IEEE SW Test Workshop
Semiconductor Wafer Test Workshop

June 7-10, 2009
San Diego, CA

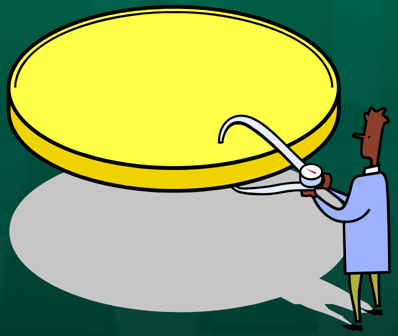
Assessing Metrology Tool Capability

RUDOLPH
TECHNOLOGIES
Process. Control. Yield.

Jeff Greenberg
Rudolph Technologies

Assessing Metrology Tool Capability

- Classical Gauge Repeatability and Reproducibility (GRR) study in simplest form:



  - Assume part is stable and unchanging
  - Measure the part “n” times by “m” operators
  - Compute the Reproducibility
  - Use statistics to determine the error contributions due to tool variation and operator variation

$$GRR_{MEASURED} = \sqrt{GRR^2{}_{TOOL} + GRR^2{}_{OPERATOR}}$$

Assessing Metrology Tool Capability

- There is a large body of work/literature available that describes various methods for determining measurement capability
- The literature provides many examples of techniques, statistically rigorous sampling plans and methods for data analysis
- Reference material for those who want to dive into the details
  - SWTW "Introduction to Gage R&R Studies" 1998 Scutoski et al
  - **Sematech** "Metrology Gauge Study Procedure for International 300mm Initiative"
  - **Sematach** "Evaluating Automated Wafer Measurement Instruments"
    - Interesting notes regarding "dealing with wafers that change over time"
  - **Journal of Industrial Technology** "Gauge R&R: An Effective Methodology for Determining the Adequacy of a New Measurement System for Micron-level Metrology"
  - **Automotive Industry Action Group** "Quantifying the Effect of Excessive Within - Part Variation"
  - **Automotive Industry Action Group** "Non-replicable GRR Case Study"

- Not a lot of examples found that deal with GRR studies of unstable objects

Assessing Metrology Tool Capability

- This section of the tutorial is focused on the *uniqueness* and challenges associated with Gauge R&R studies for Probe Card Metrology tools

- The goal of the tutorial is to provide background information and case studies that will help you obtain more meaningful results from your Gauge R&R studies

Agenda

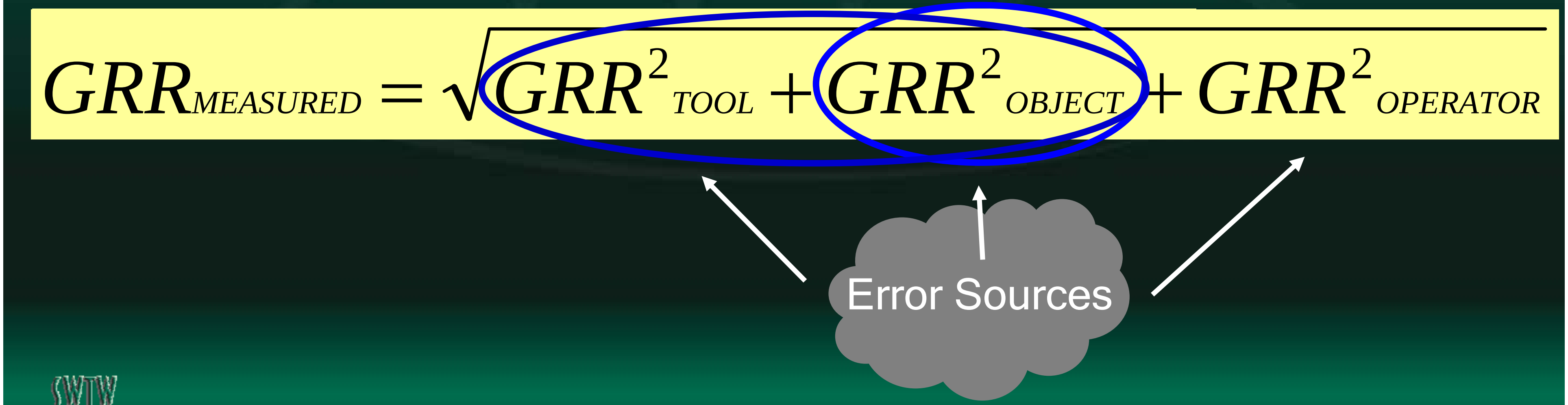
- Variation in GRR Studies
- Impact of Metrology Tool Setup on GR&R results
- Design of experiment (DOE) to gather meaningful GR&R data
- GR&R Case Studies

Is the Object Stable?

- Gage R&R studies often assume that the part is stable and unchanging during the study
  - Is this a valid assumption for a probe card?
- "In physics, the term *observer effect* refers to changes that the act of observation will make on the phenomenon being observed. This is often the result of instruments that, by necessity, alter the state of what they measure in some manner. This effect can be observed in many domains of physics"
      - » Wikipedia

GRR Results Interpretation

- Understand the error sources of your GRR study
  - Measurement object needs to be considered
- Repeatability and Reproducibility of the tool and the measurement object are often confounded
- Often requires DOE to isolate and understand the effect of different variables



