

ANSI/NCSL Z540.3

Requirements for the Calibration of Measuring and Test Equipment

Sub Clause 5.3 Assessor Training

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Sub Clause 5.3 Assessor Training

1. Welcome and overview of the session – Steve Doty (5 minutes)
2. Introduction and overview of Z540.3 / Perspectives on cal lab compliance – Del Caldwell (45 minutes)
3. Assessing cal labs to Z540.3, sub-clause 5.3 requirements / Appendix F introduction and use – Steve Doty (45 minutes)

Break - 15 minutes

4. Measurement uncertainty concepts for Z540.3 / Probability of false acceptance, concept and compliance – Dennis Jackson (115 minutes)

5. Wrap-up / Broad Q&A / Availability of Supplemental NCSLI resources [Handbook and bibliography; RP-1 (2009 rev); RP-3 (2007 rev); RP-12 (2009 rev); and RP-18 (2009) new] – Steve Doty (15 minutes)





Overview

- **Calibration Process Uncertainty**
- **Probability of False Accept (PFA)**
- **PFA Estimation Compliance Methods**
- **Guard Band Compliance Methods**
- **Test Uncertainty Ratio**



Z540.3 PFA Requirement

“Where calibrations provide for verification that measurement quantities are within specified tolerances, the probability that incorrect acceptance decisions (false accept) will result from calibration tests shall not exceed 2% and shall be documented. Where it is not practicable to estimate this probability, the test uncertainty ratio shall be equal to or greater than 4:1.

NOTE: Achieving these requirements may involve adjustment and management of calibration system parameters such as: measurement reliability, calibration intervals, measurement uncertainty, calibration tolerances, and/or guard bands.”

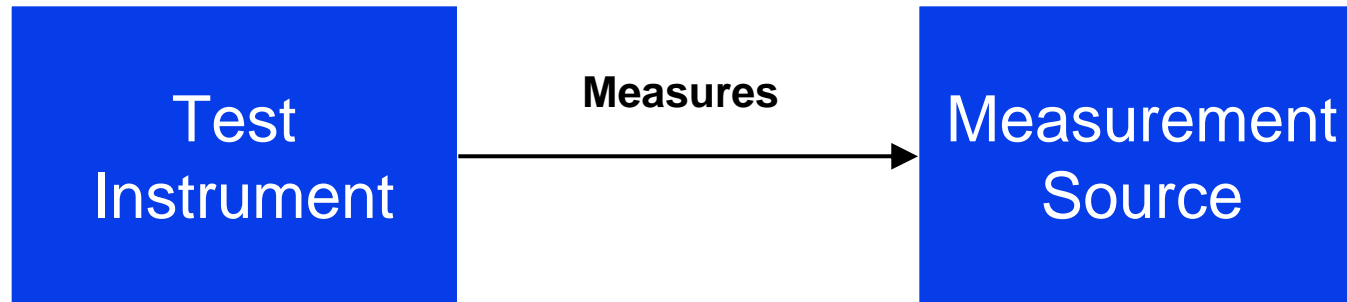


Themes

- The objective of a measurement is to estimate the true value
- Measurement error represents the error in using the measurement to estimate the true value
- The objective of calibration is to estimate and possibly correct for the UUT bias
- The difference (or deviation) between the UUT measurement/indication and the CALSTD measurement/indication estimates the UUT bias
- The error in estimating the UUT bias is called the calibration process error
- The calibration process error includes all those measurement errors we wouldn't correct for
- The calibration process error is characterized and reported as the calibration process uncertainty
- Incorrect calibration testing decisions are caused by calibration process errors
- A false accept occurs when the UUT bias is out of tolerance, but the estimate of the UUT bias (the deviation) is not



Measurement Error Model



$$\text{Measurement} = \text{True Value} + \text{Error}$$

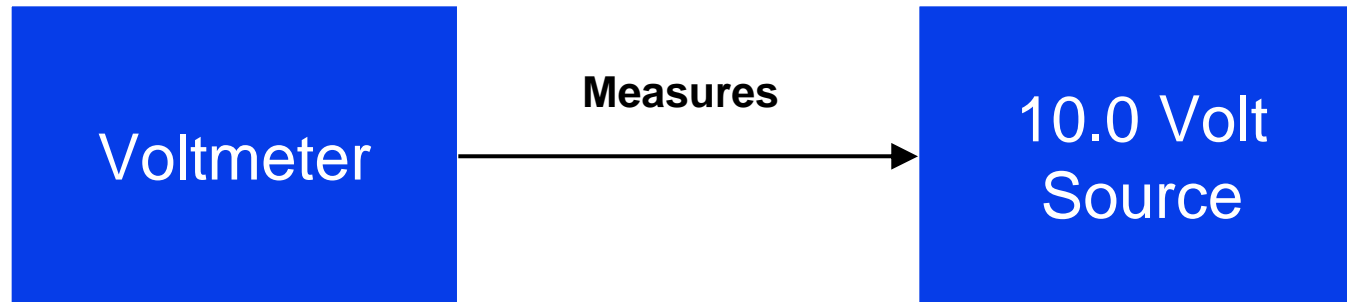
$$\text{Error} = \text{Measurement} - \text{True Value}$$

The objective of measurement is to estimate the true value

The Measurement Error represents the error in using the Measurement to estimate the True Value



Measurement Error Example



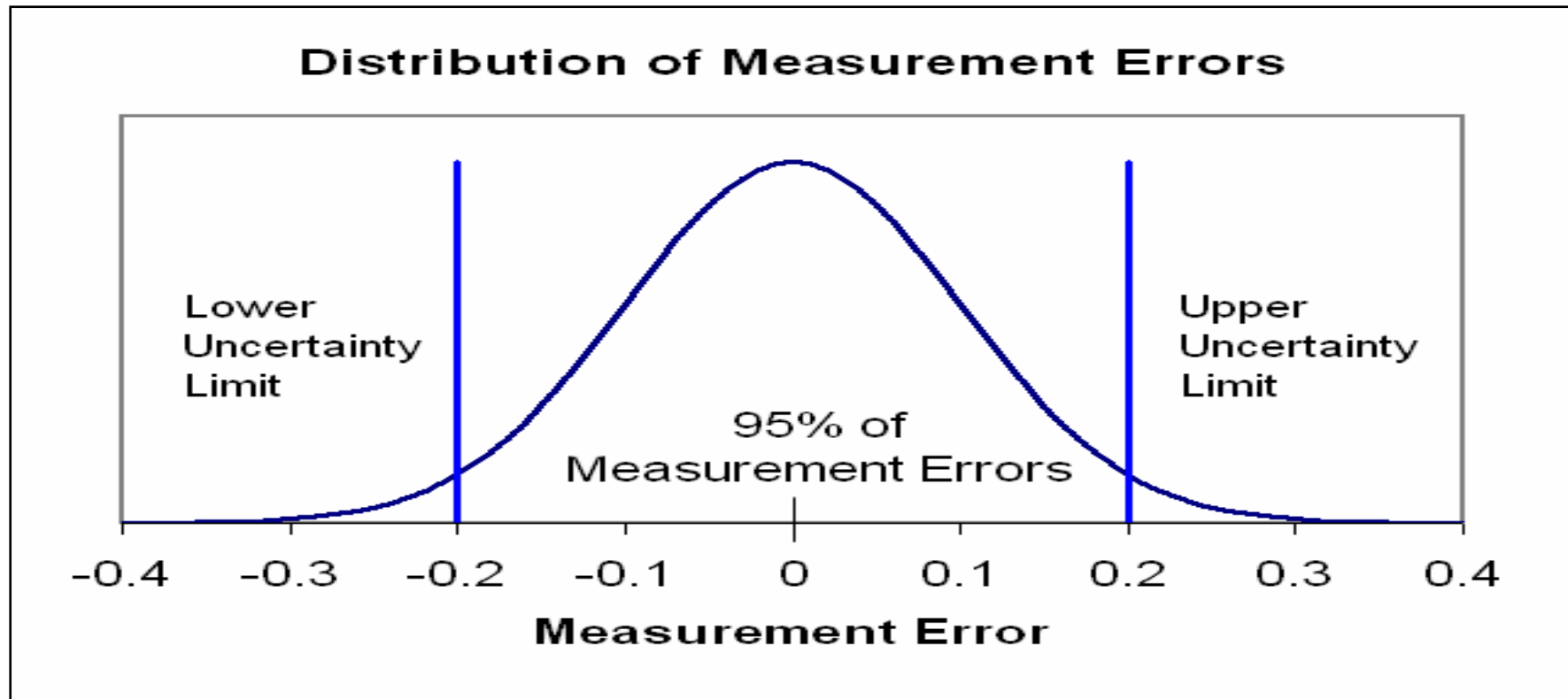
$$\text{Measurement} = 10.1 \text{ v}$$

$$\begin{aligned} \text{Measurement} &= \text{True Value} + \text{Error} \\ &= 10.0 \text{ v} + 0.1 \text{ v} \end{aligned}$$

$$\begin{aligned} \text{Error} &= \text{Measurement} - \text{True Value} \\ &= 10.1 \text{ v} - 10.0 \text{ v} \\ &= 0.1 \text{ v} \end{aligned}$$



Measurement Uncertainty



- **Measurement Uncertainty puts limits on measurement errors**
- **± 2 Standard Uncertainties ($\pm 2 u$) contains about 95% of the Measurement Errors**



Measurement Uncertainty Budget

- **Repeatability**
- **Resolution**
- **Reproducibility**
 - Environment
 - Location
 - Operators
 - Correction Factors
- **Setup/Ancillary Equipment (Cables, etc.)**
- **Calibration Certificate**



General Calibration Scenario



UUT Error = UUT Measurement – True Value

Deviation = UUT Measurement – CALSTD Measurement

- The CALSTD Measurement is used to approximate the True Value
- The Deviation is used to estimate the UUT Bias



