwave mixers has taken many forms. One of the most popular currently in use is the microwave integrated circuit (MIC), or hybrid. This type of circuit utilizes such transmission media as slot, strip, microstrip and coplanar lines to interconnect semiconductor devices into miniaturized configurations that offer size and power advantages over other techniques in many applications.

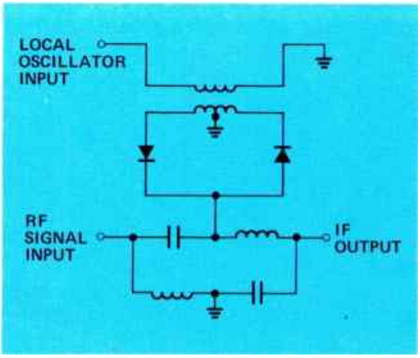

Figure 3. Equivalent circuit of a single-balanced mixer.

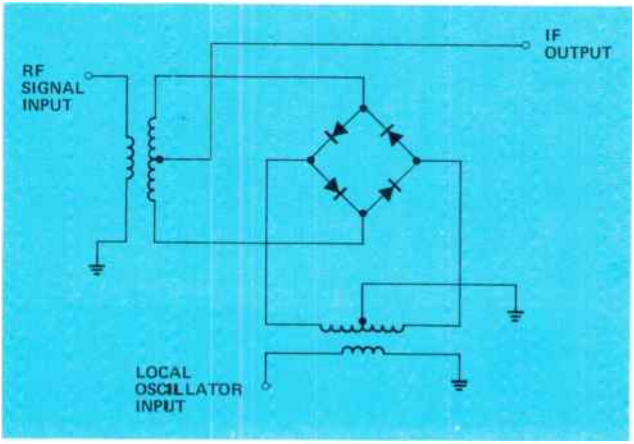

Figure 4. Equivalent circuit of a double-balanced mixer, giving improved rejection of spurious frequency products over the single-ended type.

FET Mixers

When active components are used in a mixer, there is usually a conversion gain, rather than loss, because of the amplifying characteristics of such devices. A typical example of this is the circuit shown in Figure 5, which contains a field effect transistor (FET). As in the simple diode mixer, the transconductance of the FET is varied by the LO input to produce the mixing effect. The bias voltage, however, raises the power level at which the mixing occurs and results in an overall gain, even though the conversion process itself might produce significant losses. For example, some experimental circuits using gallium arsenide metal semiconductor devices (GaAs MESFET's) in the X-band exhibited as much as 15 dB loss in the conversion portion of the operation, while the overall mixer performance had a conversion gain of up to 6 dB.

This type of circuit is particularly useful when very small signals are to be received, as in satellite communication facilities, because the mixing and IF preamplifier stages can be realized on one substrate. In the telecommunications industry, however, signal levels are usually such that the inherent amplification would cause FET mixers to overload unless costly preventive measures were taken. Diode mixers with separate IF preamplifier stages are therefore most widely found in the microwave receivers intended for such applications as telephone company systems.

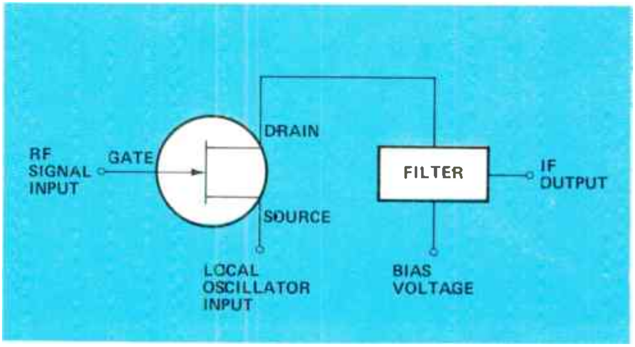

Figure 5. The electrostatic field within an FET is controlled by the local oscillator input to vary the transconductance for mixing. The inherent FET amplification produces a mixer conversion gain.