$$GRR_{MEASURED} = \sqrt{GRR^2{}_{TOOL} + GRR^2{}_{OBJECT} + GRR^2{}_{OPERATOR}}$$

Error Sources

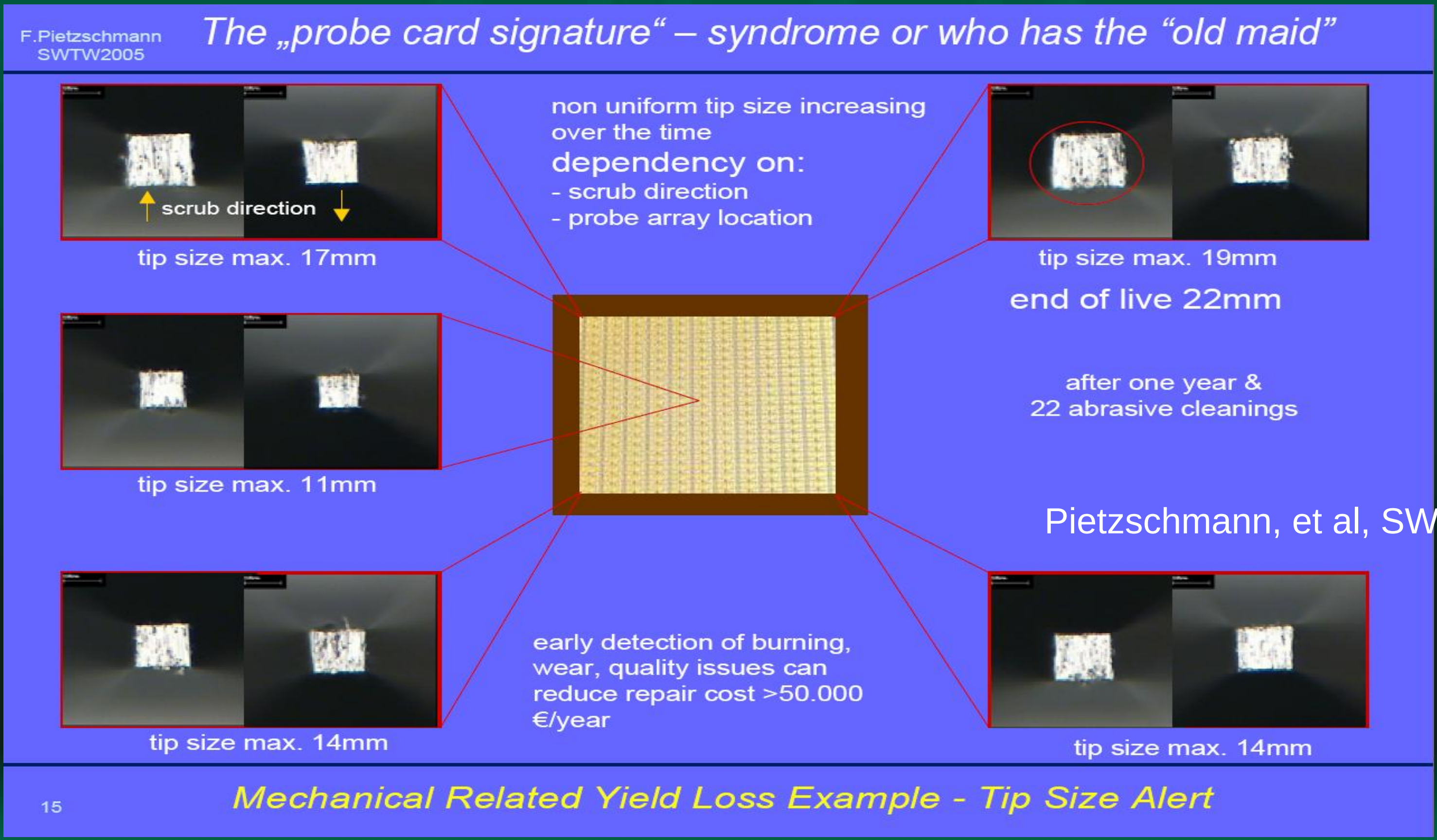
Understand the Sources of Variability

- Some generic examples of sources of variability
  - External sources of variability
    - Environment
      - Temperature
      - Humidity
    - Operator
    - Time
    - Measurement object
  - Internal sources of variability
    - System settings
    - Systems calibrations
    - System wear
    - System interactions w/ measurement object (observer effect)

Discussion will focus on these areas

Static Probe Card Variability

- Probe tip size can vary across a single card and from probe card to probe card
- Variability may influence GRR results, but not due to GRR_{OBJECT}



F.Pietzschmann
SWTW2005

The „probe card signature“ – syndrome or who has the “old maid”

non uniform tip size increasing over the time

dependency on:
- scrub direction
- probe array location

scrub direction

tip size max. 17mm

tip size max. 19mm

end of live 22mm

after one year &
22 abrasive cleanings

tip size max. 11mm

early detection of burning, wear, quality issues can reduce repair cost >50.000 €/year

tip size max. 14mm

tip size max. 14mm

15

Mechanical Related Yield Loss Example - Tip Size Alert

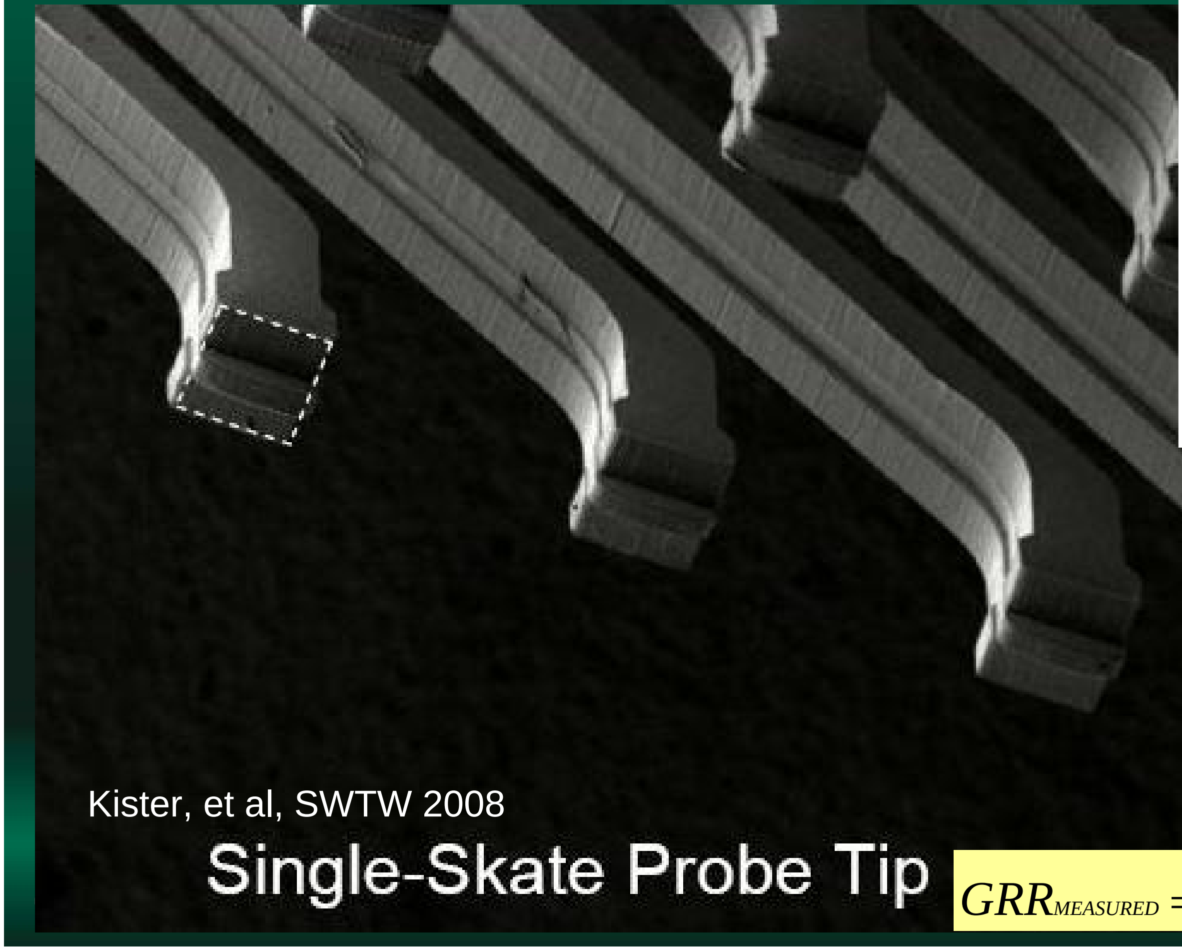
Pietzschmann, et al, SWTW 2005

June 7 to 10, 2009

$$GRR_{MEASURED} = \sqrt{\boxed{GRR^2_{TOOL}} + GRR^2_{OBJECT} + GRR^2_{OPERATOR}}$$

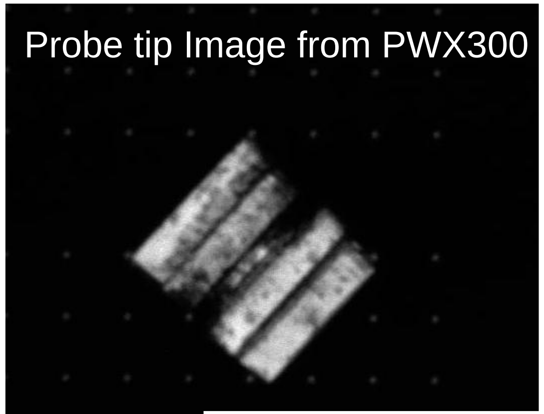
Static Probe Card Variability

- Probe tip optical properties can vary across a single probe card and from probe card to probe card
- Variability may influence GRR results, but not due to GRR_{OBJECT}

