CEOS STANDARD TERMINOLOGY FOR MICROWAVE RADIOMETRY (10 September, 2003)

ALPHABETICAL INDEX

Note: I, II, III, and IV refer to chapters of the CEOS document. IVM and GUM indicate that the definition is given in the IVM [1] and/or GUM [2] and is not repeated in this document.

CHAPTER I. GENERAL TERMINOLOGY

Calibration: set of operations that establish, under specified conditions, the relationship between sets of values of quantities indicated by a measuring instrument or measuring system and the corresponding values realized by standards. The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications. [1]

Validation: the process of assessing, by independent means, the quality of the data products derived from the system inputs.
Note: In a remote-sensing application, validation is commonly performed by comparing the value of a higher order data product (*e.g.* sea surface temperature) inferred from the measured value of the brightness temperature, with a direct measurement of that quantity.

Verification: validation

Check standard: standard that is used routinely to check measurements.

Traceability: property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. [1]

True value: value consistent with the definition of a given particular quantity. [1,2]
Notes: This is a value that would be obtained by a perfect measurement. True values are by nature indeterminate.

Experimental standard deviation: for a series of n measurements of the same measurand, the quantity s characterizing the dispersion of the results and given by the formula

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$$

x_i being the result of the ith measurement and $\bar{x}$ being the arithmetic mean of the n results considered. [1,2]
Notes: Considering the series of n values as a sample of a distribution, $\bar{x}$ is an unbiased estimate of the mean μ, and s^2 is an unbiased estimate of the variance σ^2 of that distribution. The expression $s/\sqrt{n}$ is an estimate of the standard deviation of the distribution of $\bar{x}$ and is called the experimental standard deviation of the mean.

Allan Standard Deviation (ASD): the square root of *Allan variance*. Both the ASD and the Allan variance can be used to describe different noise types and drift of a radiometer receiver. Compared to Allan variance, however, the ASD has the advantage that the units are in kelvin.

Allan variance: a two-sample variance, where the variance is taken on the variable y. Each value of y in a set has been averaged over an interval τ and the y's are taken in an adjacent series, i.e. no delay between the measurements of each:

$$\sigma_A^2(\tau) = \tfrac{1}{2}\left\langle (\Delta y)^2 \right\rangle,$$

where the brackets <> denote the expectation value. The Allan variance can be used to describe different noise types and drift of a radiometer receiver. See also: *Allan Standard Deviation (ASD)*.

Uncertainty of measurement: parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand; also a measure of the possible error in the estimated value of the measurand as provided by the result of a measurement. See [2] or [3] for details.

Relative uncertainty: uncertainty of the measurand divided by the nominal value of that measurand.

Type-A uncertainty: an uncertainty or component of uncertainty that is evaluated by the statistical analysis of series of observations. (adapted from [2])

Type-B uncertainty: an uncertainty or component of uncertainty that is evaluated by means other than the statistical analysis of series of observations. (adapted from [2])

Error: result of a measurement minus a true value of the measurand. [1,2]
Notes: Since a true value cannot be determined, in practice a conventional true value is used. When it is necessary to distinguish "error" from "relative error," the former is sometimes called the "absolute error."

Relative error: error of measurement divided by a (conventional) true value of the measurand. [1,2]

Random error: result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions. [1,2]
Notes: Random error is equal to error minus systematic error. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

Systematic error: mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand. [1,2]
Notes: Systematic error is equal to error minus random error. Like true value, systematic error and its causes cannot be completely known. For a measuring instrument, see "bias."

Uncertainty budget: a detailed tabulation of the sources of uncertainty and their respective contributions to the standard uncertainty in the measurand of interest; sometimes referred to as "error budget."

Accuracy: closeness of the agreement between the result of a measurement and a true value of the measurand. Since the true value cannot be determined exactly, the measured or calculated value of highest available accuracy is typically taken to be the true value. If a value of higher accuracy than the value in question is not available, then the accuracy cannot be assigned a meaningful quantitative value.