Calibration Error Model



$$\begin{aligned} \text{Deviation} &= \text{UUT Measurement} - \text{CALSTD Measurement} \\ &= \text{UUT Bias} + \text{Calibration Process Error} \end{aligned}$$

The objective of calibration is to estimate the UUT Bias

The Calibration Process Error represents the error in using the Deviation to estimate the UUT Bias



Calibration Error Example



Deviation = 0.09 V

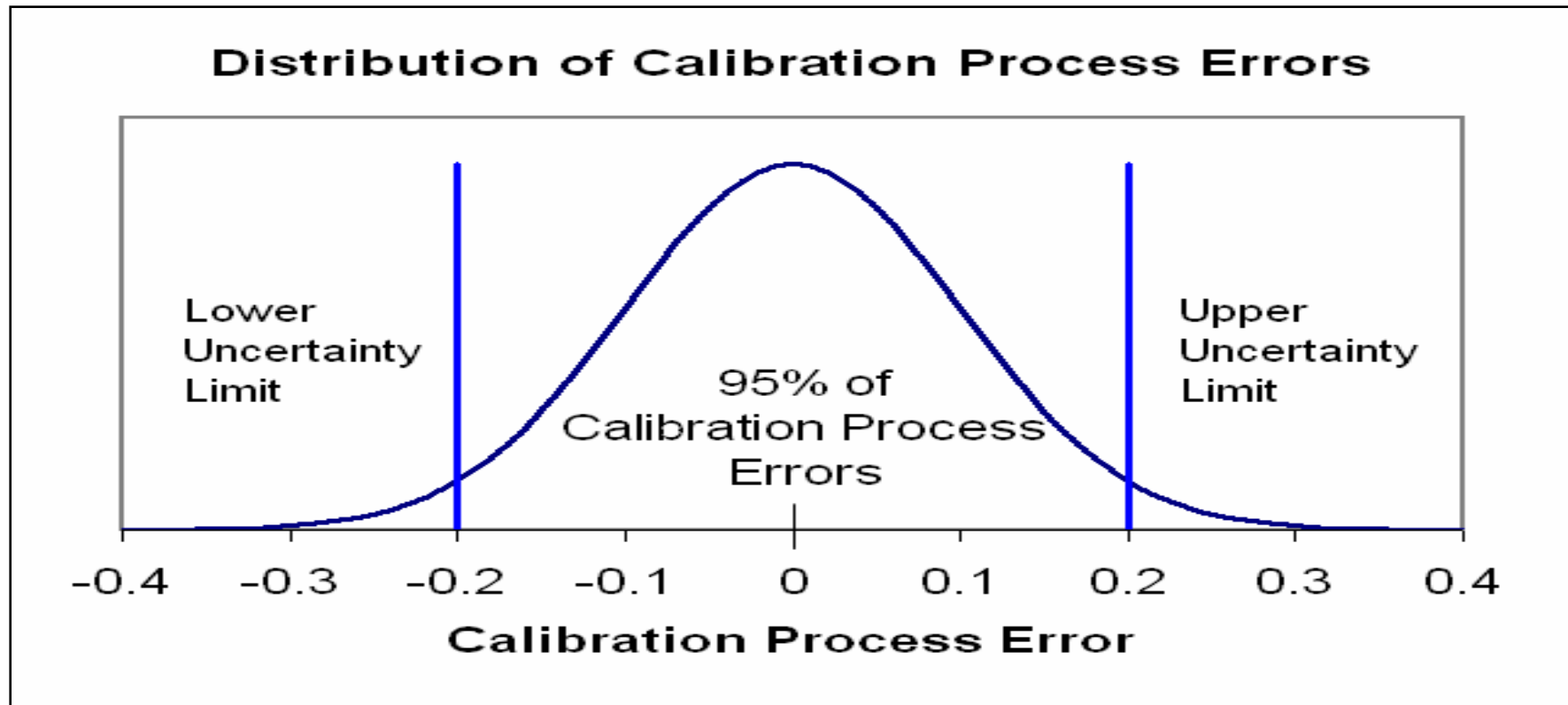
= UUT Measurement – CALSTD Measurement

= UUT Bias + Calibration Process Error

= 0.11 V + (- 0.02 V)



Calibration Process Uncertainty



- **Calibration Process Uncertainty puts limits on Calibration Process Errors**
- **± 2 Standard Uncertainties ($\pm 2 u$) contains about 95% of the Calibration Process Errors**

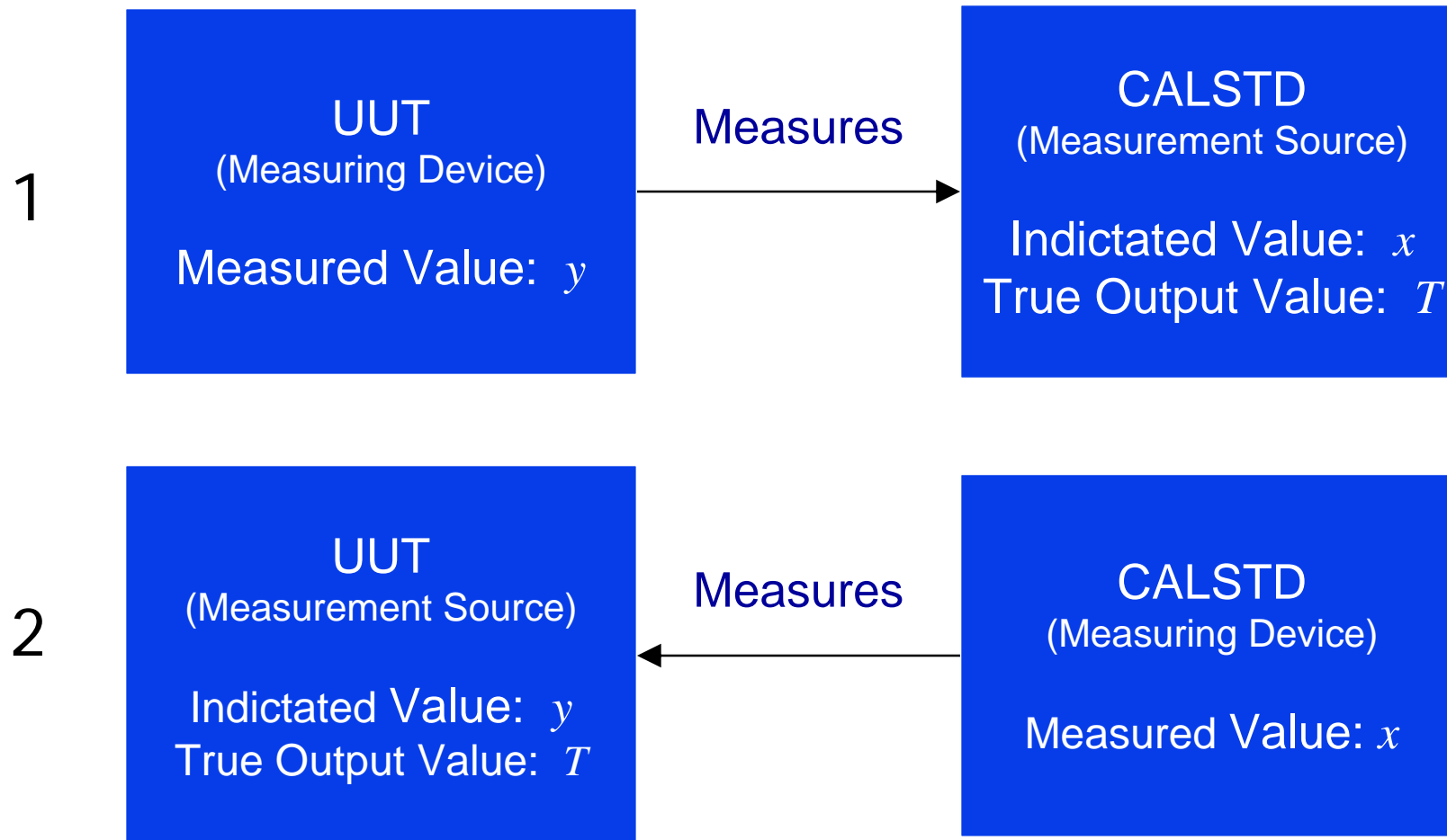


Calibration Process Uncertainty Budget

- **Calibration Standard**
 - Repeatability (UUT and CALSTD)
 - Resolution
 - Reproducibility
 - Calibration Certificate
- **Unit Under Test (UUT)**
 - Repeatability (UUT and CALSTD)
 - Resolution
 - Reproducibility
- **Setup/Ancillary Equipment (Cables, etc.)**