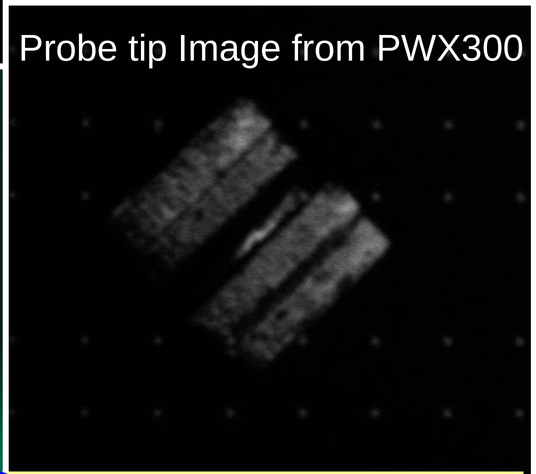


Kister, et al, SWTW 2008

Single-Skate Probe Tip



Probe tip Image from PWX300

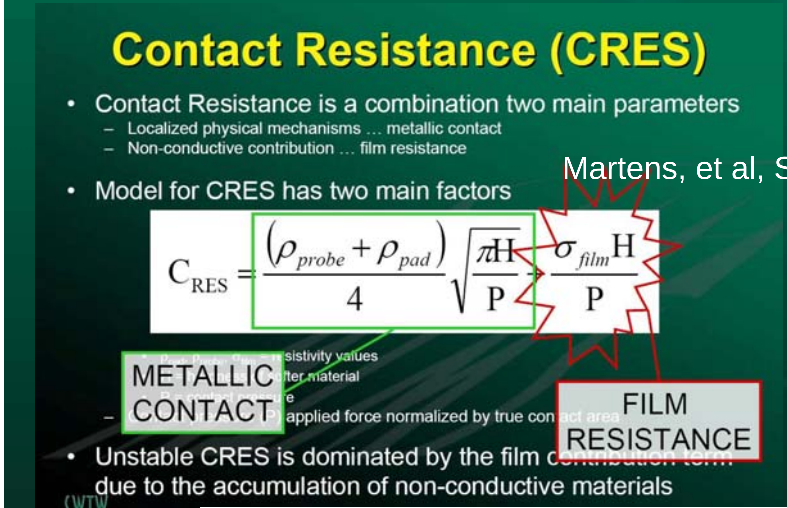


Probe tip Image from PWX300

$$GRR_{MEASURED} = \sqrt{GRR^2_{TOOL} + GRR^2_{OBJECT} + GRR^2_{OPERATOR}}$$

Dynamic Probe Card Variability

- Contact resistance is variable from touchdown to touchdown
- Variability will influence GRR results, due to large GRR_{OBJECT}



Contact Resistance (CRES)

- Contact Resistance is a combination two main parameters
  - Localized physical mechanisms … metallic contact
  - Non-conductive contribution … film resistance
- Model for CRES has two main factors

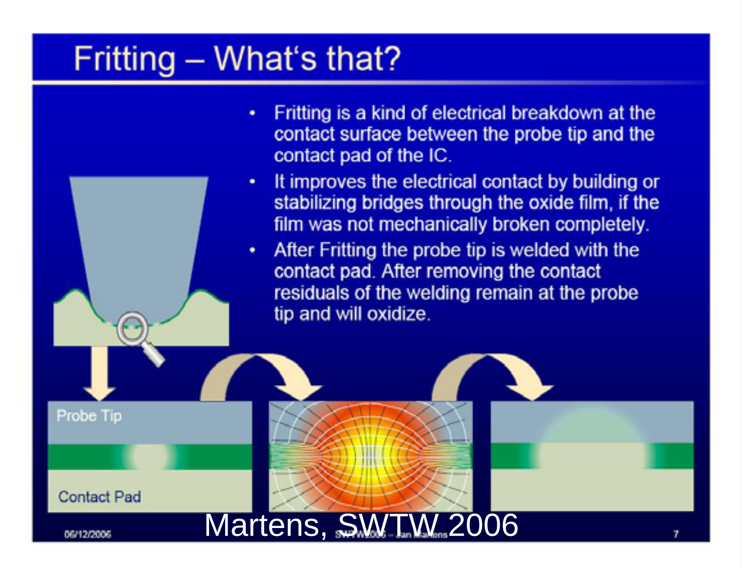
$$C_{RES} = \boxed{\frac{(\rho_{probe} + \rho_{pad})}{4}\sqrt{\frac{\pi H}{P}}} + \frac{\sigma_{film} H}{P}$$

sistivity values
ter material
e
– applied force normalized by true con

- Unstable CRES is dominated by the film contribution term due to the accumulation of non-conductive materials

June 11

Martens, et al, SWTW 2008

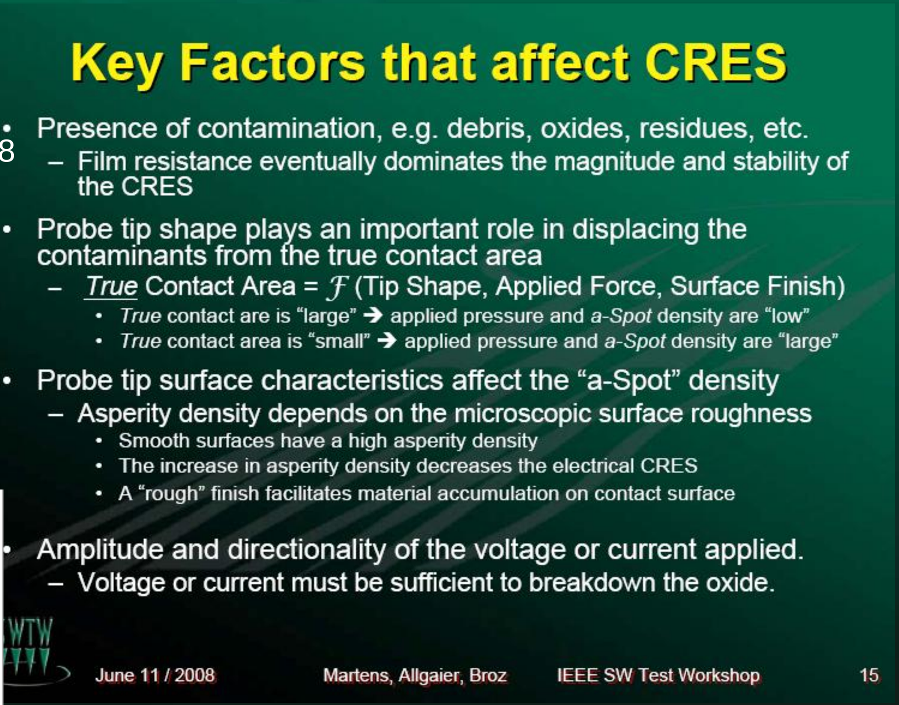


Fritting – What's that?

- Fritting is a kind of electrical breakdown at the contact surface between the probe tip and the contact pad of the IC.
- It improves the electrical contact by building or stabilizing bridges through the oxide film, if the film was not mechanically broken completely.
- After Fritting the probe tip is welded with the contact pad. After removing the contact residuals of the welding remain at the probe tip and will oxidize.

06/12/2006 SWTW2006 – Jan Martens 7

Martens, SWTW 2006



Key Factors that affect CRES

- Presence of contamination, e.g. debris, oxides, residues, etc.
  - Film resistance eventually dominates the magnitude and stability of the CRES
- Probe tip shape plays an important role in displacing the contaminants from the true contact area
  - *True* Contact Area = $\mathcal{F}$ (Tip Shape, Applied Force, Surface Finish)
    - *True* contact are is "large" ➔ applied pressure and *a-Spot* density are "low"
    - *True* contact area is "small" ➔ applied pressure and *a-Spot* density are "large"
- Probe tip surface characteristics affect the "a-Spot" density
  - Asperity density depends on the microscopic surface roughness
    - Smooth surfaces have a high asperity density
    - The increase in asperity density decreases the electrical CRES
    - A "rough" finish facilitates material accumulation on contact surface
- Amplitude and directionality of the voltage or current applied.
  - Voltage or current must be sufficient to breakdown the oxide.