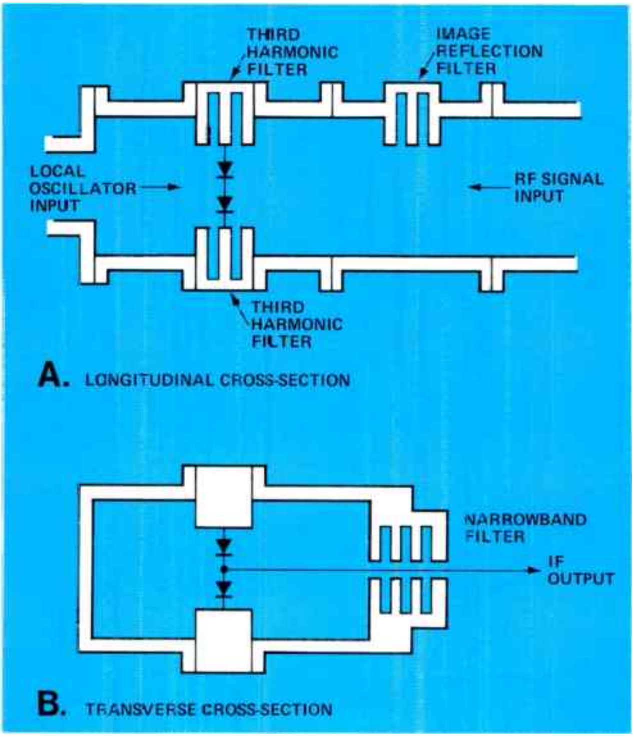

Figure 6. Accurate dimensioning and micro-machining techniques make possible a low-loss waveguide image reflection mixer that utilizes the energy normally lost in spurious products.

Reflected Energy

Whatever its form, a mixer can be treated as a multi-port device or network having a linearity characteristic as one of its properties. That is, the energy at any given port is the product of contributions at all of the other ports. The spurious frequencies generated by the mixing process are, therefore, not only present in the IF output, where they are suppressed by filtering techniques, but appear at the input ports as well. If conditions at these ports are correct, the energy contained in the unwanted frequencies can be reflected back into the mixer and added to the desired signal. If conditions are not proper, the reflected energy interferes with the IF and increases the mixer's conversion loss.

For example, a short circuit at the image frequency appearing one quarter-wavelength outside the rf input port can return an internally generated image component to the mixer in the correct phase to aid the IF output. In communications systems, however, a wide range of spurious frequencies is present; what is a quarter-wave short circuit to the image is not a short to the others. To avoid returning components that would interfere with the IF, therefore, all of the unwanted energy components, including the image, are generally absorbed by pads and isolators placed at the mixer ports. Because it reduces the power available for inclusion in the IF output, this technique necessarily limits the conversion efficiency of the mixer, and directly influences the receiver's noise figure.

Image Reflection Mixer

An ideal image reflection mixer would circumvent this problem by actually returning all of the spurious frequencies in the proper phase to add to the IF. Ideals are not, unfortunately, usually realizable, but a new mixer now in use in GTE Lenkurt's 775A3/B3 microwave radio systems employs image reflection that re-mixes the greater part of the energy to achieve a mixer conversion loss of only 2 dB, producing an over-all receiver noise figure of only 7 dB within the 6-GHz band.

This mixer – the first practical realization of theories that have been known for many years – consists of a low-loss waveguide section into which Schottky-barrier diodes are suspended in a manner that properly couples the various wave components, allowing the diodes to make any reflected energy add constructively to the IF output. Filters micro-machined into the guide reflect spurious products through the third harmonic in such a way that their energy is released for use in the IF. For example, grooves cut into the diode mountings to a depth equal to one quarter-wavelength at three times the rf input give the effect of parallel resonant circuits at that frequency (see Figure 6). The third harmonic component is thus not allowed to form and the power that would have gone into it is available to the diodes for addition to the IF. Similarly, slots cut into the guide at the IF output to form a narrowband filter make that port appear as an open circuit to all microwave frequencies, reflecting them back to the diodes for re-mixing.

To keep the reflected energy from coupling out of the LO input port, the waveguide feeding the local oscillator signal into the mixer is mounted at 90° with respect to the rf input guide. The LO port thus acts as an iris that is a short circuit to the frequencies of interest, returning them to the diodes for re-mixing. Finally, a resonator tuned to the image frequency is placed at the rf input port to reflect that energy back into the mixer in phase to add to the IF.

