

SEMI E89-0999

GUIDE FOR MEASUREMENT SYSTEM CAPABILITY ANALYSIS

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1 Purpose

1.1 The purpose of this guide is to provide a consistent set of terminology and describe a constructive experimental approach to planning and carrying out a measurement system capability analysis.

2 Scope

2.1 Primary focus is on describing and estimating measurement uncertainty associated with the behavior of automated wafer measurement systems under normal operating conditions, but the definitions and methodologies are extendible to many other measurement situations involving items such as wafers, dies, packaged devices, flat panel displays, piece parts, etc. While examples are included to illustrate concepts, the intent is to avoid specific measurement situation details wherever possible and focus instead on general planning and analysis issues.

2.2 This guide does not address those aspects of measurement uncertainty associated with change in the object being measured, either spatially or temporally.

2.3 This guide does not address those aspects of measurement uncertainty associated with calibration of the measurement system.

2.4 This guide does not address estimating measurement capability in the case of destructive measurements on samples, or when the metrology system alters the object being measured as the measurement is made.

2.5 This guide does not apply to inter-laboratory measurements designed to measure inter-laboratory precision.

2.6 This standard does not purport to address all of the safety issues associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

3 Referenced Standards

3.1 SEMI Standard

SEMI M27 — Practice for Determining the Precision over Tolerance (P/T) Ratio of Test Equipment

3.2 ISO Standards¹

Guide to the Expression of Uncertainty in Measurement

International Vocabulary of Basic and General Terms in Metrology, Second Edition

NOTE 1: As listed or revised, all documents cited shall be the latest publications of adopted standards.

4 Terminology

4.1 General Definitions

accuracy — closeness of agreement between a measurement made on an object and its true value [International Vocabulary of Basic and General Terms in Metrology].

NOTE 2: This is a qualitative term measured by bias.

bias — the difference between the average of measurements made on the same object and its true value. Sufficient measurements are needed to mitigate the effects of variability.

NOTE 3: In many cases the true value is unknown. A value established by reference instruments or a consensus value might be used as a substitute.

capability (C_p) — a dimensionless figure of merit that indicates how many times larger the tolerance (see Section 4) is than the measurement system precision (see Section 4). Example: for a two sided specification, if USL is the upper specification limit, LSL is the lower limit and σ_R is reproducibility (see Section 4.1), then $C_p = (USL - LSL)/6\sigma_R$.

NOTE 4: This defines C_p for the measurement system in a particular application. If $\sigma_{Product}$ (see Section 4.1) is used, instead of σ_R , then C_p defines process capability.

gauge — any tool used to assign a value to a quantitative or qualitative characteristic of a physical entity or phenomenon. Example: film thickness is a quantitative characteristic and defect type is a qualitative characteristic.

gauge repeatability and reproducibility (R&R) study — see Section 4.1, measurement system capability analysis.

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linearity — the absence of changes in bias as measurements are made at different points within the measurement range. Bias and linearity issues are related to calibration and are beyond the scope of this document.

NOTE 5: Traditional definitions of linearity ignore the fact that variability can change over the measurement range, as well as bias. The assumption of constant variability over the measurement range should be verified during the measurement system capability study.

lower specification limit (LSL) — the lower (or minimum) engineering specification limit for a given parameter.

measurement — the value a gauge assigns to a characteristic. In most cases, measurements will be numerical, although this is not a requirement. Example: defect classification equipment assigns non-numerical types to wafer defects.

NOTE 6: Measurement may also be used as an adjective when referring to the measurement process of assigning a value to an object.

measurement subsystem — any set of entities, processes or conditions that share a common purpose in the measurement.

NOTE 7: A subsystem may contain one or more of its own subsystems. For example, a wafer handling mechanism may be further composed of wafer loading and wafer positioning subsystems.

measurement system — all entities, processes, and conditions that may affect measurements made

- on the same object or identical objects (apart from true value differences)
- with a specific set of measurement tools and
- under normal operating conditions as described in gauge specifications.

The measurement system may include, but is not limited to, operators, setup mechanics, wafers, locations on a wafer, environmental conditions, software used by the gauge, measurement method, etc. The system may be comprised of measurement subsystems.

NOTE 8: The purpose of a measurement system capability analysis is to characterize sources of variation associated with the measurement system. In most cases, however, the total number of contributors is exceedingly large. Typically, one focuses on a subset that accounts for a large portion of total measurement system variability.

measurement system capability analysis — the technique by which one estimates all relevant individual sources of variability associated with a gauge in a measurement system. It is also called a gauge study

or a gauge repeatability and reproducibility (R&R) study.

measurement uncertainty — parameter, associated with a measurement, that characterizes the dispersion of values that can be reasonably attributed to the object being measured [International Vocabulary of Basic and General Terms in Metrology].

precision — a multiple of σ_R , often chosen to be $6\sigma_R$.