June 11 / 2008 Martens, Allgaier, Broz IEEE SW Test Workshop 15

$$GRR_{MEASURED} = \sqrt{GRR^2_{TOOL} + GRR^2_{OBJECT} + GRR^2_{OPERATOR}}$$

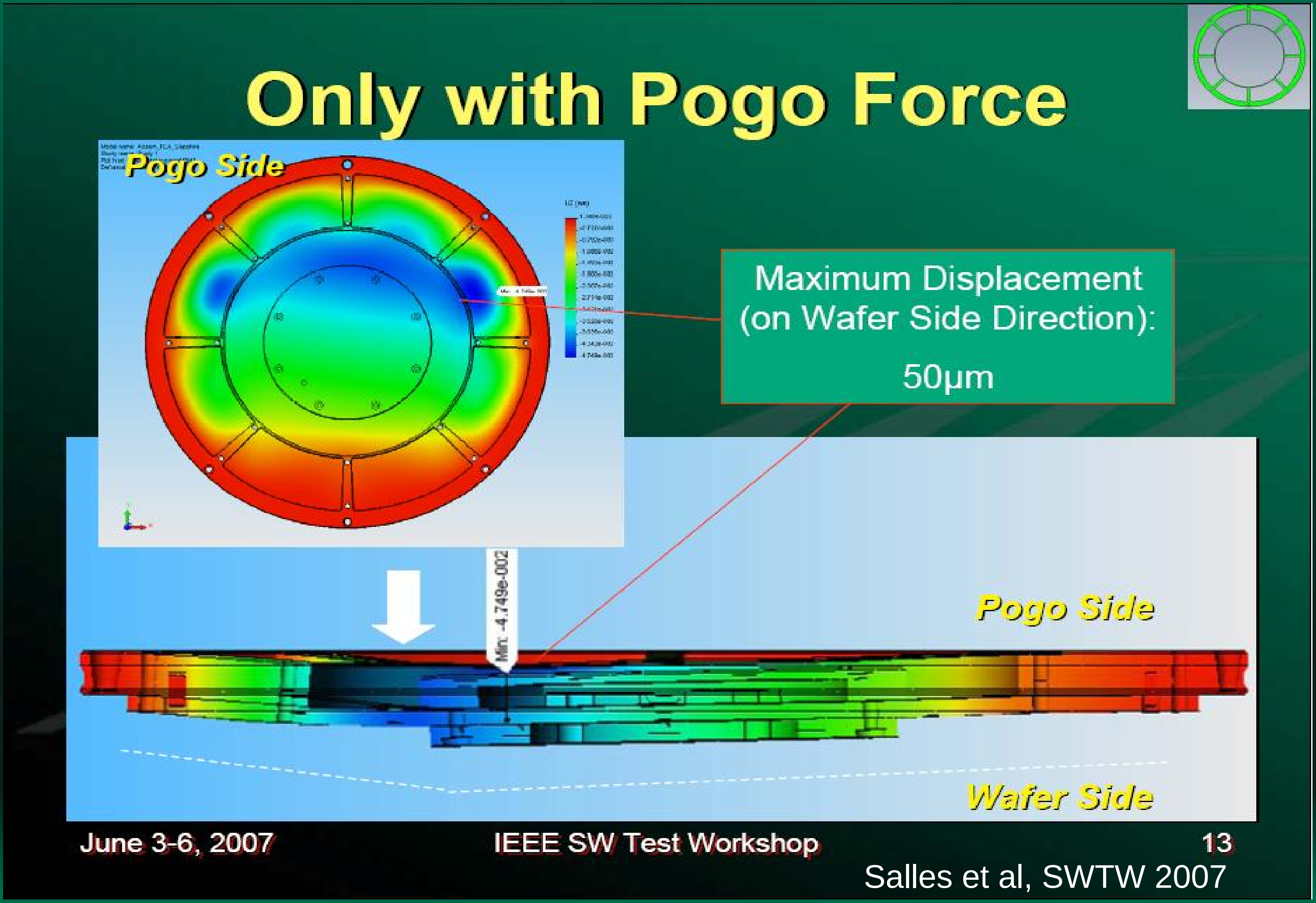
Observer Effect -- Dynamic Variability

- Probe card metrology requires invasive probe card/tool interaction and can be rife with the observer effect
  - Probe card docking forces can be high
  - Probe card overtravel forces can be high
  - Probe tips are affected by the interactions between the probes and the measurement surfaces during contact measurements
  - Probe card measurements pass electric current through the probe needles
- Observer effect makes this term larger than you might think…

$$GRR_{Measured} = \sqrt{GRR^2{}_{TOOL} + \boxed{GRR^2{}_{OBJECT}} + GRR^2{}_{OPERATOR}}$$

How the *Observer Effect* Can Impact Results

Probe Card Response to Docking Forces



Only with Pogo Force

Maximum Displacement (on Wafer Side Direction):

50µm

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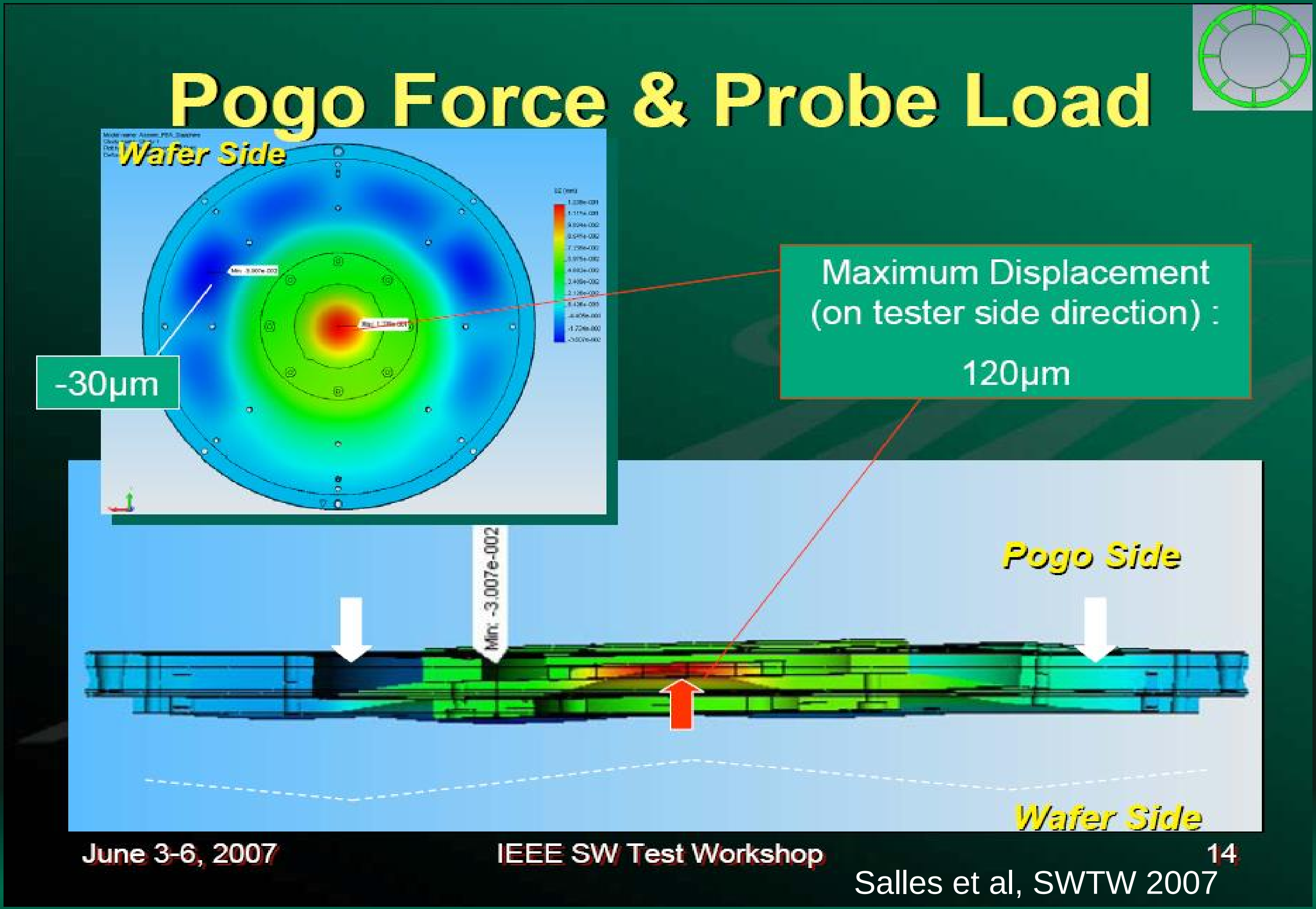
Salles et al, SWTW 2007