With the introduction of the image reflection mixer as a reliable, effective device, the telecommunications industry has been presented with another valuable tool in its efforts to increase the sensitivity, and the information-bearing capacity, of microwave radio systems.

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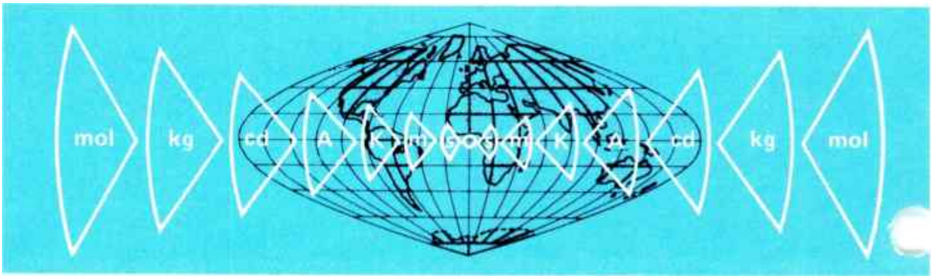


INTERNATIONAL SYSTEM METRICS

The United States is officially committed to conversion from customary to International System (SI) metric units of measure. Although certain aspects of the metric system have always been an important part of the telecommunications industry, universal familiarity with the SI version is essential if the conversion is to be smoothly accomplished.

Although systems of measurement may differ from one another in detail, all stem from the same fundamental concept: comparison of the quantities of things. A "quantity" in this context refers to those scalar physical characteristics, such as length, area, time, volume, mass and temperature, that can be measured and expressed in numerical terms. A "unit of measure" is a precisely defined value in terms of which a given quantity can be described. "Fundamental," or "base," units refer to those quantities whose scale of measurement is arbitrarily assigned, usually through general agreement within a society, and is independent of other measurement scales. All other quantities are described by "derived" units that are formed by the algebraic combination of base units, or of other derived units. For example, velocity is a quantity that is measured in terms of the fundamental units of length and time; its units are therefore derived (miles per hour, meters per second, etc.).

The magnitude of a quantity, which is one of the essential properties that permit numerical expression, is determined by comparing it with the magnitude of the accepted unit by the equation:

$$\text{magnitude of quantity} = N \times |U|$$

where $|U|$ is the unit of measure and N is a pure number indicating how many times the unit must be taken to make up the quantity. Thus, when it is said that a tower has a height of 200 feet, the magnitude of the quantity height (vertical length) is indicated to be 200 times the "foot" unit that has been agreed upon as acceptable in expressing that quantity.

Customary Units

The types of units agreed upon as acceptable in the United States constitute what is commonly referred to as the "customary units" system of measurement. The customary system derives, for the most part, from the traditional British system, which in turn evolved from Roman, Anglo-Saxon and Norman-French systems in what can, at best, be called a process of unregulated development. For example, a definition of the yard dating from the early 14th Century specifies that a yard equals three feet, each foot being equal to twelve inches; the measurement standard for the inch is given as three round and dry barleycorns laid end-to-end.

The result of this haphazard development has been a complex agglomeration of units and standards in which any number of units can be applied to a given quantity. Length, for example, is essentially the shortest straight-line distance between two points; in the customary system, it can be measured in terms of inches, yards, miles, nautical miles, furlongs, fathoms, leagues, or any of several other units.

Aside from the sheer number of units, the customary system is complicated by the fact that units for one quantity are not directly related to those for another. Thus, for example, volume cannot be related to length without laborious mathematical manipulation.