Resolution: smallest difference between values of a measurand that can be meaningfully distinguished. (modified [1])

Sensitivity: change in the response of a measuring instrument divided by the corresponding change in the stimulus. [1]

Quantization level: in the quantization process, the discrete value assigned to a particular subrange of the analog signal being quantized [4].

Stability: ability of a measuring instrument to maintain constant its metrological characteristics with time. [1]
Notes: Stability may be quantified in several ways, for example: in terms of the time over which a metrological characteristic changes by a stated amount, or in terms of the change in a characteristic over a stated time.

Reproducibility (of results of measurements): closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of mesurement. [1]
Notes: A valid statement of reproducibility requires specification of the conditions changed. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.

Repeatability (of results of measurements): closeness of the agreeement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. [1]
Notes: Repeatability conditions include: the same measurement procedure, the same observer, the same measuring instrument used under the same conditions, the same location, and repetition over a short period of time. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

Bias (of a measuring instrument): systematic error of the indication of a measuring instrument . [1]
Note: The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

Drift: slow change of a metrological characteristic of a measuring instrument. [1]

Response time: time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits around its final steady value. [1]

Radiance (L): the radiated power per unit solid angle per unit area normal to the direction defined by the solid angle Ω,

$L = \frac{dP}{d\Omega dA_{\perp}}$, where $dA_{\perp} = \cos\theta dA$

Spectral radiance density (L_f): the radiance per unit frequency interval, $L_f \equiv \frac{dL}{df}$

Brightness: the radiance, the radiated power per unit solid angle per unit area normal to the direction defined by the solid angle Ω.

Note: Brightness is often used for Spectral brightness [IEEE, Krause]. The meaning is usually clear from the context.

Spectral brightness density: the brightness per unit frequency, the spectral radiance density.

Effective Black-Body Brightness Temperature: the physical temperature of an ideal black body that would produce the spectral brightness density or spectral radiance density under consideration.

System equation (of a microwave radiometer): equation relating the primary measurand of the radiometer, *e.g.*, the brightness temperature, to subsidiary measurands, such as powers, and to calibration quantities, such as standard values.

Noise temperature (at a reference plane in a microwave circuit/network, T_n): the available noise power spectral density at the reference plane divided by Boltzmann's constant (k_B); thus $\frac{dP_n^{av}}{df} = k_B T_n$ by definition, where the subscript *n* denotes "noise." For a resistor at physical temperature T_{phys}, the noise temperature is given by

$k_B T_n = \frac{hf}{e^{\frac{hf}{k_B T_{phys}}} - 1}$, so that for $\frac{hf}{k_B T_{phys}} << 1$, $T_n \approx T_{phys}$.

Reference Temperature (T_0): Temperature used in ratios to set a scale, conventionally taken as T_0 = 290 K.

Emissivity (of a surface): the spectral radiance of the surface relative to the spectral radiance of an ideal black body radiator at the same temperature, $e(\theta,\phi) = \frac{L(T,\theta,\phi)}{L_{BB}(T)}$.

CHAPTER II. REAL-APERTURE RADIOMETERS

Radiometer: a very sensitive receiver, typically with an antenna input, that is used to measure radiated electromagnetic power.

End-to-end calibration: calibration of entire radiometer system as a unit, achieved by observing the values of output quantities (voltage, power, …) for known values of incident radiance at the antenna aperture.

Two-point calibration: fixing the relationship between the input signal and the output response of a radiometer using two distinct input stimuli. Assuming a linear receiver, all possible input signal levels can now be retrieved from the radiometer output responses. Using external end-to-end calibration, the input signal equals the antenna temperature of the radiometer.

Blackbody load: microwave load with characteristics very close to those of a perfect black body within a certain frequency range.

External calibration: calibration method that applies reference signals from targets that lie outside the radiometer. In the case that these targets illuminate the antenna of the radiometer, and end-to-end calibration is obtained.