How the ***Observer Effect*** Can Impact Results

Probe Card Response to Forces from Docking and OT



Pogo Force & Probe Load

Maximum Displacement
(on tester side direction) :
120µm

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Salles et al, SWTW 2007

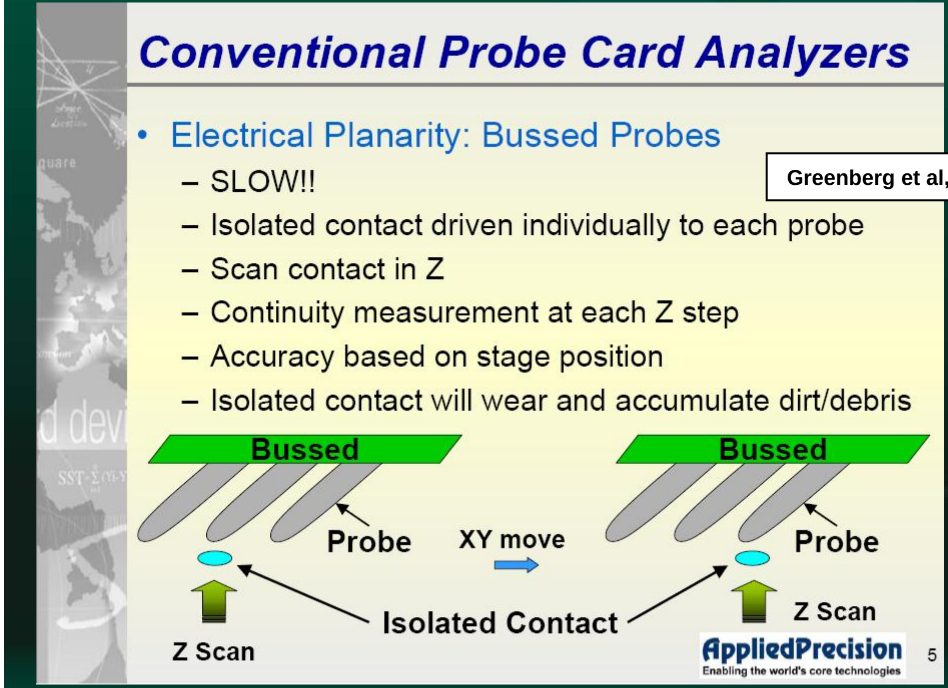
How the *Observer Effect* Can Impact Results

- Docking and OT forces can impact measured Planarity and GR&R results even with a perfect metrology tool
- This could manifest itself in several ways:
  - Repeatability
    - Probe card drift during the tests can influence repeatability
  - Reproducibility
    - Variation in the static probe card shape due to changes in loading conditions from insertion to insertion
      - Influenced by quality of mating reference surfaces, tolerances between PCI and probe card alignment features, etc.

$$GRR_{Measured} = \sqrt{GRR^{2}_{TOOL} + \overset{?}{\boxed{GRR^{2}_{OBJECT}}} + GRR^{2}_{OPERATOR}}$$

How the *Observer Effect* Can Impact Results

- Impact of Probe Card/Measurement Surface Interaction on Measured Planarity and Alignment
  - PCA systems come in two flavors
    - Many touch (conventional) PCA systems – PRVX3, Other



Conventional Probe Card Analyzers

- Electrical Planarity: Bussed Probes
  - SLOW!!
  - Isolated contact driven individually to each probe
  - Scan contact in Z
  - Continuity measurement at each Z step
  - Accuracy based on stage position
  - Isolated contact will wear and accumulate dirt/debris

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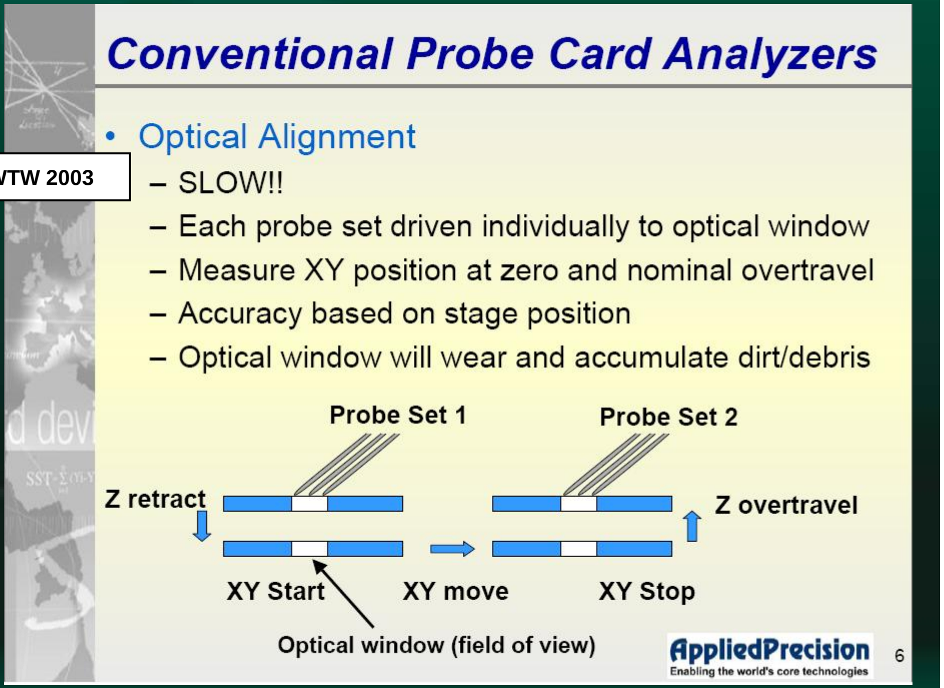
Greenberg et al, SWTW 2003



Conventional Probe Card Analyzers

- Optical Alignment
  - SLOW!!
  - Each probe set driven individually to optical window
  - Measure XY position at zero and nominal overtravel
  - Accuracy based on stage position
  - Optical window will wear and accumulate dirt/debris