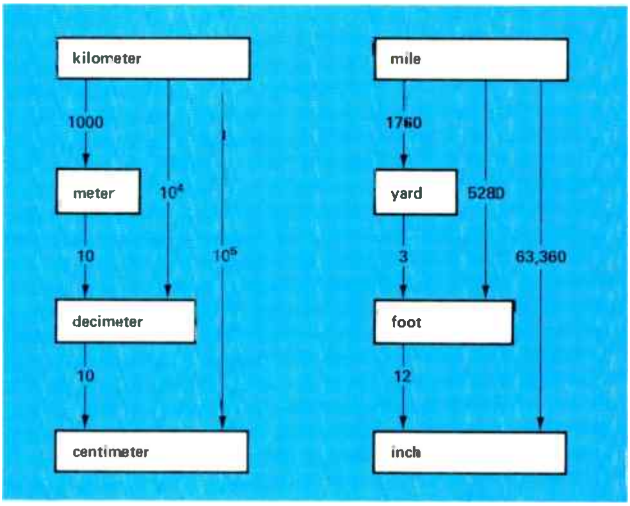
Metric Units

As first realized in the late 18th Century, metric units were specified for length, mass, and capacity or volume. These units were based on a constant of the physical universe, as determined by the most advanced scientific principles of the time. This constant was the size of the earth, and the unit derived from it was the meter, defined as being equal to one ten-millionth of the length of an arc along a meridian representing the distance between the Equator and the North Pole. Cubing some part of this length and filling it with water established a unit of mass, and the same technique provided a measure of capacity. All of the units were thus derived from a single measurement, making them precisely interrelated.

To make the system even more rational, it was decimally based. The convenience of this is evident when conversion from miles to inches is compared with conversion from kilometers to centimeters (see Figure 1): the former requires an awkward conversion factor (one mile = 63,360 inches) while the latter requires only that the decimal point be moved (one kilometer = 10^5 centimeters).

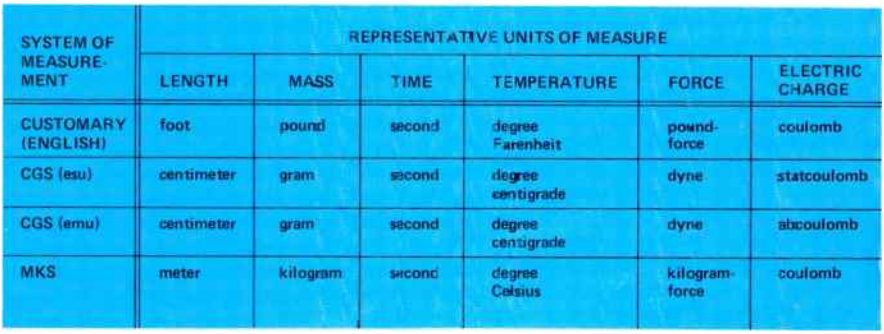
As so often happens, this original metric system underwent a process of evolution, during which some units were renamed, some removed and some added to meet the needs of the emerging technological world. This actually had a divisive effect on what was to have been a universal, unifying system. For example, scientists measuring the phenomena associated with static electricity and capacitance added a unit of time and modified the basic metric into the centimeter-gram-second, electrostatic unit – CGS (esu) – system. However, when dealing with magnetism and electric currents, a CGS (emu) – centimeter-gram-second, electromagnetic unit – system was employed. It was eventually realized that the two systems, which together were frequently called the "Gaussian

Figure 1. The decimal relationships between metric units make conversion from one to another simpler than is possible in the customary system.



System of Units," were related by the speed of light, and a meter-kilogram-second (MKS) system was introduced in an effort to regain the unity promised by the original creation (see Figure 2).

These metric systems recognized only three base units, from which all other units were derived. A fourth unit, the ampere, was later added as a link between the mechanically derived units and those of electromagnetics. The most recent version, the *Système International d'Unités* — the International System of Units — (SI), consists of seven base and two supplementary units (see Figure 3). (The supplementary units radian and steradian are, respectively, the ratio of two lengths and the ratio of two areas: they are therefore not considered to be true base units, nor are they derived from other units.) The major differences between SI and CGS/MKS metrics lie in the precision of the unit definitions and in the use of explicitly distinct units for mass and force. In SI usage, the unit "kilogram" is restricted to the quantity mass; the "kilogram-force" unit is replaced by the "newton,"



SYSTEM OF MEASUREMENT	REPRESENTATIVE UNITS OF MEASURE					
	LENGTH	MASS	TIME	TEMPERATURE	FORCE	ELECTRIC CHARGE
CUSTOMARY (ENGLISH)	foot	pound	second	degree Farenheit	pound-force	coulomb
CGS (esu)	centimeter	gram	second	degree centigrade	dyne	statcoulomb
CGS (emu)	centimeter	gram	second	degree centigrade	dyne	abcoulomb
MKS	meter	kilogram	second	degree Celsius	kilogram-force	coulomb

Figure 2. The original metric system evolved into what are essentially major subsystems for use in different applications.