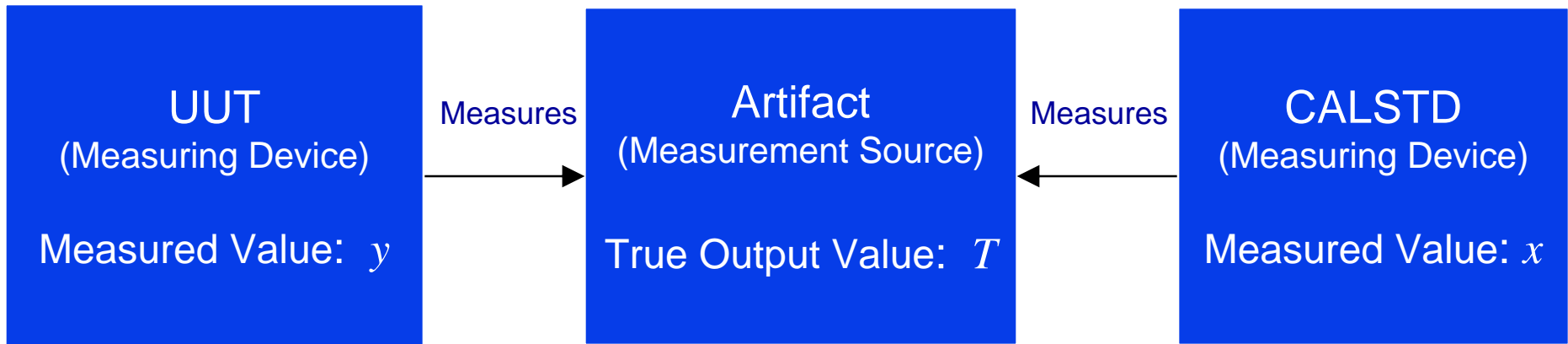
Calibration Scenarios



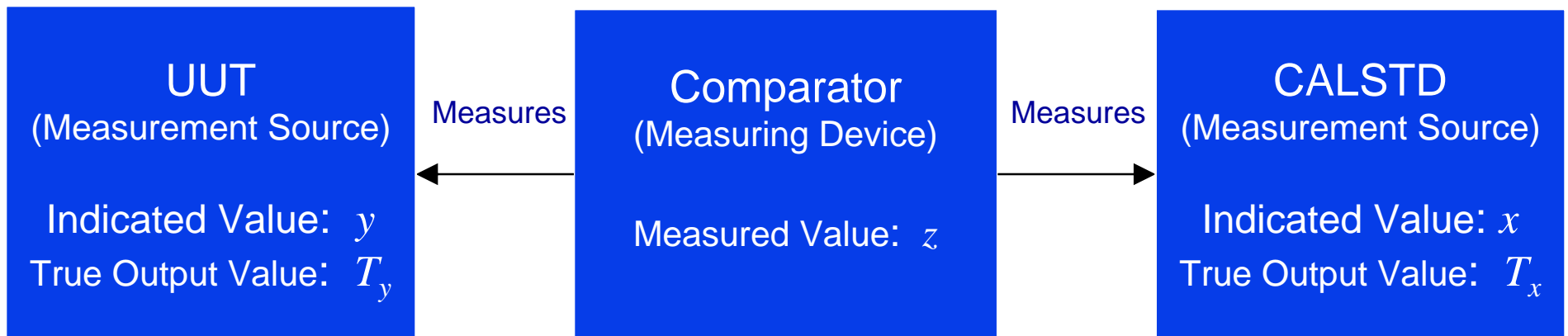


Calibration Scenarios

3



4





Summary

- There are four major calibration scenarios:
 1. UUT measures CAL
 2. CAL measures UUT
 3. UUT and CAL measure artifact
 4. UUT and CAL are compared
- During a calibration the UUT is compared to the CAL using the deviation
- Generally, $\text{Deviation} = \text{UUT measurement} - \text{CAL measurement}$
- The deviation contains the UUT bias and the calibration process error
- The point of the calibration is to determine the UUT bias
- The calibration process error represents the error in using the deviation to estimate the UUT bias

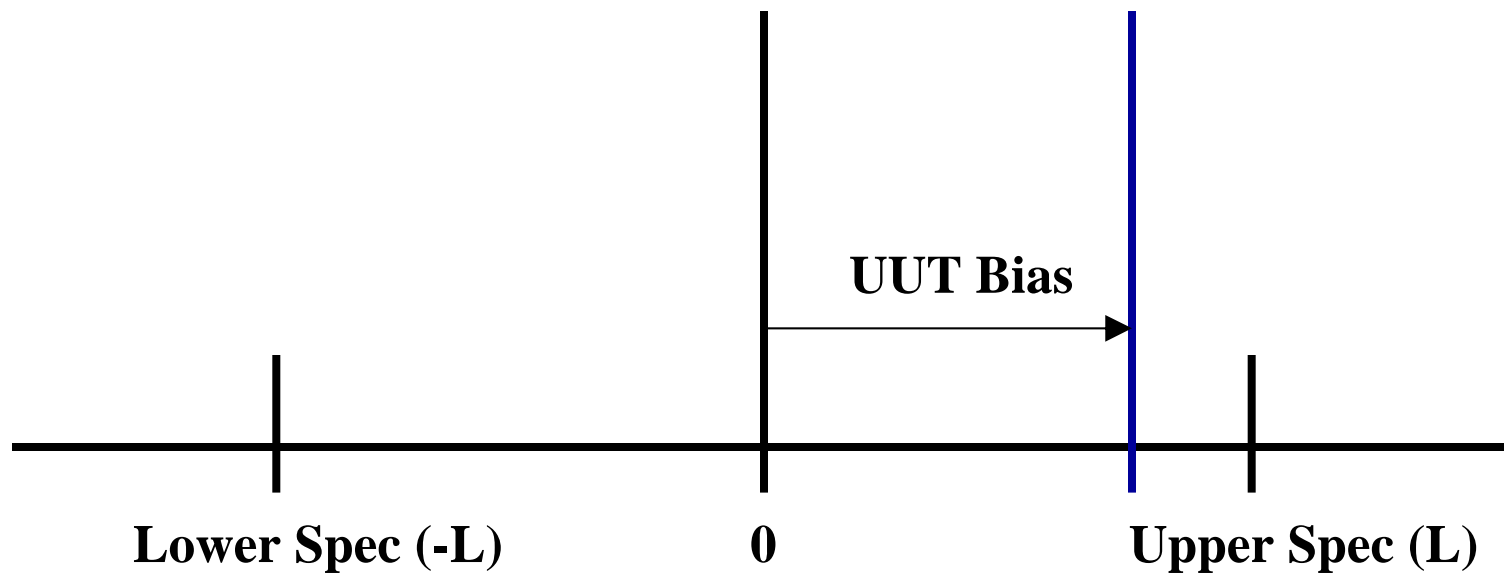


True In Tolerance

(Calibration Tolerance Testing Objective)

A Unit Under Test (UUT) is truly in tolerance if:

$$\text{Lower Spec} \leq \text{UUT Bias} \leq \text{Upper Spec}$$



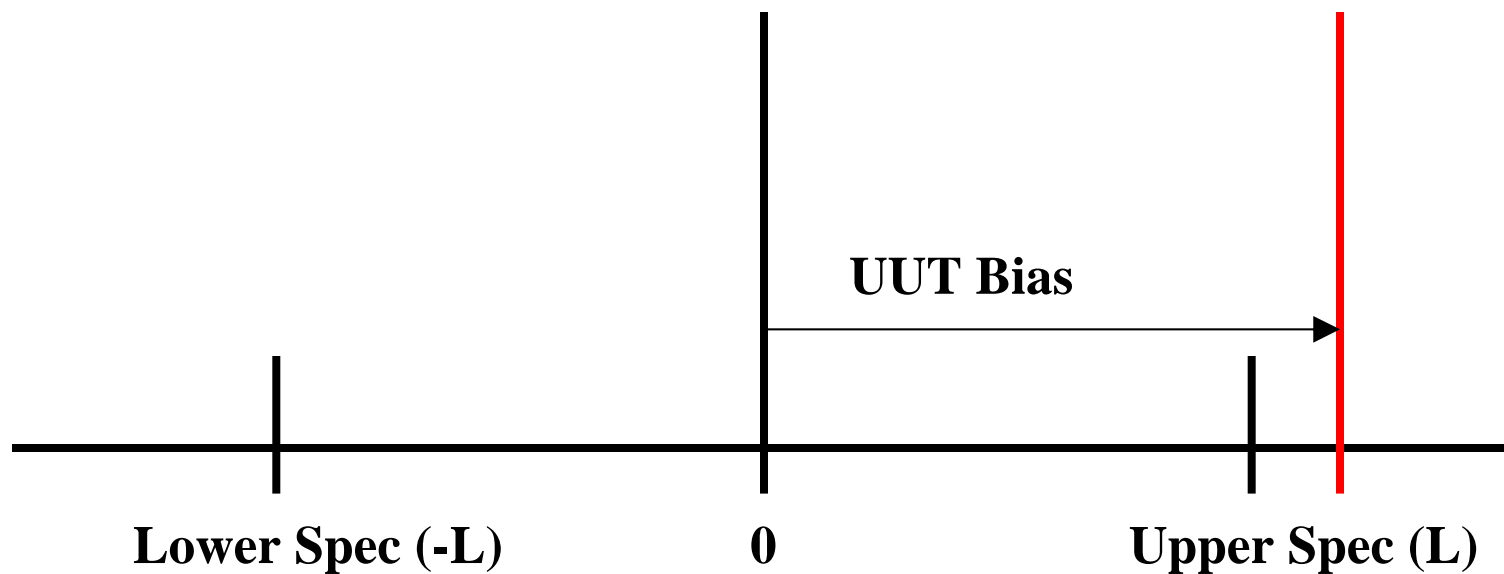
The UUT Bias is unknown



True Out Of Tolerance

A Unit Under Test (UUT) is truly out of tolerance if:

UUT Bias < Lower Spec or UUT Bias > Upper Spec



The UUT Bias is unknown

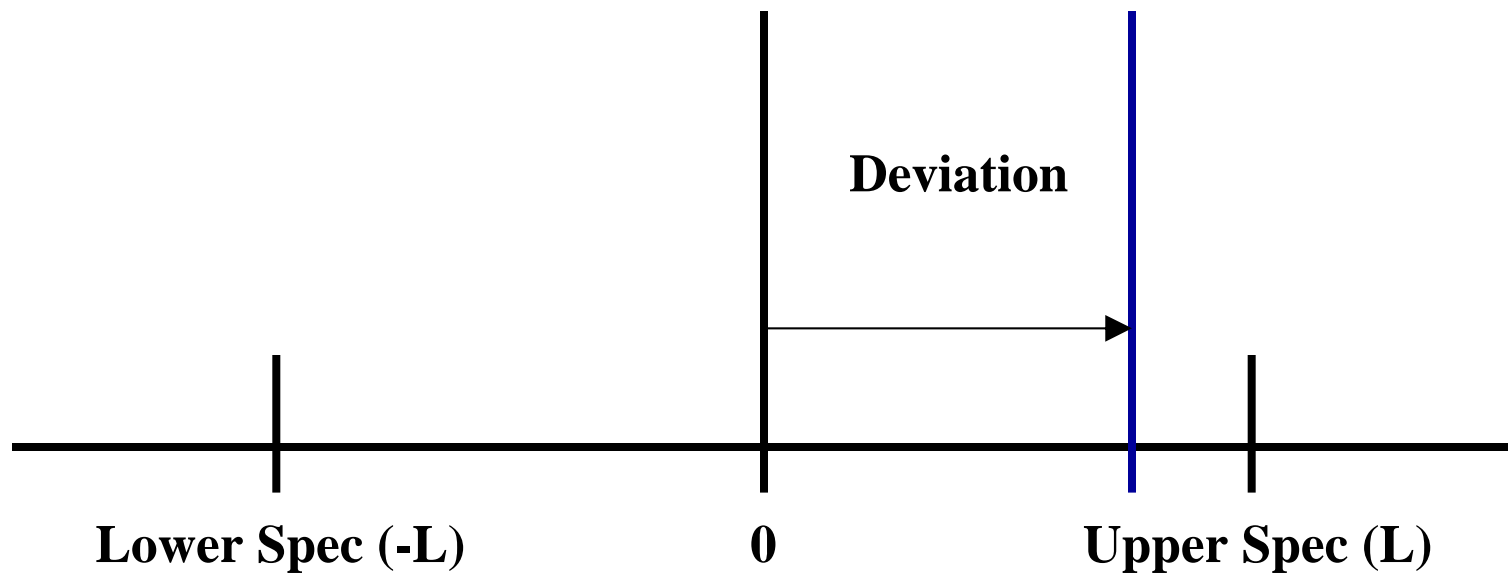


Observed In Tolerance

(Calibration Testing in Practice)

A Unit Under Test (UUT) is observed in tolerance if:

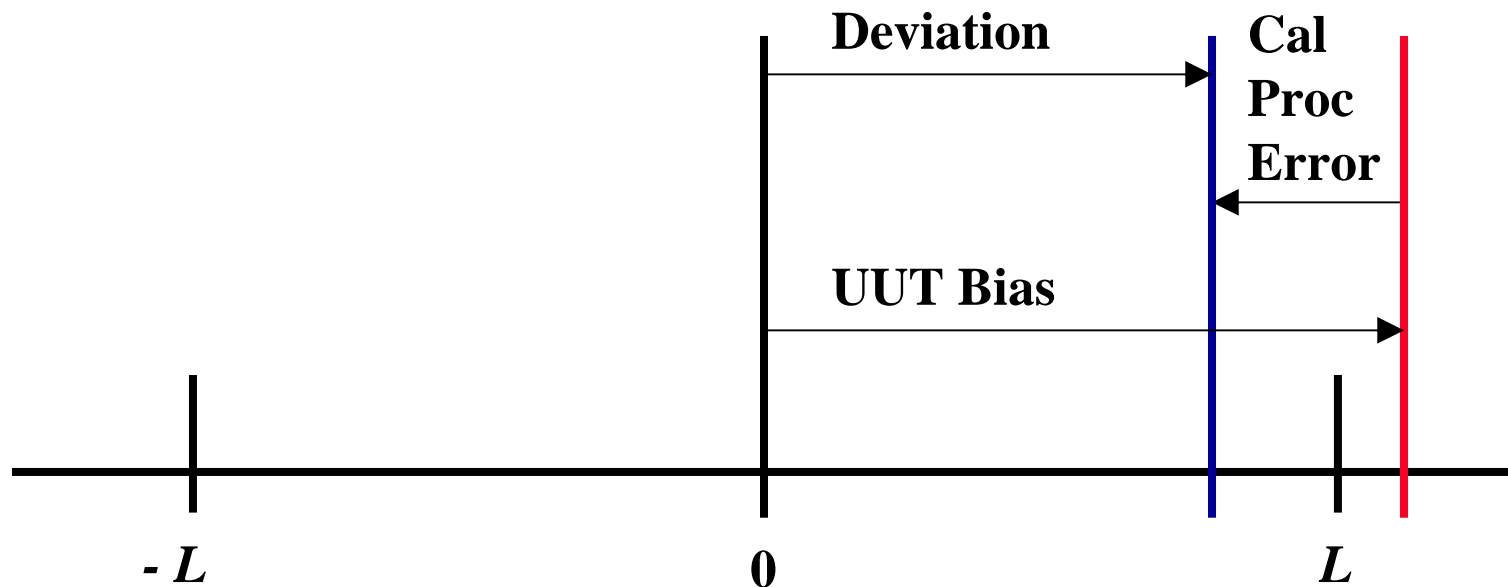
$$\text{Lower Spec} \leq \text{Deviation} \leq \text{Upper Spec}$$



The Deviation is the observed difference between the UUT and the CALSTD



False Accepts

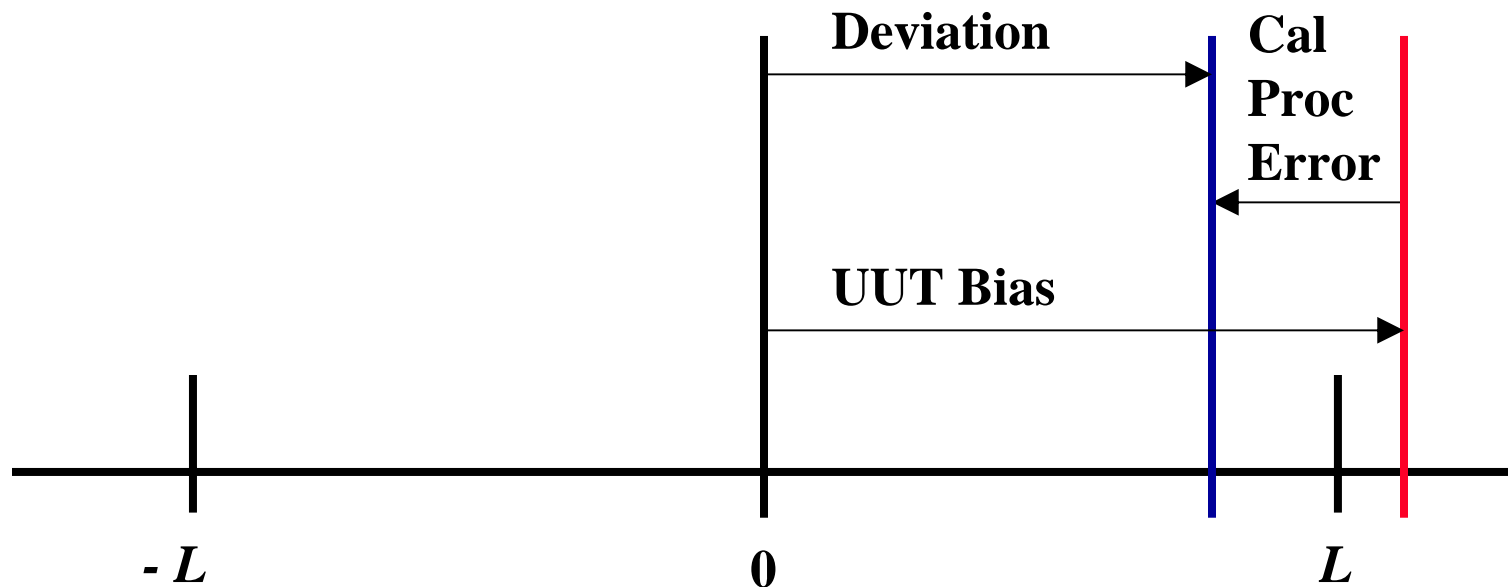


False Accept (FA):

- The Deviation is observed in tolerance [$-L \leq \text{Deviation} \leq L$]
- The UUT Bias is out of tolerance [$\text{Bias} > L$ or $\text{Bias} < -L$]
- The decision to accept the UUT is incorrect



Probability of False Accept



Probability of False Accept (PFA):

$$\text{PFA} = \Pr([\text{Observed In Tolerance}] \text{ and } [\text{True Out Of Tolerance}])$$

$$= \Pr([-L \leq \text{Deviation} \leq L] \quad \text{and} \quad [\text{Bias} > L \text{ or } \text{Bias} < -L])$$

PFA is the probability of making an incorrect acceptance decision



Inputs Needed to Calculate PFA

Probability of False Accept (PFA):

$$\begin{aligned} \text{PFA} &= \text{Pr}(\text{ [Observed In Tolerance] and [True Out Of Tolerance] }) \\ &= \text{Pr}([-L \leq \text{Deviation} \leq L] \quad \text{and} \quad [\text{Bias} > L \text{ or Bias} < -L]) \end{aligned}$$

- **The Tolerance Limits (-L, L)**
 - The Calibration Procedure for the UUT
- **The Measurement Uncertainty for the Calibration Process**
 - The calibration process uncertainty is a 17025 and Z540.3 requirement
 - This requires an uncertainty analysis for each calibration procedure
- **The Observed Test Point Measurement Reliability for the UUT**
 - Measurement reliability is obtained from calibration history data
 - Using equipment level measurement reliability provides an upper bound on PFA



PFA Examples

Scenario	Tolerance	Cal Proc	TUR	Test Pt	PFA
	Limits	Std Unc		Meas Rel	
1	0.10	0.01276	4	80%	1.98%
2	0.10	0.01701	3	80%	2.49%
3	0.10	0.02551	2	80%	3.27%
4	0.10	0.01276	4	90%	1.33%
5	0.10	0.01701	3	90%	1.58%
6	0.10	0.02551	2	90%	1.76%

$$PFA = \int_L^{\infty} \int_{-A}^A f_{d,e_{Bias}}(d, e_{Bias}) dd de_{Bias} +$$

$$\int_{-\infty}^{-L} \int_{-A}^A f_{d,e_{Bias}}(d, e_{Bias}) dd de_{Bias}$$



PFA Tool

PFA Estimation (Methods 1 and 2)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Upper Acceptance Limit	0.1000
Lower Acceptance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Test Pt False Accept Rate (PFA)	3.27%
Test Pt False Reject Rate (PFR)	5.77%
Wrong Decision Rate	9.04%

PFA Estimation (Methods 1 and 2)

The inputs for this spreadsheet are black:

- Tolerance Limits
- Acceptance Limits (Guard Banded)
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Restore Limits

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.