AppliedPrecision
Enabling the world's core technologies

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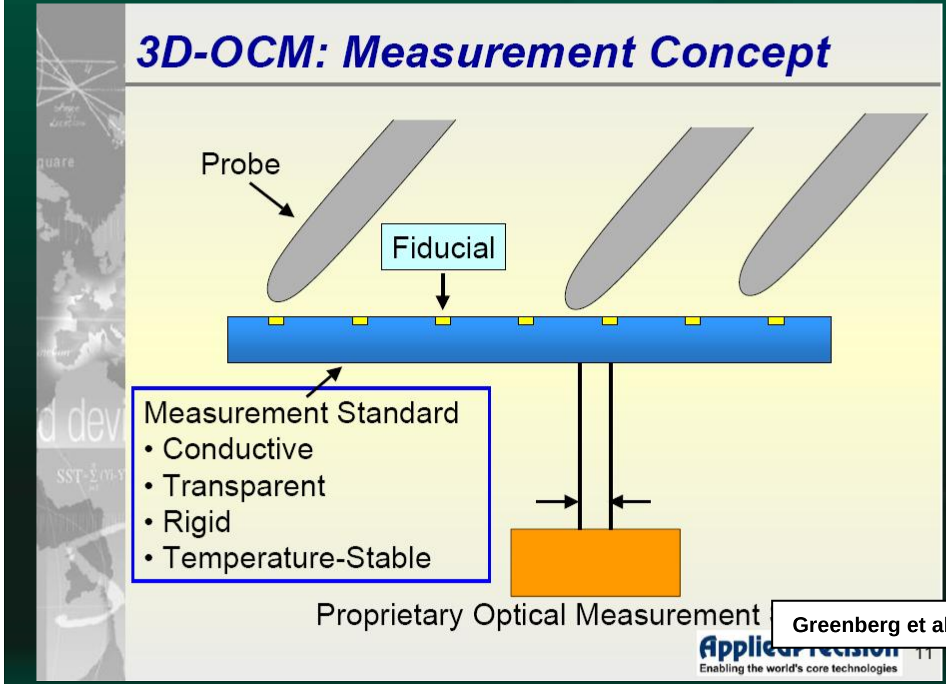
?

$$GRR_{Measured} = \sqrt{GRR^2{}_{TOOL} + GRR^2{}_{OBJECT} + GRR^2{}_{OPERATOR}}$$

How the *Observer Effect* Can Impact Results

- Impact of Probe Card/Measurement Surface Interaction on Measured Planarity and Alignment
  - PCA systems come in two flavors
    - One-touch P&A systems – ProbeWoRx300

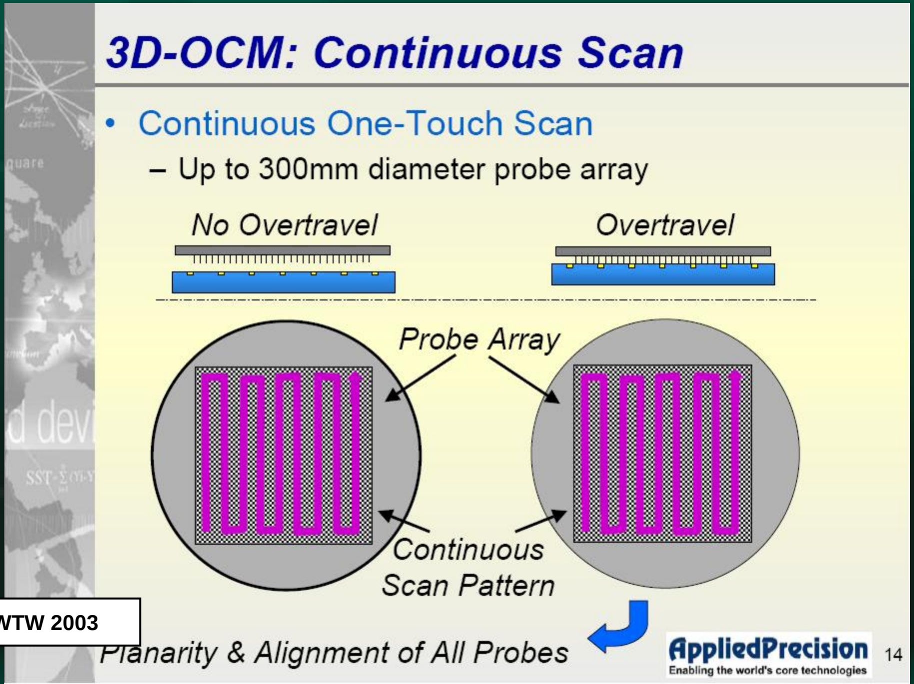


3D-OCM: Measurement Concept

Measurement Standard
- Conductive
- Transparent
- Rigid
- Temperature-Stable

Proprietary Optical Measurement

Greenberg et al, SWTW 2003



3D-OCM: Continuous Scan

- Continuous One-Touch Scan
  - Up to 300mm diameter probe array

Planarity & Alignment of All Probes

?

$$GRR_{Measured} = \sqrt{GRR^2_{TOOL} + GRR^2_{OBJECT} + GRR^2_{OPERATOR}}$$

How the *Observer Effect* Can Impact Results

- **Impact of Probe Card/Measurement Surface Interaction on Measured Planarity and Alignment**
  - One-touch P&A systems – ProbeWoRx300
  - Many touch PCA systems – PRVX3, Other

	1,000 pin probe card		10,000 pin probe card	
PCA Type	**TDs per test**	**TDs per 30 tests**	**TDs per test**	**TDs per 30 tests**
Many touch P&A	> 1,000	> 30,000	> 10,000	> 300,000
One touch P&A	1	30	1	30

  - Is it reasonable to expect the probe tips and the probe positions to be unchanged after > 30K touchdowns?
  - How about 300K touchdowns?

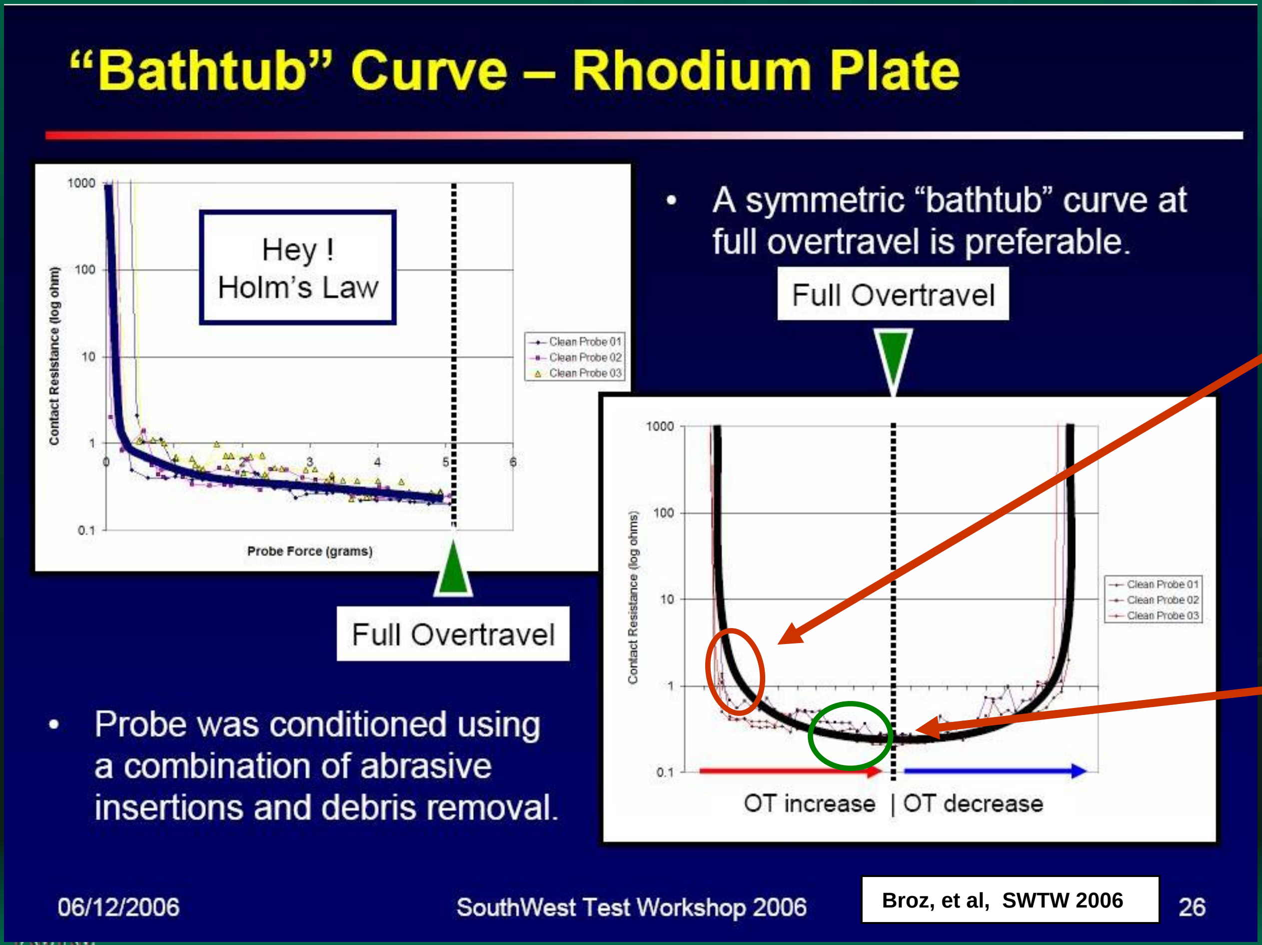
$$GRR_{Measured} = \sqrt{GRR^2_{TOOL} + \overset{?}{\boxed{GRR^2_{OBJECT}}} + GRR^2_{OPERATOR}}$$