Internal calibration: calibration of a radiometer by connecting embedded reference noise sources to the receiver chain; also called injection calibration.

Tip-curve calibration: N-point calibration ($N \geq 2$) using the atmosphere at different zenith angles as calibration target.

Close-coupling: the technique by which the receiving aperture of a radiometer is coupled to a blackbody load so that the system is closed to stray radiation.

Noise figure (of receiver or system): at a specified input frequency, the ratio of 1) the total noise spectral power density at a corresponding output frequency available at the output port when the noise temperature of the input termination is T_0 = 290 K, to 2) that portion of the total output noise spectral power density that is engendered by the input termination. [5] The noise figure depends on the impedance or reflection coefficient of the input termination and on the location of the input reference plane. Unless otherwise stated, the receiver noise figure is assumed to be defined at the receiver input, and the system noise figure is assumed to be defined at the antenna aperture.

Effective input noise temperature (of receiver, T_{Rec}, or system, T_{Sys}): the input termination noise temperature which, when the input termination is connected to a noise-free equivalent of the receiver, would result in the same output noise power as that of the actual receiver connected to a noise-free input termination. [5] It is related to the receiver noise figure by

$$F_{\mathrm{Rec}} = \left(\frac{T_{\mathrm{Rec}} + T_0}{T_0} \right),$$

where $T_0 = 290$ K. It is a function of frequency, and it depends on the impedance or reflection coefficient of the input termination. It also depends on the location of the input reference plane; unless otherwise stated, the receiver noise temperature is assumed to be defined at the receiver input, and the system noise temperature is assumed to be defined at the antenna aperture.

Operating noise figure (of receiver or system): at a specified input frequency, the ratio of 1) the total noise spectral power density at a corresponding output frequency available at the output port when the noise temperature of the input termination is the actual input noise temperature (or brightness temperature, for a system), to 2) that portion of the total output noise spectral power density that is engendered by the input termination. (adapted from [6]) In terms of the **Effective input noise temperature**, the **Operating noise figure** is given by

$$F_{Op} = \left(\frac{T_{\mathrm{Rec}} + T_{in}}{T_{in}} \right),$$

where T_{in} is the nominal value of the input noise temperature.

Half-power bandwidth (B_{3dB}): the width at which the power response is half the maximum value; also called the 3-dB width.

Noise bandwidth (B_n): the width of an ideal rectangular filter (or other circuit or component) having the same maximum (available) gain as the real filter, and which produces the same output available power (integrated over frequency) as the real one when the input is white noise. In terms of the filter (available) gain G, $B_n = \dfrac{\int_0^\infty G(f)df}{G_{\max}}$.

(Equivalent) predetection bandwidth (B_{pre}): the effective bandwidth of the predetection section of a radiometer, used in computing the ideal radiometer resolution.

In terms of the gain G of the predetection section, $B_{pre} = \dfrac{\left\{ \int_0^\infty G(f)df \right\}^2}{\int_0^\infty G^2(f)df}$.

Boresight: the beam-maximum direction of a highly directive antenna. [7]

Directivity (of antenna in a given direction, ($D(\theta,\varphi)$)): The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. [7]

Notes: The average radiation intensity is equal to the total power radiated by the antenna divided by 4π. If the direction is not specified, the direction of maximum radiation is implied.

Antenna gain ($G(\theta,\varphi)$): The ratio of the radiation intensity in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. [8]
Note: This is equivalent to the commonly used definition that the antenna gain is the product of the directivity and the ohmic efficiency (sometimes called the ohmic loss factor). If the direction is not specified, the direction of maximum radiation is implied.

(Normalized) antenna pattern ($t(\theta,\varphi)$): The antenna gain (or directivity) in a specified direction divided by the maximum value of the antenna gain (or directivity).

Radiation intensity: The magnitude of the Poynting vector.

Emissivity of antenna (ε): $\varepsilon = (1-\tau)$. Here τ is the transmission coefficient of the loss element of the antenna.