Summary

- Calibration testing determines if a UUT is out of tolerance
- True out of tolerance means the UUT bias is outside the tolerances
- The UUT bias is unknown and is estimated using the deviation (UUT meas – CALSTD meas)
- An observed in tolerance means the deviation is inside the tolerances
- The calibration process error represents the error in using the deviation to estimate the UUT bias
- Calibration process error can cause a true out of tolerance to be observed as in tolerance
- A false accept means the UUT is observed in tolerance when the bias is out of tolerance
- The probability of a false accept (PFA) is the probability of making a wrong acceptance decision during a calibration test



Z540.3 PFA Requirement

“Where calibrations provide for verification that measurement quantities are within specified tolerances, the probability that incorrect acceptance decisions (false accept) will result from calibration tests shall not exceed 2% and shall be documented. Where it is not practicable to estimate this probability, the test uncertainty ratio shall be equal to or greater than 4:1.

NOTE: Achieving these requirements may involve adjustment and management of calibration system parameters such as: measurement reliability, calibration intervals, measurement uncertainty, calibration tolerances, and/or guard bands.”



PFA Compliance Methods

PFA Estimation

- **Method 1, Unconditional - Test Point Population Data:**
Provides an unconditional PFA estimate which is a direct determination of compliance to the Standard.
- **Method 2, Unconditional - M&TE Population Data:**
Provides a conservative unconditional PFA estimate using measurement reliability data at the M&TE model and manufacturer level.
- **Method 3, Conditional – Acceptance Subpopulation:**
Provides a conditional PFA estimate where the subpopulation includes calibration tests that result in acceptance at the test point level.
- **Method 4, Conditional – Bayesian:**
Determines conditional PFA for measurement result; if conditional PFA is OK then unconditional PFA OK.



Information Requirements PFA Estimation

Method	Information Requirements				
	M&TE Test Tolerances	M&TE Acceptance Limits	M&TE Test Point Measurement Reliability	M&TE Overall Measurement Reliability	Calibration Process Measurement Uncertainty
Test Point Population	X	X (if used)	X	-	X
M&TE Population	X	X (if used)	-	X	X
Acceptance Subpopulation	X	X (if used)	X	-	X
Bayesian	X	-	X	-	X



PFA Estimation Method 1 Unconditional - Test Point Population Data

PFA Estimation (Methods 1 and 2)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Upper Acceptance Limit	0.1000
Lower Acceptance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	90.00%
Calibration Process Std Uncertainty	0.012760
Calibration Process Exp Uncertainty	0.025009
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	4.00
Test Pt False Accept Rate (PFA)	1.33%
Test Pt False Reject Rate (PFR)	2.00%
Wrong Decision Rate	3.41%

PFA Estimation (Methods 1 and 2)

The inputs for this spreadsheet are black:

- Tolerance Limits
- Acceptance Limits (Guard Banded)
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary. Restore Limits

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Test Point Measurement Reliability

Shows compliance to 2% requirement



PFA Estimation Method 1 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	PFA Method 1
1	± 0.10	4	80 %	1.98 %
2	± 0.10	3	80 %	2.49 %
3	± 0.10	2	80 %	3.27 %
4	± 0.10	4	90 %	1.33 %
5	± 0.10	3	90 %	1.58 %
6	± 0.10	2	90 %	1.76 %



PFA Estimation Method 2 Unconditional – M&TE Population Data

PFA Estimation (Methods 1 and 2)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Upper Acceptance Limit	0.1000
Lower Acceptance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.012760
Calibration Process Exp Uncertainty	0.025009
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	4.00
Test Pt False Accept Rate (PFA)	1.98%
Test Pt False Reject Rate (PFR)	2.59%
Wrong Decision Rate	4.57%

PFA Estimation (Methods 1 and 2)

The inputs for this spreadsheet are black:

- Tolerance Limits
- Acceptance Limits (Guard Banded)
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

M&TE Measurement Reliability

Shows compliance to 2% requirement



PFA Estimation Method 2 Examples

Scenario	Test Limits	TUR	Equipment Measurement Reliability	PFA_{eop}
1	± 0.10	4	80 %	1.98 %
2	± 0.10	3	80 %	2.49 %
3	± 0.10	2	80 %	3.27 %
4	± 0.10	4	90 %	1.33 %
5	± 0.10	3	90 %	1.58 %
6	± 0.10	2	90 %	1.76 %



PFA Estimation Method 3 Conditional – Acceptance Subpopulation

CPFA Estimation (Method 3)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Upper Acceptance Limit	0.1000
Lower Acceptance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	90.00%
Calibration Process Std Uncertainty	0.012760
Calibration Process Exp Uncertainty	0.025009
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	4.00
Test Pt Cond False Accept Rate (CPFA)	1.48%
Test Pt False Reject Rate (PFR)	2.08%

CPFA Estimation (Method 3)

The inputs for this spreadsheet are black:

Tolerance Limits
Acceptance Limits (Guard Banded)
Observed EOP Test Pt In Tol (REOP)
Calibration Process Standard Uncertainty
Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Restore Limits

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Shows compliance to 2% requirement



PFA Estimation Method 3 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	PFA Method 1	CPFA
1	± 0.10	4	80 %	1.98 %	2.47 %
2	± 0.10	3	80 %	2.49 %	3.12 %
3	± 0.10	2	80 %	3.27 %	4.09 %
4	± 0.10	4	90 %	1.33 %	1.48 %
5	± 0.10	3	90 %	1.58 %	1.76 %
6	± 0.10	2	90 %	1.76 %	1.96 %



PFA Estimation Method 4 Conditional – Bayesian

BPFA Estimation (Method 4)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	90.00%
Calibration Process Std Uncertainty	0.012760
Calibration Process Exp Uncertainty	0.025009
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	4.00
Calibration Difference (Measured)	0.0750
Test Pt Bayes False Accept Rate (BPFA)	1.16%

BPFA Estimation (Method 4)

The inputs for this spreadsheet are black:

- Measured Calibration Difference
- Tolerance Limits
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidences

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Calibration Result (Deviation)

Shows compliance to 2% requirement



PFA Estimation Method 4 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Difference (Specific Result)	BPFA
1	± 0.10	4	80 %	0.07	0.6 %
2	± 0.10	3	80 %	0.07	2.2 %
3	± 0.10	2	80 %	0.07	6.0 %
4	± 0.10	4	90 %	0.07	0.4 %
5	± 0.10	3	90 %	0.07	1.5 %
6	± 0.10	2	90 %	0.07	3.4 %



PFA Estimation Method Comparisons

- **Method 1, Unconditional - Test Point Population Data:** Direct determination of compliance, need test point reliability.
- **Method 2, Unconditional - M&TE Population Data:** Conservative estimate (larger than Method 1), uses calibration interval measurement reliability data (generally available).
- **Method 3, Conditional – Acceptance Subpopulation:** Conservative estimate (larger than Method 1), appropriate for organizations that work with PFA conditioned on acceptance, need test point reliability.
- **Method 4, Conditional – Bayesian:** Very conservative estimate (larger than Method 1), need test point reliability.

All methods require calibration process uncertainty



Z540.3 PFA Requirement

“Where calibrations provide for verification that measurement quantities are within specified tolerances, the probability that incorrect acceptance decisions (false accept) will result from calibration tests shall not exceed 2% and shall be documented. Where it is not practicable to estimate this probability, the test uncertainty ratio shall be equal to or greater than 4:1.

NOTE: Achieving these requirements may involve adjustment and management of calibration system parameters such as: measurement reliability, calibration intervals, measurement uncertainty, calibration tolerances, and/or guard bands.”

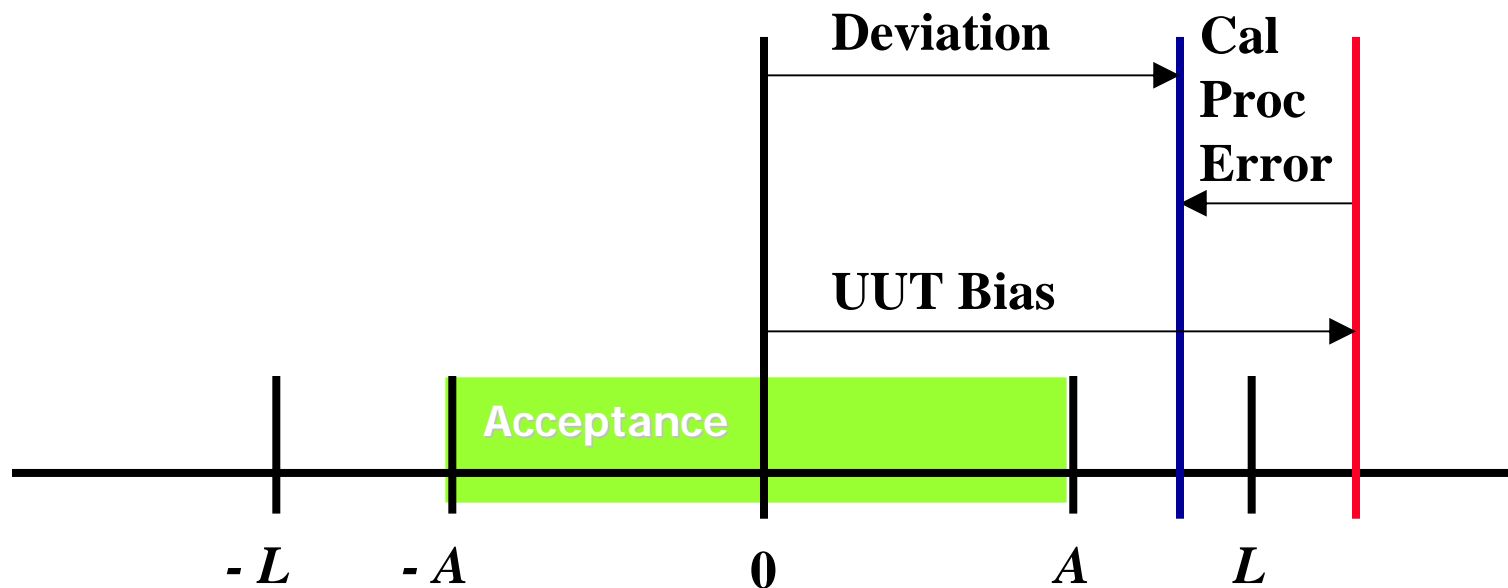


Altering PFA

- **PFA may be altered through adjustment of calibration system controls including:**
 - Measurement reliability
 - Calibration intervals
 - Calibration process uncertainty
 - Calibration tolerances
 - Guard bands
- **Guard Band use may lower the probability of making false accepts during a calibration test**