Metrology Tool Setup

- Choose your tool settings wisely based on your requirements to be less sensitive to variation
  - Some examples to follow
- There are usually trade-offs between measurement precision and measurement speed

Metrology Tool Setup

- Example CRES – select OT setting wisely



“Bathtub” Curve – Rhodium Plate

Hey !
Holm’s Law

Full Overtravel

- A symmetric “bathtub” curve at full overtravel is preferable.

Full Overtravel

OT increase | OT decrease

- Probe was conditioned using a combination of abrasive insertions and debris removal.

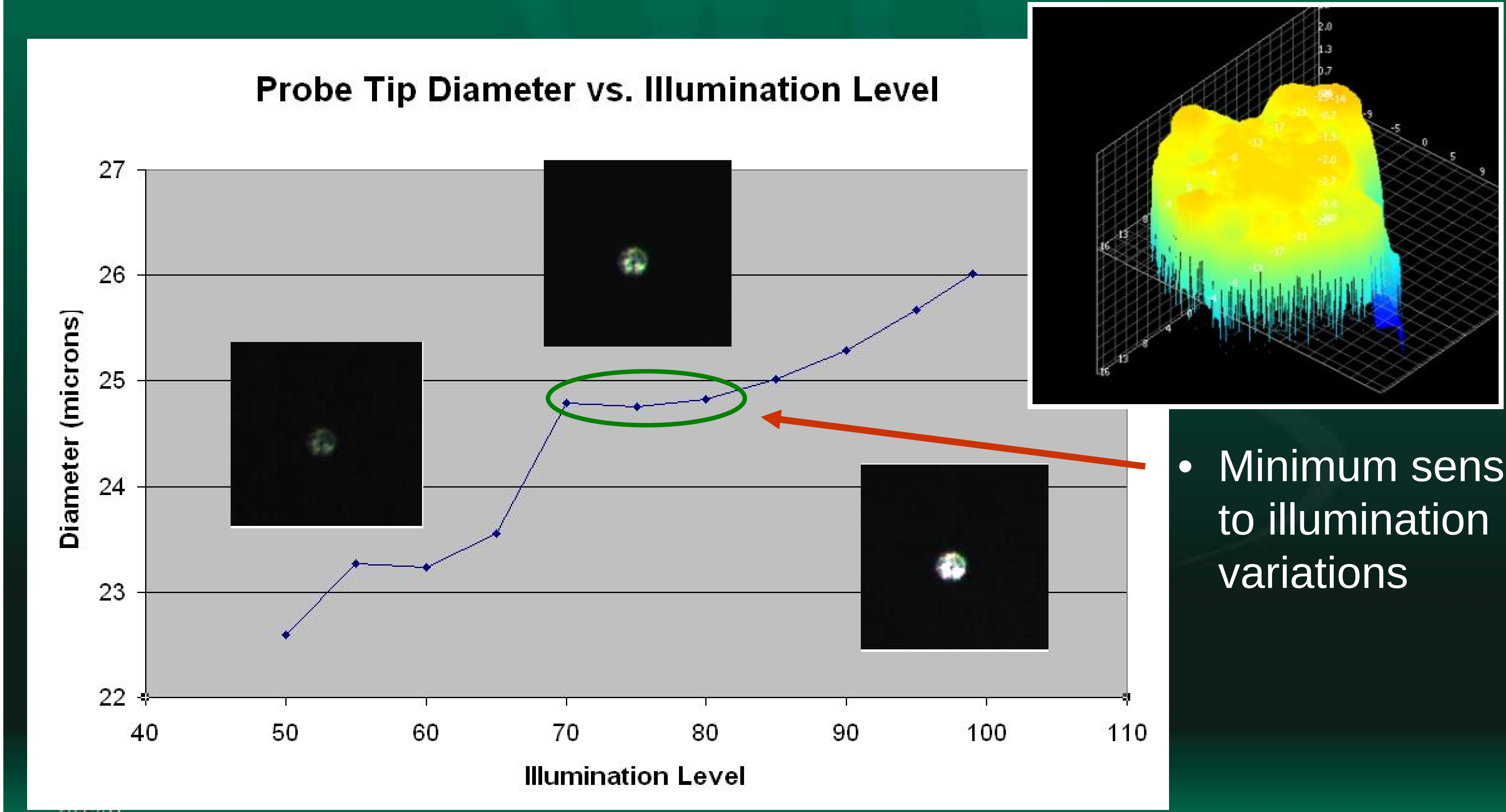
06/12/2006 SouthWest Test Workshop 2006 26

Broz, et al, SWTW 2006

- Very sensitive to small OT/Force variations!
- Much less sensitive to small OT/Force variations

Metrology Tool Setup

- Example Probe Diameter -- choose your tool settings wisely



- Minimum sensitivity to illumination variations

GR&R Design of Experiment

- Be aware of the sources of variability that impact your GR&R results
- Be aware of confounding influences
- Be aware of the Observer Effect
- Design your experiment to ensure you interpret the results correctly
  - What is GRR_{TOOL}?
- May require iteration based on initial results

$$GRR_{Measured} = \sqrt{\boxed{GRR^2_{TOOL}} + GRR^2_{OBJECT} + GRR^2_{OPERATOR}}$$

GR&R Design of Experiment

- Example of how to isolate GRR_{TOOL}
- Contact Resistance Measurement
  - Measure repeatability of known resistors to determine system measurement capability without confounding influence of CRES variability
  - Measure the repeatability of multiple CRES measurements taken during a single touchdown to eliminate variations in resistance

?

$$GRR_{Measured} = \sqrt{\boxed{GRR^2{}_{TOOL}} + GRR^2{}_{OBJECT} + GRR^2{}_{OPERATOR}}$$

GR&R Design of Experiment

- Examples of how to isolate GRR_{TOOL}
- Planarity Measurement
  - Measure different probe card technologies to try and isolate probe card effects from system effects
  - Limit sample size to minimize touchdown effects
  - Look at differences between best-fit plane and median plane to characterize changes in tilt that occur

$$GRR_{Measured} = \sqrt{\overset{?}{\boxed{GRR^{2}{}_{TOOL}}} + GRR^{2}{}_{OBJECT} + GRR^{2}{}_{OPERATOR}}$$