NOTE 9: The QS9000 Standard, as well as other automotive industry documents, uses $5.15\sigma_R$.

precision over tolerance (P/T) ratio — a relative comparison that shows how much of the tolerance (see Section 4) is used up by the measurement instrument's precision (see SEMI M27). Example: $P/T = 6\sigma_R / (USL - LSL) = 1/C_p$, where C_p is the measurement system capability defined in Section 4. P/T is often expressed as a percent, by multiplying the previous ratio by 100.

product variability ($\sigma_{Product}$) — the population standard deviation associated with the distribution of measurements taken on all possible realizations of an entity manufactured under specified operating conditions. It is estimated by taking a representative sample from the population and calculating its sample standard deviation ($s_{Product}$).

repeatability (σ_r) — the variability associated with repeated measurements taken under the most ideal (identical) conditions. The ideal estimate would require instantaneous measurements taken under conditions that hold all elements of the measurement system constant. Two different methods of estimating repeatability are common, because of the different ways measurement instruments are used. They are:

dynamic repeatability — the standard deviation of measurements taken under the following conditions:

- A very small amount of time, typically minutes or seconds, has lapsed between the first and last measurements.
- All factors that may influence the measurement are held constant.
- The object is removed and immediately put back into the gauge between measurements.

NOTE 10: When it is possible to calculate both kinds of repeatability, the Root Sum of Squares (RSS) difference (see Section 4.2) between dynamic repeatability and static repeatability is a measure of the variability introduced by the wafer insertion (or stage accuracy) process.

static repeatability — the standard deviation of measurements taken under the following conditions:

- A very small amount of time, typically minutes or seconds, has lapsed between the first and last measurements.
- All factors that may influence the measurement are held constant.
- The object is not reloaded in the gauge between measurements.

reproducibility (σ_R) — the total variability associated with the measurement system when measurements are made under different (but typical) conditions. Changes associated with subsystems or conditions are potential sources of variation to be estimated. Reproducibility is measured by the square root of the sum of all sources of variation. Repeatability is one of these sources. Other relevant sources of variability may include time, operator, wafer, location on a wafer, environment, etc. Reproducibility does not include variability due to measuring objects with different “true” measurement values.

resolution — the ability of the measurement system to detect and faithfully indicate small changes in the characteristic of the measured result.

NOTE 11: A general rule of thumb is that a gauge should have resolution that is more than two digits beyond what is required for the measurement result.

signal to noise ratio (SNR) — the ratio of the variation in the manufactured product to the precision of the measurement instrument. Since it is difficult to directly measure the standard deviation of the product without including variation due to the measurement instrument, SNR is generally defined as:

$$SNR = \sqrt{\frac{\sigma_{Total}^2 - \sigma_R^2}{\sigma_R^2}},$$

where σ_{Total}^2 is the variance obtained by measuring a large representative sample of the product.

NOTE 12: SNR is an objective measurement in the sense that it does not depend on a specification, which can be changed at any time. In practice, a SNR of 10 or more generally means the instrument is suitable for the product, while an SNR less than 3 or 4 might be a concern in a particular situation.

stability — the absence of additional variability due to taking measurements over time (typically several days or longer).

tolerance — the difference between the maximum and minimum engineering specification limits (as used in P/T ratio) for a given parameter. This is just (USL – LSL).

total variability (σ_{Total}) — the square root of the product variability squared plus the reproducibility squared.

$$\sigma_{Total} = \sqrt{\sigma_{Product}^2 + \sigma_R^2}$$

upper specification limit (USL) — the upper (or maximum) engineering specification limit for a given parameter.

4.2 Statistical Definitions

effect — the coefficient, or its estimate, associated with an input variable. It is a measure of influence that a particular variable level has on the output variable.

crossed effect — effects that do not possess a hierarchical relationship.

fixed effect — an effect associated with input variables that have a limited number of levels or in which a limited number of levels are of interest to the experimenter.

nested effect — an effect that is part of a hierarchical relationship such that it is contained within another effect.

random effect — an effect associated with input variables chosen at random from a population having a large or infinite number of possible values.

level — unique value associated with a nominal or categorical variable (see Section 4.2). Also called setting of a variable.

(statistical) model — a mathematical function relating one or more responses to known and measurable inputs plus one or more unknown stochastic (error) terms. The errors represent values from the distribution of differences between the model and observed values. An example of a statistical model is:

$$Y_j = \sum_{i=1}^p \beta_i X_i + e_j$$

where Y_j is the j th observation, β_i and X_i the i th input variable and its corresponding coefficient, respectively, and e_j the error associated with the j th observations. In many cases the error distribution(s) are specified before the model is fit (e.g., normal). If the model contains nested effects (see Section 4.2) there may be more than one error term.

root sum of squares (RSS) sum — the RSS sum of two or more numbers is the square root of the sums of the squares of the numbers.

root sum of squares (RSS) difference — the RSS difference of two numbers is the square root of the difference of the squares of the two numbers.

standard deviation — a numerical measure of dispersion.