Antenna ohmic efficiency (η_Ω): Ratio of the total radiated power divided by the total power accepted by the antenna. It is also equivalent to the ratio of the antenna radiation resistance (R_{rad}) divided by the sum of the antenna radiation resistance and the antenna ohmic losses resistance (R_Ω).

$$\eta_\Omega = \frac{P_{rad}}{P_{in}} = \frac{R_{rad}}{R_{rad} + R_\Omega}$$

System gain: There are three different definitions of gain:

- Power gain: $G_p = \frac{P_L}{P_i}$
- Transfer power gain: $G_T = \frac{P_L}{P_{av\,G}}$
- Available power gain: $G_a = \frac{P_{av\,L}}{P_{av\,G}}$

where P_L is the maximum power that can be delivered to the load, P_i is the maximum power that can be delivered by the source to the input port, and $P_{av\,G}$ and $P_{av\,L}$ are the available powers from the generator and delivered to the load.
These three definitions of power gain are related by the following relationships:

$$G_T = \frac{G_p}{M_g} = \frac{G_a}{M_L}$$

$$M_g = \frac{\left|1-\Gamma_i\Gamma_G\right|^2}{\left(1-\left|\Gamma_i\right|^2\right)\left(1-\left|\Gamma_G\right|^2\right)}$$

$$M_L = \frac{\left|1-\Gamma_o\Gamma_L\right|^2}{\left(1-\left|\Gamma_o\right|^2\right)\left(1-\left|\Gamma_L\right|^2\right)}$$

and

$$G_p = \frac{\left|S_{21}\right|^2}{\left|1-S_{22}\Gamma_L\right|^2}\frac{1-\left|\Gamma_L\right|^2}{1-\left|\Gamma_i\right|^2}$$

where Γ_i,Γ_o,Γ_G and Γ_L are respectively: the receiver (amplifier) input (*i*) and output (*o*) reflection coefficients, and the source (*G*) and load (*L*) reflection coefficients.
We usually refer to G_a, since in practice the amplifiers, filters and other subsystems are never perfectly matched.

Antenna temperature (T_a): The temperature (K) equivalent of the power received with an antenna. The distinction between the Antenna Temperature, $\boldsymbol{T}_{\mathbf{a}}$, from the Brightness Temperature, T_b , is as follows. The Antenna Temperature is the equivalent of T_b after being spatially averaged by the directional dependent Antenna Directivity D(Ω). To eliminate ambiguity, one should specify the point to which the calibrated antenna temperature is referenced. If no point is specified, it is assumed to be at the antenna aperture.

For example, in traditional radio astronomy this point is usually the output port of the antenna, because that is the point in the system where the calibration loads are situated. Because an antenna always has some ohmic loss which absorbs the incoming power and re-emits, the output T_a consists of the brightness temperature entering the antenna aperture reduced by the loss, plus the re-emission of the loss element at its own physical temperature T_p:

$$T_a(\Omega_o) = [\tau/4\pi] \int D(\Omega-\Omega_o)\, T_b(\Omega)\, d\Omega + (1-\tau)\, T_p,$$

when the Rayleigh-Jeans approximation applies. Here, D is the antenna directivity, as a function of direction Ω, relative to its isotropic value; $d\Omega = \sin\Theta d\Theta d\Phi$; and τ is the transmission coefficient of the loss element. The antenna is pointed at Ω_o (boresight) direction.

In other systems, particularly those with small antennas, the calibration targets are outside the antenna. In such a case, the calibrated antenna temperature refers to a point outside the antenna aperture, and the ohmic losses of the antenna are irrelevant.

In still other cases, the calibration targets may lie between a large main reflector and a smaller feed antenna. Then the calibration of antenna temperature would remove feed antenna losses but not those of the main reflector.