Guard Bands



Guard Bands provide better test decision limits (acceptance limits)

- Deviations just inside the specification can be caused by the Calibration Process error
- Guard Bands lower the probability of making false accepts
- The determination of the guard bands depends on how big the Calibration Process Error could be



Guard Band Methods

- **Method 1, Based on Unconditional PFA Estimation - Test Point Population Data:** Calculates guard bands based on unconditional PFA.
- **Method 2, Based on Unconditional PFA Estimation - M&TE Population Data:** Calculates guard bands based on conservative PFA estimate from M&TE equipment level measurement reliability.
- **Method 3, Based on Conditional PFA Estimation – Acceptance Subpopulation:** Calculates conservative guard bands based on conditional PFA.
- **Method 4, Based on Conditional PFA Estimation – Bayesian:** Calculates guard bands based on conditional Bayesian PFA (Condition is deviation at acceptance limit).
- **Method 5, Based on the Expanded Calibration Process Uncertainty:** Uses guard bands based on 95% expanded calibration process uncertainty.
- **Method 6, Based on the Test Uncertainty Ratio:** Uses guard bands based on the Test Uncertainty Ratio which meets the PFA requirement at the worst case test point measurement reliability.



Information Requirements Guard Band Methods

Method	Information Requirements			
	M&TE Test Tolerances	M&TE Test Point Measurement Reliability	M&TE Overall Measurement Reliability	Calibration Process Measurement Uncertainty
Test Point Population	X	X	-	X
M&TE Population	X	-	X	X
Acceptance Subpopulation	X	X	(X)	X
Bayesian	X	X	(X)	X
Expanded Uncertainty	X	-	-	X
TUR	X	-	-	X



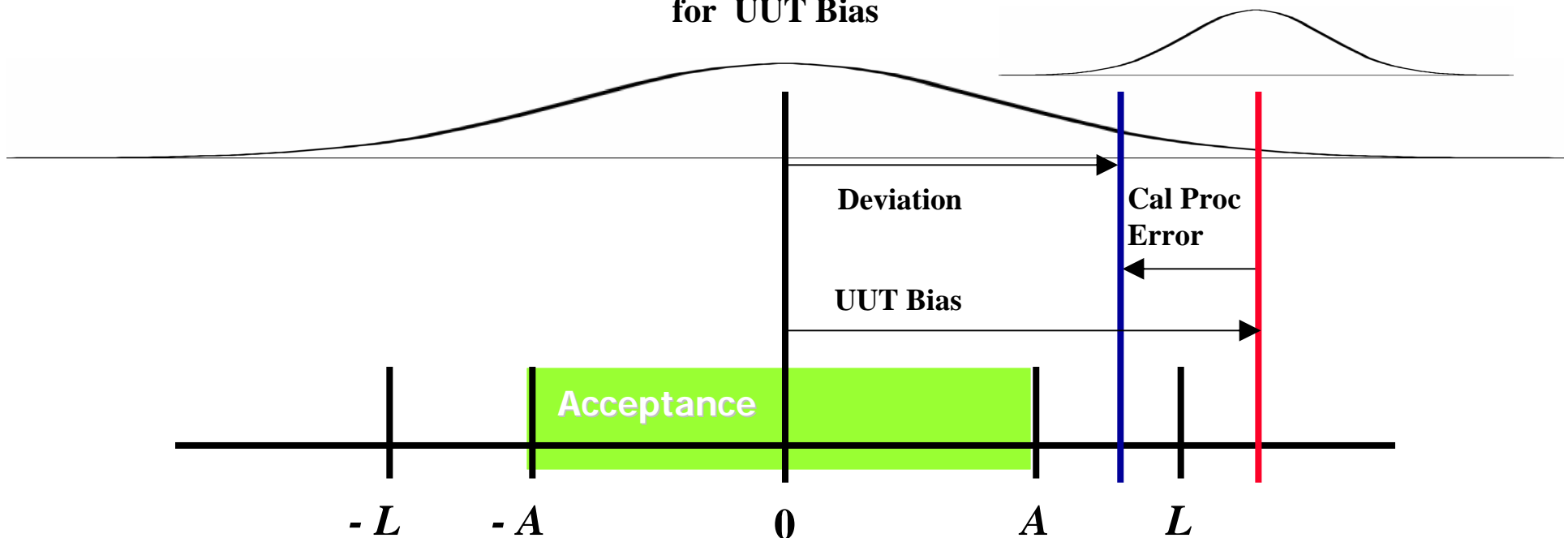
Guard Band Method 1 Unconditional - Test Point Population Data

Test Point Population (Method 1) approach for Guard Bands:

- Use uncertainty information on the Calibration Process and the UUT test point population data to calculate the probability of a false accept (PFA)
- Choose a guard band which gives an acceptably low PFA

Error Distribution
for UUT Bias

Error Distribution
for Cal Process





Guard Band Method 1 Unconditional - Test Point Population Data

PFA Guard Bands (Methods 1 and 2)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Test Pt PFA Requirement	2.00%
Test Pt False Reject Rate (PFR)	9.29%
Wrong Decision Rate	11.29%
Upper Acceptance Limit	0.0901
Lower Acceptance Limit	-0.0901
Acceptance Limit Multiplier	90.14%

PFA Guard Bands (Methods 1 and 2)

The inputs for this spreadsheet are black:

- Tolerance Limits
- Acceptance Limits (Guard Banded)
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Test Point Measurement Reliability

Acceptance limits that meet the 2% requirement



Guard Band Method 1 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Acceptance Limits	PFA Method 1
1	± 0.10	4	80 %	± 0.10	1.98 %
2	± 0.10	3	80 %	± 0.10	2.49 %
3	± 0.10	2	80 %	± 0.10	3.27 %
4	± 0.10	4	90 %	± 0.10	1.33 %
5	± 0.10	3	90 %	± 0.10	1.58 %
6	± 0.10	2	90 %	± 0.10	1.76 %

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Acceptance Limits	PFA Method 1
2a	± 0.10	3	80 %	± 0.097	2 %
3a	± 0.10	2	80 %	± 0.090	2 %

After applying guard bands, the PFA meets the 2% requirement for Scenarios 2 and 3



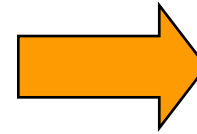
M&TE Population Data

- M&TE measurement reliability is the probability an M&TE passes all the steps of a calibration procedure.

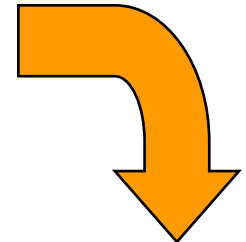


M&TE

ICP



Calibration Tests



Test Steps

PROC. NO. NA 17-20AQ-356		MFR	MODEL	SER. NO.		
PROCEDURE	FUNCTION TESTED	NOMINAL	MEASURED VALUES		OUT	CALIBRATION TOLERANCES
STEP NO			FIRST RUN	SECOND RUN	OF TOL	
(1)	(2)	(3)	(4)	(5)	(6)	(7)
4.1.7	TI Range (V)	(V)				(V)
→ "	1 V	1.000000				0.999953 to 1.000047
→ "	10 V	10.00000				9.99960 to 10.00040
→ "	10 V	-10.00000				-9.99960 to -10.00040



Guard Band Method 2 Unconditional – M&TE Population Data

M&TE Population Data (Method 2) approach for Guard Bands:

- M&TE Measurement Reliability is the probability of being in tolerance (the probability all the ICP steps pass).
- UUT Bias Uncertainty can be calculated from the Test Point Measurement Reliability (the probability a single ICP test point set passes).
- A conservative estimate of the UUT Bias Uncertainty can be calculated from the M&TE Measurement Reliability.
- Use the Calibration Process Uncertainty and the Conservative UUT Bias Uncertainty to calculate a conservative probability of a false accept.
- Choose a guard band which gives an acceptably low conservative PFA.
- This guarantees at least as low of a non-conservative PFA.