QUANTITY	UNIT OF MEASURE	UNIT SYMBOL
LENGTH	meter	m
MASS	kilogram	kg
TIME	second	s
TEMPERATURE	kelvin	K
ELECTRIC CURRENT	ampere	A
AMOUNT OF SUBSTANCE	mole	mol
LUMINOUS INTENSITY	candela	cd
*PLANE ANGLE	radian	rad
*SOLID ANGLE	steradian	sr

*SUPPLEMENTARY UNITS

Figure 3. The International System of Units (SI) consists of seven base and two supplementary units.

eliminating the confusion caused by using the same term for units of force and mass.

SI Units

The SI is a complete system of measurement with most units precisely defined in terms of universal constants that can be duplicated in any properly equipped laboratory. The kilogram is the only base unit not so defined; its standard is a platinum-iridium cylinder that is kept in Paris under carefully controlled conditions first specified in 1889. Duplicates of this international prototype are maintained by the nations of the world.

The names and relationships of the SI units were taken from the original metric system and augmented by units for other physical quantities. Because each unit is related to a particular constant or standard, they are dimensionally independent: for example, the meter is defined in terms of wavelengths of the radiation of the krypton-86 atom, while the unit of time, the second, is related to the cesium-133 atom. This independence means that there is only one unit for each fundamental quantity, and that unit is the same regardless of application.

From the base units can be derived other units to measure such quantities as area, force, volume and power, according to the algebraic relationships that link the corresponding quantities. The symbols for these derived units contain the mathematical notation (multiplication and division signs, etc.) used in the combination process, although some are so frequently used that they have been assigned special names and symbols (see Figure 4). Because every quantity has a unique unit, the symbols and abbreviations are also unique and well-defined. The great advantage of this is that it eliminates the confusion arising from the practice of using the same symbol or abbreviation for different quantities in different applications, as in the use of "b" as the symbol for a unit of pressure (the "bar") and a unit of area (the "barn," employed in nuclear physics to measure cross-sections of subatomic particles).

As in the CGS and MKS systems, multiples and submultiples of the SI units are formed by addition of prefixes or their symbols directly to the names or symbols of the units (the kilogram is an exception: prefixes are added to the stem "gram"). In general, the prefixes (see Figure 5) are selected so that the numerical value of the quantity lies between 0.1 and 1000 (15 m is easier to handle than 15000 mm, for example). When dealing with large values, prefixes are also selected to represent multiples of 1000. Compound prefixes are not used; that is, two or more prefixes are never combined to make a multiple or submultiple (1 $\mu\mu$F should properly be 1 pF). When an exponent is attached to an SI unit containing a prefix, the entire unit is raised to that power: e.g., 1 $\text{km}^3 = (10^3\ \text{m})^3 = 10^9\ \text{m}^3$.

SI Style and Usage

The International System of Units was developed, and is maintained, by the General Conference on Weights

QUANTITY	UNIT OF MEASURE	DERIVED SYMBOL	SPECIAL NAME	SPECIAL SYMBOL
ACCELERATION	meter per second squared	m/s^2		
ANGULAR VELOCITY	radian per second	rad/s		
AREA	square meter	m^2		
CURRENT DENSITY	ampere per square meter	A/m^2		
ELECTRIC CAPACITANCE		C/V	farad	F
ELECTRIC CHARGE		A · s	coulomb	C
ELECTRIC CONDUCTANCE		1/Ω	siemens	S
ELECTRIC FIELD STRENGTH	volt per meter	V/m		
ELECTRIC FLUX DENSITY	coulomb per square meter	C/m^2		
ELECTRIC POTENTIAL		W/A	volt	V
ELECTRIC RESISTANCE		V/A	ohm	Ω
ENERGY DENSITY	joule per cubic meter	J/m^3		
ENERGY (WORK)		N · m	joule	J
FORCE		kg · m/s^2	newton	N
FREQUENCY		1/s	hertz	Hz
ILLUMINANCE		lm/m^2	lux	lx
INDUCTANCE		Wb/A	henry	H
LUMINOUS FLUX		cd · sr	lumen	lm
MAGNETIC FIELD STRENGTH	ampere per meter	A/m		
MAGNETIC FLUX		V · s	weber	Wb
MAGNETIC FLUX DENSITY		Wb/m^2	tesla	T
MASS DENSITY	kilogram per cubic meter	kg/m^3		
PERMEABILITY	henry per meter	H/m		
PERMITTIVITY	farad per meter	F/m		
POWER		J/s	watt	W
PRESSURE (STRESS)		N/m^2	pascal	Pa
SPECIFIC ENERGY	joule per kilogram	J/kg		
VELOCITY	meter per second	m/s		
VOLUME	cubic meter	m^3		