Antenna aperture temperature ($T_{A,ap}$): the temperature of an ideal black body that would result in the same received power at the antenna aperture as in the actual case. In the Rayleigh-Jeans approximation, it is equal to the average incident brightness temperature weighted by the antenna directivity pattern,

$$T_A(\Omega_0) = \frac{1}{4\pi}\iint_{4\pi} D(\Omega - \Omega_0)\, T_B(\Omega)\, d\Omega \quad .$$

Antenna output temperature ($T_{A,out}$): the physical temperature of a matched impedance that delivers to the receiver the same noise power as the antenna. It includes two terms: the noise coming from the environment attenuated by the antenna ohmic efficiency and the thermal noise added by the antenna ohmic losses. In the Rayleigh-Jeans approximation,

$$T_A^{'}(\Omega_0) = \eta_\Omega\, T_A(\Omega_0) + (1-\eta_\Omega) T_{ph} \ ,$$

where T_{ph} is the physical temperature of the antenna and η_Ω is the ohmic efficiency of the antenna. The antenna output temperature is related to the input noise temperature to the receiver ($T_{Rec,in}$) by

$$T_{\mathrm{Re}c,in} = \frac{hf}{e^{hf/kT_{A,out}} - 1} \ .$$

Brightness Temperature (T_b): The temperature (K) equivalent, by the inverse Planck function, to a Spectral Radiance (W Hz^{-1} m^{-2} sr^{-1}), emitted by a blackbody at temperature $\boldsymbol{T_b}$.

(My reason to add the word "spectral" is as follows: Since in microwave radiometry usage, we relate power P to Tb as P=BkTb, i.e. power is received with a finite Bandwidth B.Therefore, it seems to me that, to be precise, Tb should be called Spectral Radiance, so that only when it is multiplied by the bandwidth, it yields power.)

(Looking at the literature: The term Intensity seems to relate to per solid angle the term Radiance seems to relate to Radiation –in watts—per unit surface area, and the term Spectral seems to relate to Per Unit frequency interval; see W.L. Wolfe, in "Handbook of Military IR Technology," ONR publication, 1965, also M.L. Wolfe, in "Introduction to Radiometry," 1998, SPIE Optical Engineering Series, D.C. O'Shea, Ed. The later reference calls the "Radiance" in W per meter square and per S.R..)

In general, T_b is a function of frequency and direction Ω, where Ω stands for angles Θ and Φ. Thus for unpolarized radiation, T_b is the temperature of a black body that would emit the same radiance at the specified frequency and direction. By extension, for polarized radiation, the brightness temperature of each polarization is the temperature of a black body that would emit the same radiance in the specified polarization at the specified frequency and direction. In the Rayleigh-Jeans limit, the microwave power, per unit bandwidth, received by a radiometer is P=k $\boldsymbol{T_b}$**, where** k is the Boltzmann's constant.

Radiometric (or radiometer) resolution: the smallest change in input brightness temperature or radiance that can be detected in the system output. The radiometric resolution can be measured by computing the Type-A uncertainty, *e.g.*, the standard deviation of the mean of a number of measurements of the same quantity made over a short enough time period that the system can be considered to be stable. It is also often estimated by using the equation $\Delta T_{\min} = \frac{T_{Sys}}{\sqrt{B_{pre}\tau}}$, or the variant of this equation that is appropriate for the particular radiometer in question.

Radiometric sensitivity: often used to mean radiometric resolution, but this use is discouraged in light of the definition of sensitivity.

Absolute accuracy: commonly used to denote the total uncertainty excluding the radiometric resolution. When the radiometric resolution is evaluated by statistical means (type-A uncertainty) and all other uncertainties are estimated by other means, the absolute accuracy corresponds to the total type-B uncertainty.

Pixel-to-pixel accuracy: the brightness temperature accuracy in measuring only one resolution element; the values of other resolution elements are not used for correction.

Angular resolution: angular width of antenna beam, usually defined as the half-power beam width.

Spatial resolution: the antenna beam width.