Guard Band Method 2 Unconditional – M&TE Population Data

PFA Guard Bands (Methods 1 and 2)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Test Pt PFA Requirement	2.00%
Test Pt False Reject Rate (PFR)	9.29%
Wrong Decision Rate	11.29%
Upper Acceptance Limit	0.0901
Lower Acceptance Limit	-0.0901
Acceptance Limit Multiplier	90.14%

PFA Guard Bands (Methods 1 and 2)

The inputs for this spreadsheet are black:

- Tolerance Limits
- Acceptance Limits (Guard Banded)
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

M&TE Measurement Reliability

Acceptance limits that meet the 2% requirement



Guard Band Method 2 Examples

Scenario	Test Limits	TUR	Equipment Measurement Reliability	Acceptance Limits	PFA_{exp}
1	± 0.10	4	80 %	± 0.10	1.98 %
2	± 0.10	3	80 %	± 0.10	2.49 %
3	± 0.10	2	80 %	± 0.10	3.27 %
4	± 0.10	4	90 %	± 0.10	1.33 %
5	± 0.10	3	90 %	± 0.10	1.58 %
6	± 0.10	2	90 %	± 0.10	1.76 %

Scenario	Test Limits	TUR	Equipment Measurement Reliability	Acceptance Limits	PFA_{exp}
2a	± 0.10	3	80 %	± 0.097	2 %
3a	± 0.10	2	80 %	± 0.090	2 %

After applying guard bands, the PFA meets the 2% requirement for Scenarios 2 and 3



Guard Band Method 3 Conditional – Acceptance Subpopulation

Acceptance Subpopulation (Method 3) approach for Guard Bands:

- This chooses the guard band based on a conditional version of PFA (CPFA)
- This conditional probability answers the question:

“What percentage of the acceptances is expected to be still out-of-tolerance?”
- The methodology is essentially the same as Methods 1 and 2, though because of the use of CPFA, the guard bands are somewhat larger



Guard Band Method 3 Conditional – Acceptance Subpopulation

CPFA Guard Bands (Method 3)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Test Pt PFA Requirement	2.00%
Test Pt False Reject Rate (PFR)	11.82%
Upper Acceptance Limit	0.0845
Lower Acceptance Limit	-0.0845
Acceptance Limit Multiplier	84.49%

CPFA Guard Bands (Method 3)

The inputs for this spreadsheet are black:

Tolerance Limits
Acceptance Limits (Guard Banded)
Observed EOP Test Pt In Tol (REOP)
Calibration Process Standard Uncertainty
Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Restore Limits

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Acceptance limits that meet the 2% requirement



Guard Band Method 3 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Acceptance Limits	PFA Method 1	CPFA
1	± 0.10	4	80 %	± 0.10	1.98 %	2.47 %
2	± 0.10	3	80 %	± 0.10	2.49 %	3.12 %
3	± 0.10	2	80 %	± 0.10	3.27 %	4.09 %
4	± 0.10	4	90 %	± 0.10	1.33 %	1.48 %
5	± 0.10	3	90 %	± 0.10	1.58 %	1.76 %
6	± 0.10	2	90 %	± 0.10	1.76 %	1.96 %

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Acceptance Limits	PFA Method 1	CPFA
1a	± 0.10	4	80 %	± 0.098	1.6 %	2 %
2a	± 0.10	3	80 %	± 0.094	1.5 %	2 %
3a	± 0.10	2	80 %	± 0.084	1.5 %	2 %

After applying guard bands, the PFA meets the 2% requirement for Scenarios 1, 2, and 3

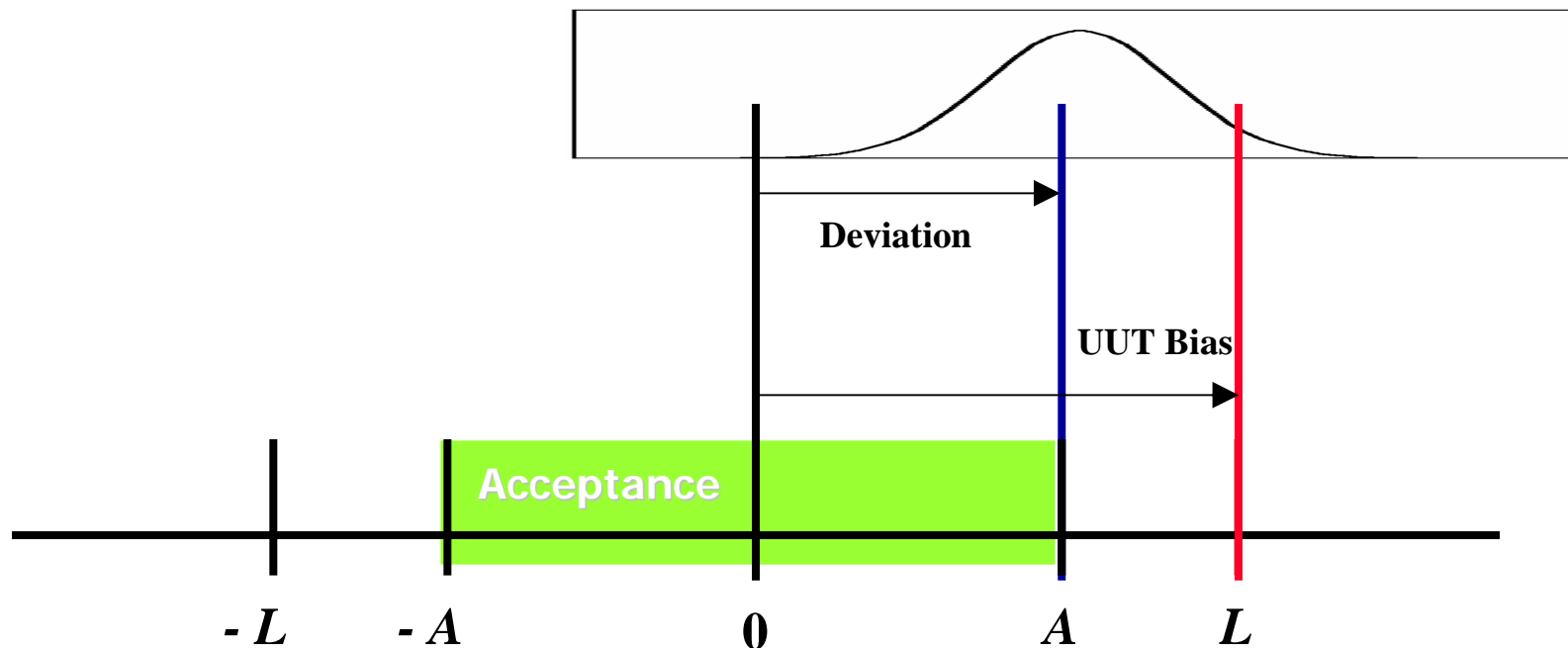


Guard Band Method 4 Conditional – Bayesian

The Bayesian approach (Method 4) for Guard Bands:

- Use uncertainty information on the Calibration Process to calculate the conditional probability of a false accept
- Assumes calibration result (deviation) is at the acceptance limit
- Choose a guard band which gives an acceptably low conditional PFA

Conditional Distribution for UUT Bias
Given Deviation is at Acceptance Limit





Guard Band Method 4 Conditional – Bayesian

BPFA Guard Bands (Method 4)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Observed EOP Test Pt In Tol (REOP)	80.00%
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Test Pt PFA Requirement	2.00%
Test Pt False Reject Rate (PFR)	29.54%
Upper Acceptance Limit	0.0565
Lower Acceptance Limit	-0.0565
Acceptance Limit Multiplier	56.53%

BPFA Guard Bands (Method 4)

The inputs for this spreadsheet are black:

- Tolerance Limits
- PFA Requirement
- Observed EOP Test Pt In Tol (REOP)
- Calibration Process Standard Uncertainty
- Uncertainty Confidences

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Note: The observed equipment level Observed In Tolerance probability can be used for REOP to obtain a conservative PFA estimate.

Acceptance limits that meet the 2% requirement



Guard Band Method 4 Examples

Scenario	Tolerance Limits	TUR	Test Point Measurement Reliability	Acceptance Limits	PFA Method 1	BPFA
1	± 0.10	4	80 %	± 0.076	0.06 %	2 %
2	± 0.10	3	80 %	± 0.069	0.09 %	2 %
3	± 0.10	2	80 %	± 0.057	0.17 %	2 %
4	± 0.10	4	90 %	± 0.078	0.06 %	2 %
5	± 0.10	3	90 %	± 0.072	0.09 %	2 %
6	± 0.10	2	90 %	± 0.064	0.18 %	2 %

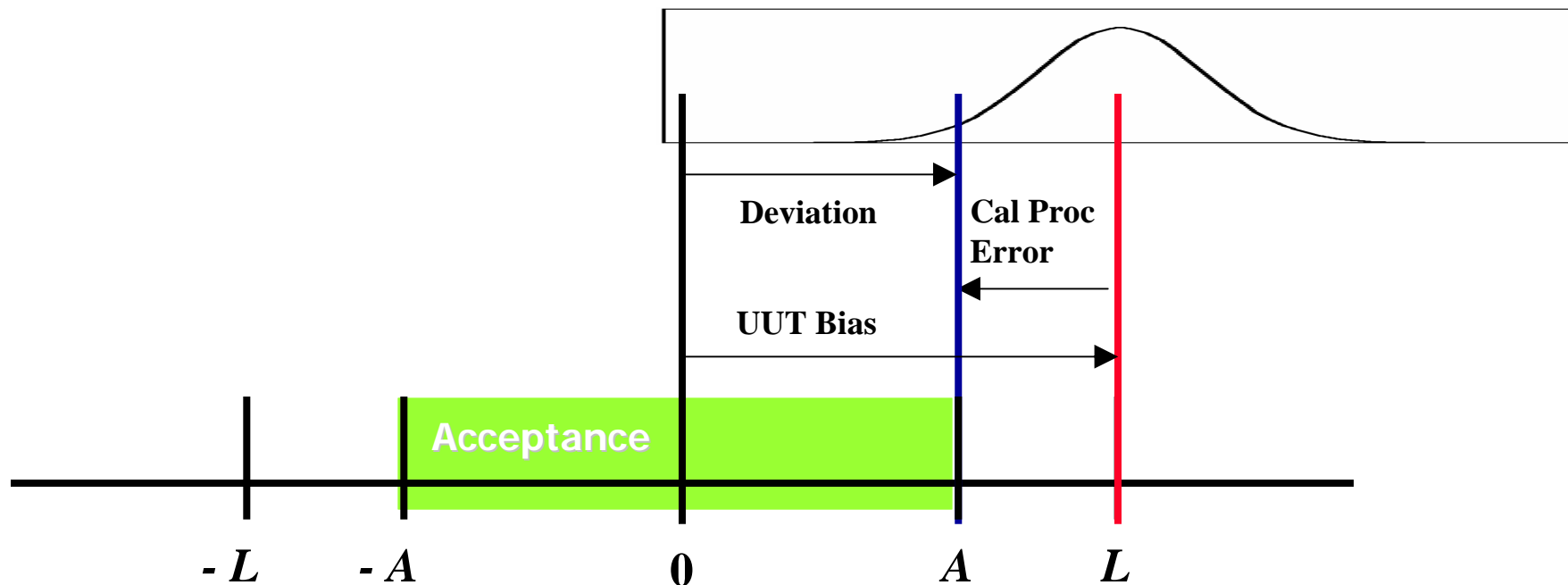


Guard Band Method 5 Expanded Calibration Process Uncertainty

The Expanded Calibration Process Uncertainty approach:

- Assume the UUT bias is at the tolerance limit
- Choose the guard band so that the probability that a calibration process error would cause an acceptance is small (2.5%)
- By general practice, this is done using $A = L - U_{95}$
- This meets the 2% requirement for every conceivable scenario

Error Distribution for
Calibration Process





Guard Band Method 5 Expanded Calibration Process Uncertainty

Expanded Uncertainty Guard Bands (Method 5)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Upper Acceptance Limit	0.0500
Lower Acceptance Limit	-0.0500
Acceptance Limit Multiplier	50.00%

Expanded Uncertainty GB (Method 5)
The inputs for this spreadsheet are black:
Tolerance Limits
Calibration Process Expanded Uncertainty
Uncertainty Confidence
Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.
<input type="button" value="Restore Limits"/>

Acceptance limits that meet the 2% requirement



Guard Band Method 5 Examples

Scenario	Tolerance Limits L	Expanded Calibration Process Uncertainty $U_{95\%}$	Acceptance Limits A	TUR	PFA Method 1 ($R_{tp} = 0.80$)
1	± 0.10	0.025	± 0.075	4	0.049 9 %
2	± 0.10	0.033	± 0.067	3	0.067 6 %
3	± 0.10	0.050	± 0.050	2	0.088 5 %



Guard Band Method 6 Test Uncertainty Ratio

The Test Uncertainty Ratio (Method 6) approach for Guard Bands:

- PFA is driven by the calibration process uncertainty, the test point measurement reliability, and the tolerance limits
- The TUR is obtained from the calibration process uncertainty and the tolerance limits
- For a given TUR, a guard band can be chosen which meets the PFA requirement for any measurement reliability value
- The guard band is a function of the TUR and the tolerance limits
- Using this guard band obviates the need to obtain measurement reliability data while providing smaller guard bands than Method 5

$$A_{2\%} = L - U_{95\%} \times \left[1.04 - e^{(0.38 \log(TUR) - 0.54)} \right]$$



Guard Band Method 6 Test Uncertainty Ratio

TUR Guard Bands (Method 6)	
Upper Tolerance Limit	0.1000
Lower Tolerance Limit	-0.1000
Calibration Process Std Uncertainty	0.025510
Calibration Process Exp Uncertainty	0.049999
Uncertainty Confidence	95.00%
Degrees of Freedom (Blank = Infinite)	
Test Uncertainty Ratio (TUR)	2.00
Upper Acceptance Limit	0.0859
Lower Acceptance Limit	-0.0859
Acceptance Limit Multiplier	85.92%

TUR Guard Bands (Method 6)

The inputs for this spreadsheet are black:

Tolerance Limits (Assumed symmetric)
Calibration Process Expanded Uncertainty
Uncertainty Confidence

Note: The limits have functions to support symmetric limits which can be overwritten, as necessary.

Acceptance limits that meet the 2% requirement



Guard Band Method 6 Examples

Scenario	Test Limits	TUR	Expanded Calibration Process Uncertainty ($U_{95\%}$)	Acceptance Limits ($A_{2\%}$)	PFA Method 1 ($R_{tp} = 0.80$)
1	± 0.10	4	0.025	± 0.099	1.74%
2	± 0.10	3	0.033	± 0.095	1.69%
3	± 0.10	2	0.050	± 0.086	1.57%



Guard Band Method Comparisons

- **Method 1, Based on Unconditional PFA Estimation - Test Point Population Data:** Smallest guard bands, need test point reliability.
- **Method 2, Based on Unconditional PFA Estimation - M&TE Population Data:** Fairly small guard bands, uses calibration interval measurement reliability data (generally available).
- **Method 3, Based on Conditional PFA Estimation – Acceptance Subpopulation:** Appropriate for organizations that work with PFA conditioned on acceptance.
- **Method 4, Based on Conditional PFA Estimation – Bayesian:** Larger guard bands, need test point reliability.
- **Method 5, Based on the Expanded Calibration Process Uncertainty:** Largest guard bands, doesn't require test point reliability.
- **Method 6, Based on the Test Uncertainty Ratio:** Smallest of the guard bands that do not require test point reliability.

All methods require calibration process uncertainty



ANSI Z540.3 Testing

- **ANSI Z540.3 was adopted July 2007 and is being used by US industry**
- **Changes caused by Z540.3**
 - Calibration procedures are based on Probability of False Accept (PFA) rather than Test Accuracy Ratio (TAR)
 - Test points in calibration procedures must have $PFA < 2\%$
 - A Test Uncertainty Ratio (TUR) of 4:1 can be used when PFA calculation is not practicable
 - Calculation of PFA and TUR both require estimation of the calibration process uncertainty
 - The Test Accuracy Ratio (TAR) is not used in ANSI Z540.3



Test Uncertainty Ratio

- The ratio of the unit under test specifications to the calibration process uncertainty is called the Test Uncertainty Ratio (TUR)

$$\text{TUR} = \frac{\text{Upper Test Spec} - \text{Lower Test Spec}}{\text{Upper 95\% Uncertainty} - \text{Lower 95\% Uncertainty}}$$

- Generally, the requirement for good testing is to have:

$$\text{TUR} \geq 4.0$$

- A TUR greater than 4.0 helps keep the probability of bad decisions to an acceptable level.
- This is usually referred to with ratio jargon as 4 : 1 (4 to 1)



Test Uncertainty Ratio Example

- Test at 10.0 volts with ± 0.1 volt specifications:

$$\begin{array}{lcl} \text{Upper Test Specification} & = & 10.1 \text{ volts} \\ \text{Lower Test Specification} & = & 9.9 \text{ volts} \end{array}$$

- The calibration process has ± 0.025 volt 95% measurement uncertainty:

$$\begin{array}{lcl} \text{Upper 95\% Uncertainty} & = & +0.025 \text{ volts} \\ \text{Lower 95\% Uncertainty} & = & -0.025 \text{ volts} \end{array}$$

- Applying this to the TUR equation, we get:

$$\begin{aligned} \text{TUR} &= \frac{10.1 \text{ volts} - 9.9 \text{ volts}}{+0.025 \text{ volts} - (-0.025 \text{ volts})} \\ &= 4.0 \end{aligned}$$



Test Accuracy Ratio

- Much of industry has historically used the Test Accuracy Ratio (TAR) rather than the TUR
- The Test Accuracy Ratio is the ratio of the unit under test specifications to the calibrator specifications

$$\text{TAR} = \frac{\text{Upper Test Spec} - \text{Lower Test Spec}}{\text{Upper Calibrator Spec} - \text{Lower Calibrator Spec}}$$

- The 4:1 requirement for the TAR is the same as for the TUR.
- Since the calibrator specifications are based on calibrator uncertainties rather than calibration process uncertainties, TAR and TUR can be very different



Test Accuracy Ratio Example

- Test at 10.0 volts with ± 0.1 volt specifications:

$$\begin{array}{lcl} \text{Upper Test Specification} & = & 10.1 \text{ volts} \\ \text{Lower Test Specification} & = & 9.9 \text{ volts} \end{array}$$

- The calibrator has ± 0.025 volt specifications:

$$\begin{array}{lcl} \text{Upper Calibrator Spec} & = & 10.025 \text{ volts} \\ \text{Lower Calibrator Spec} & = & 9.975 \text{ volts} \end{array}$$

- Applying this to the TAR equation, we get:

$$\begin{aligned} \text{TAR} &= \frac{10.1 \text{ volts} - 9.9 \text{ volts}}{10.025 \text{ volts} - (9.975 \text{ volts})} \\ &= 4.0 \end{aligned}$$



TAR vs TUR

- **The calibrator specification used in the TAR is usually based on the calibrator measurement uncertainty**
- **The calibration process uncertainty used in the TUR includes:**
 - The Calibrator (CALSTD) measurement uncertainty
 - The Calibration setup uncertainty (connections, etc.)
 - The UUT nonbias uncertainty (Repeatability, Resolution, Reproducibility)
- **If the UUT nonbias uncertainty is large, the TUR could be much worse than the TAR**
- **TAR and TUR will be close to the same if:**
 - The calibrator specifications are based on 95% measurement uncertainties
 - The UUT nonbias uncertainty is a small part of the calibration process uncertainty



Summary

- TAR is not TUR
- TAR is not used in ANSI Z540.3
- The TUR can be used when PFA calculation is not “practicable”.
- The estimation of the calibration process uncertainty is the hardest part of PFA compliance methods
- The calculation of TUR requires the estimation of the calibration process uncertainty
- PFA compliance methods should rarely be not “practicable” if TUR can be calculated
- A 4:1 TUR meets the requirements of the Standard
- The Probability of False Accept (PFA) is the preferred measure of test quality