Figure 4. Derived SI units are formed by the algebraic combination of other units. Some of the more frequently used derived units have been given special names; those that are not named are also sometimes called compound units.

and Measures (CGPM) as a basis for worldwide standardization of measurement units. It is the modernized form of the metric system that is recommended for all applications, and is intended to replace both customary units and metric units that are now obsolete. To make SI units truly universal, it is necessary that rules concerning matters of style and usage be established and followed. This is especially true for those who regularly deal with written and illustrated material, because even a seemingly minor error can have serious consequences. For example, if an order for 50 milligrams of some item were written as 50 Mg rather than as 50 mg, an excessive amount of the item would be delivered. Among the most pertinent of the rules for SI usage are:

1. International System units are not used in conjunction with customary units, nor with units from the older metric systems. This is especially true of those CGS/MKS units having special names (erg, dyne, gauss, maxwell, etc.).
2. The term "weight" is not used, the proper term in most applications being "mass," expressed in kilograms. When "weight" refers to the force of gravity exerted on a body or an object. the proper quantity is "force," and the unit of measure is the newton.
3. When written in full, the names of SI units always begin with lower

MULTIPLICATION FACTOR IN POWERS OF TEN	PREFIX	SYMBOL
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
*10^{2}	hecto	h
*10^{1}	deca	da
*10^{-1}	deci	d
*10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*TO BE AVOIDED WHENEVER POSSIBLE

Figure 5. Multiples and submultiples of SI units are formed by the addition of prefixes.

case letters, even when they appear in tabular form. The only exceptions are the common expression "degrees Celsius" (not properly an SI unit, but acceptable for some applications) and cases in which units appear as the first word in a sentence.

4. The SI symbols and abbreviations are always lower case, unless they derive from a unit named for a person. Even in headings or titles in which all capital letters are used, any SI symbol appears in the correct form: "MASS IN mg," not "MASS IN MG."
5. The symbols and abbreviations for SI units are never followed by a period unless they appear at the end of a sentence.
6. Symbols for SI units are always singular in form; that is, a plural is never formed by addition of the letter "s" as that is the symbol for the unit of time, the second.
7. Mathematical notations and symbols are not combined with written-out names. If symbols are being used, a solidus (/) is used rather than the word "per" (km/s, not km per s).
8. Attaching letters to unit symbols to give information about the nature of the quantity is incorrect; MWe for "megawatt electrical (power)" and Vac for "volts ac" are not acceptable.
9. The special name "liter" has been approved for the cubic decimeter, but its use is restricted to the measurement of liquids and gases.
10. When writing the unit of length and the special name for the cubic decimeter, the English spelling is preferred ("metre" and "litre"), but the American spelling is also acceptable ("meter" and "liter").

Other Units

The developers of the SI recognized that some units are so important and so widely used as to be virtually impossible to replace. These units are accepted for use with the SI (see Figure 6). There are also some other units, useful in specialized fields, whose values in SI units can only be determined through experimentation and are consequently not exactly known; these units, which include the electronvolt, unified atomic mass unit, astronomical unit and the parsec, are accepted for use with the International System. A certain number of customary/CGS/MKS units are accepted

UNIT NAME	SYMBOL	VALUE IN SI UNITS
minute-time	min	60 s
hour	h	3600 s
day	d	86400 s
degree	°	$(\pi/180)$ rad
minute-angular	′	$(\pi/10{,}800)$ rad
second-angular	″	$(\pi/648{,}000)$ rad
liter	l	$dm^3 = 10^{-3} m^3$

Figure 6. Non-SI units acceptable for use with the SI.

for use with the SI on a temporary basis only (see Figure 7).