Limiting radiometric resolution: the radiometric resolution evaluated for the case of zero input radiance or brightness temperature. Referred to as the "temperature sensitivity" in Radio Astronomy.

Radiometric resolution per beam width: (for a continuously scanning radiometer) the radiometric sensitivity evaluated for an integration time equal to the dwell time.

Dwell time: time required for the antenna beam to scan across one beam width, at constant speed, along the scan direction.
Note: This and the preceding definition assume one sample per footprint; if the radiometer samples at twice this rate, the integration time is halved and the radiometric resolution per beam width is increased by a factor of $\sqrt{2}$.

Antenna beam width: the antenna beam width. It is the (full) angle at which the antenna's radiation pattern (in power units) is at half its maximum value. It is also known as the "Half-power full width" (HPFW), or simply the "Half-power beam width," (HPBW). In engineering convention, it is also known as the "3 dB beam width."

The antenna radiation pattern depends on the specific plane of cut, and two principal planes are generally given. For a linearly polarized antenna they are the E-plane (plane containing the radiation maximum and the E-field) and the H-plane (plane containing the radiation maximum and the H-field, which is perpendicular to the E-plane).

Instantaneous field of view (IFOV): the antenna beam width**.**
Since the antenna radiation pattern depends on the specific plane (containing the beam axis) of cut, so does the IFOV value. Conventionally, IFOVs at two principal planes are given: the E-plane (containing the E-vector of the diple) and the H-plane (perpendicular to the E-plane). When a single IFOV value is used, it is the (arithmetic) mean of the IFOVs of the two principal planes.

Static IFOV: When the IFOV is express in length units, it is used to express the diameter (arc length) of a circular area, which is the intersection of the antenna beam (assumed to be a right circular cone) and the earth surface (assumed to be spherical). This is valid in the case of normal incidence.

When the radiometer antenna is viewing the earth at an oblique angle, then the intersection area (between the right circular cone of the antenna beam and the spherical earth surface) is a pear-shaped figure. In this case two arc lengths are used to represent the IFOV, a Major diameter or IFOV-Maj, and a Minor diameter or IFOV-Min.

Static IFOV-DT, static IFOV-CT: For a cross-track scanning beam, the words Minor and Major diameters can be replaced by Down-Track and Cross-Track, respectively. Here D-T and C-T also signify the directions parallel to, and perpendicular to the sub-satellite track direction, respectively.
For a conical-scanning beam, the terms D-T and C-T still apply. (….)

Effective Field of View (EFOV): When the radiometer antenna is scanning across the earth surface while the radiometer integrates, then the static IFOV (in length unit and along the scanning direction), which are based purely on geometrical projections of the antenna beam and the earth surface, is no longer valid. Instead, the Scanned EFOV or ESFOV along the scan direction is used in its place. The ESFOV takes into account scan induced "smear" effect, and in general is slightly larger that the static IFOV. The extent of the smear depends on the length of the integration time, the shape of the original antenna beam, as well as the scan velocity profile.

In order to be specific, the EFOV-CT is defined only for the case where: (i) the scan velocity is constant, and (ii) the integration time is equal to the time it takes to move the antenna beam one IFOV. Again CT implies the scanning direction, which may or may not be the cross-track direction.

As an example, the EFOV-CT of a Gaussian shaped beam is 25% larger than its IFOV, according to the above definition (i) and (ii).

The EFOV-CT is determined as follows:
First obtain the Exposure function E(x) which is the integral of antenna pattern G(x-m) and the integration-time Δt.
Here m=vt is the coordinate of the antenna beam center, which is moving at a scan velocity of v.

$$E(x) = \int G(x-m)\,\Delta t$$

The integration limits is from t=0 to t=τ
Following the same half-power point principle, the SEFOV-CT is determined by obtaining the points x1 and x2 (x2>x1 assumed) where the values of E(x) is half of its maximum value.
And the SEFOV-CT value is equal to: (x2-x1).

REFERENCES

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