The SI unit of temperature is the kelvin (K). However, the degree Celsius (formerly called centigrade) is so widely used in engineering and non-scientific areas that its continued use is accepted. A Celsius temperature (t) is related to a kelvin temperature (T) by:

$$T = 273.15 + (t), \text{ exactly.}$$

UNIT NAME	SYMBOL	VALUE IN SI UNITS
nautical mile		1852 m
angstrom	Å	10^{-10} m
hectare	ha	10^4 m^2
roentgen	R	2.58×10^{-4} C/kg

Figure 7. Some of the non-SI units that are acceptable for use with the SI for a limited time only.

Conversion and Rounding

Until all measurements are in SI units, there will be a need to convert from one system to another. The conversion process is accomplished by multiplying or dividing the specified quantity by a conversion factor (see Figure 8). In most cases, a rounding-off process is also required to make the number of digits manageable.

In rounding off, the general rule is that the number of significant digits retained should neither reduce nor exaggerate accuracy. For example, 8.2 feet converts to 2.49936 meters. This level of accuracy may be required for tolerances and limiting values, but is exaggerated for many applications; it should be rounded (2.499 m, 2.5 m, etc.) as needed.

To obtain an approximate value with the least effort, a conversion factor can be rounded before multiplication. The resulting accuracy is diminished, but it is usually sufficient for common usage. One temperature conversion, for example, can be accomplished with the precise equation:

$$t_C = (t_F - 32)/1.8$$

where t_C is in degrees Celsius and t_F is in degrees Farenheit. For most everyday purposes, however, sufficient accuracy can be achieved with the simple rule, "subtract 30 and divide by two": $t_C = (t_F - 30)/2$. Measurements expressed in degrees Celsius likewise can be converted to rough Farenheit equivalents with the "multiply by two and add 30" approximation. As shown in Figure 9, the error caused by this rounding off of the conversion factor increases as temperatures become more extreme, but the accuracy over the range generally encountered in everyday life is quite adequate.

The movement of the United States from customary to SI metric units of measure has begun, and is apparently

Figure 8. To change a customary unit measurement to SI units, it is multiplied by a conversion factor. To change from SI to customary units, the measurement is divided by the conversion factor.

TO CONVERT FROM	TO	MULTIPLY BY
angstrom	meter	1.000×10^{-10}
foot	meter	3.048×10^{-1}
mile	meter	1.609×10^{3}
mile/hour	kilometer/hour	1.609
oersted	ampere/meter	7.958×10^{1}
pound	kilogram	4.536×10^{-1}
ton (short, 2000 lb)	kilogram	9.072×10^{2}
foot-pound-force	joule	1.356
foot-candle	lux	1.076×10^{1}
pound-force/inch (psi)	pascal	6.895×10^{3}
gauss	tesla	1.000×10^{-4}
maxwell	weber	1.000×10^{-8}

TEMPERATURE IN DEGREES CELSIUS (t_c)	APPROXIMATE TEMPERATURE IN DEGREES FARENHEIT [$t_F = (t_c \times 2) + 30$]	ACTUAL TEMPERATURE IN DEGREES FARENHEIT [$t_F = (t_c \times 1.8) + 32$]	ERROR
50	130	122	+8°
45	120	113	+7°
40	110	104	+6°
35	100	95	+5°
30	90	86	+4°
25	80	77	+3°
20	70	68	+2°
15	60	59	+1°
10	50	50	0°
5	40	41	−1°
0	30	32	−2°
−5	20	23	−3°
−10	10	14	−4°
−15	0	5	−5°
−20	−10	−4	−6°

Figure 9. A temperature conversion sufficiently accurate for general use can be performed with a rounded-off conversion factor.

irrevocable. For example, the Federal Communications Commission recently announced that it has adopted a program for converting to the use of SI metrics, which will be used in all new and amended rules as well as on all license, equipment authorization, and construction permit applications; this program calls initially for customary units to be stated parenthetically, but these will eventually be dropped.

Although there will undoubtedly be a period of confusion and misunderstanding during the transition period, this can be minimized by acceptance of the inherent simplicity and logic of the SI units, and their constant and correct use.

* * *

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