Assessing Metrology Tool Capability

Case Study #1

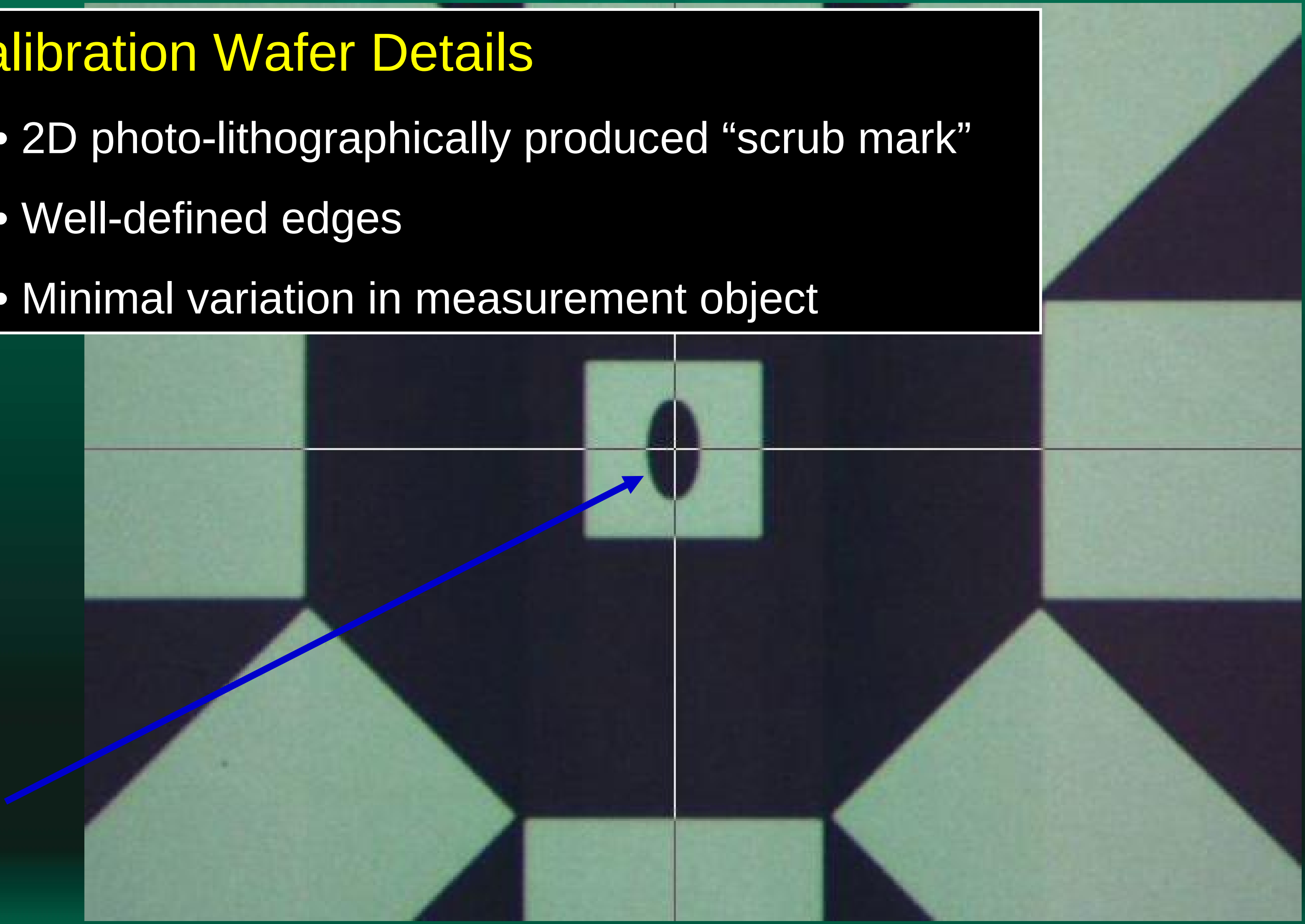
Case Study1 – WWX300 Tool to Tool Correlation

- Calibration wafer
  - WWX 300 #1 Repeatability Study
  - WWX 300 #2 Repeatability Study
  - WWX300 Tool to Tool Correlation

- Customer wafer
  - WWX 300 #1 Repeatability Study
  - WWX 300 #2 Repeatability Study
  - WWX300 Tool to Tool Correlation

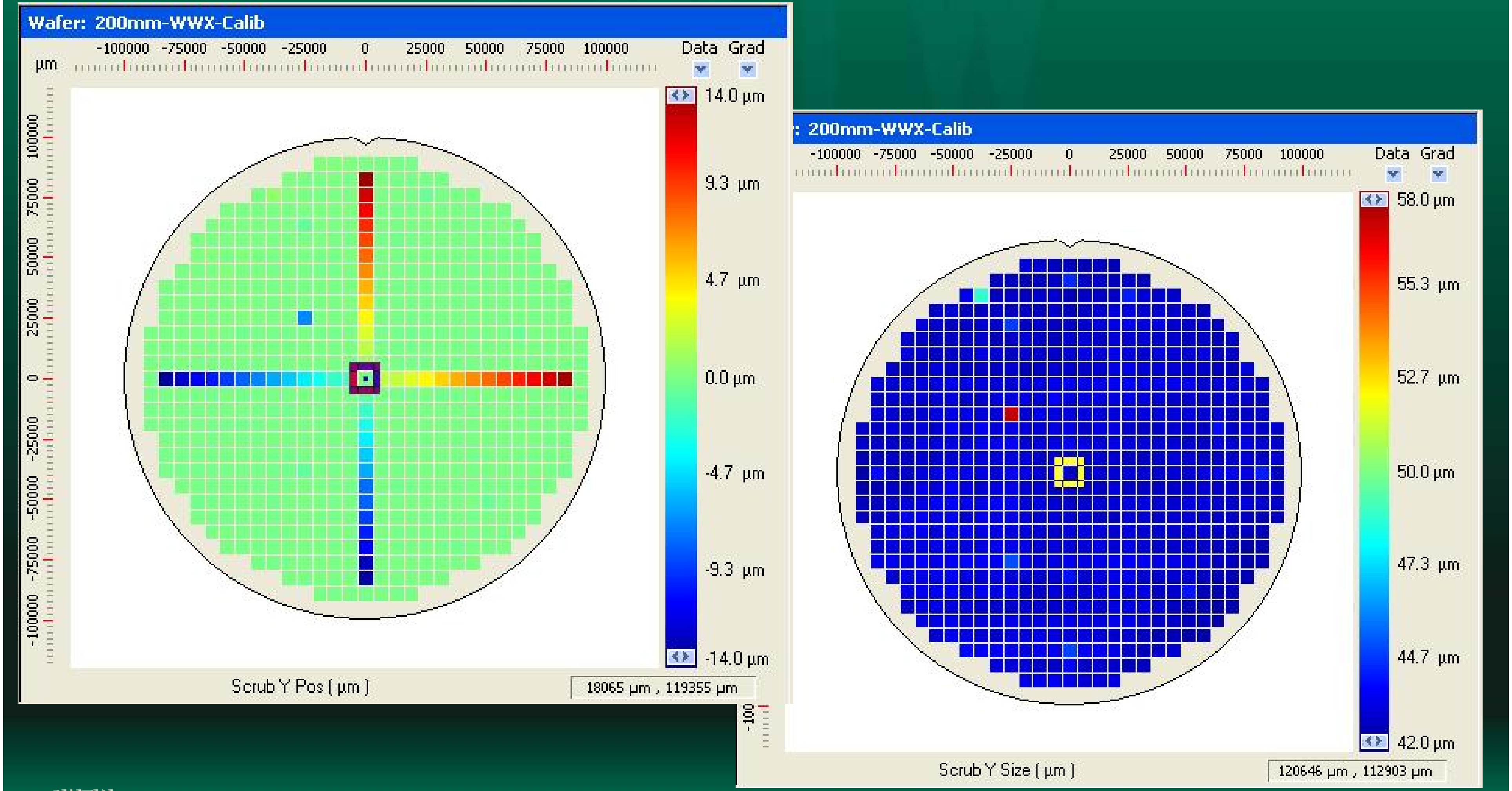
Case Study1 - WWX300 Tool to Tool Correlation

- Calibration Wafer Details
  - 2D photo-lithographically produced “scrub mark”
  - Well-defined edges
  - Minimal variation in measurement object



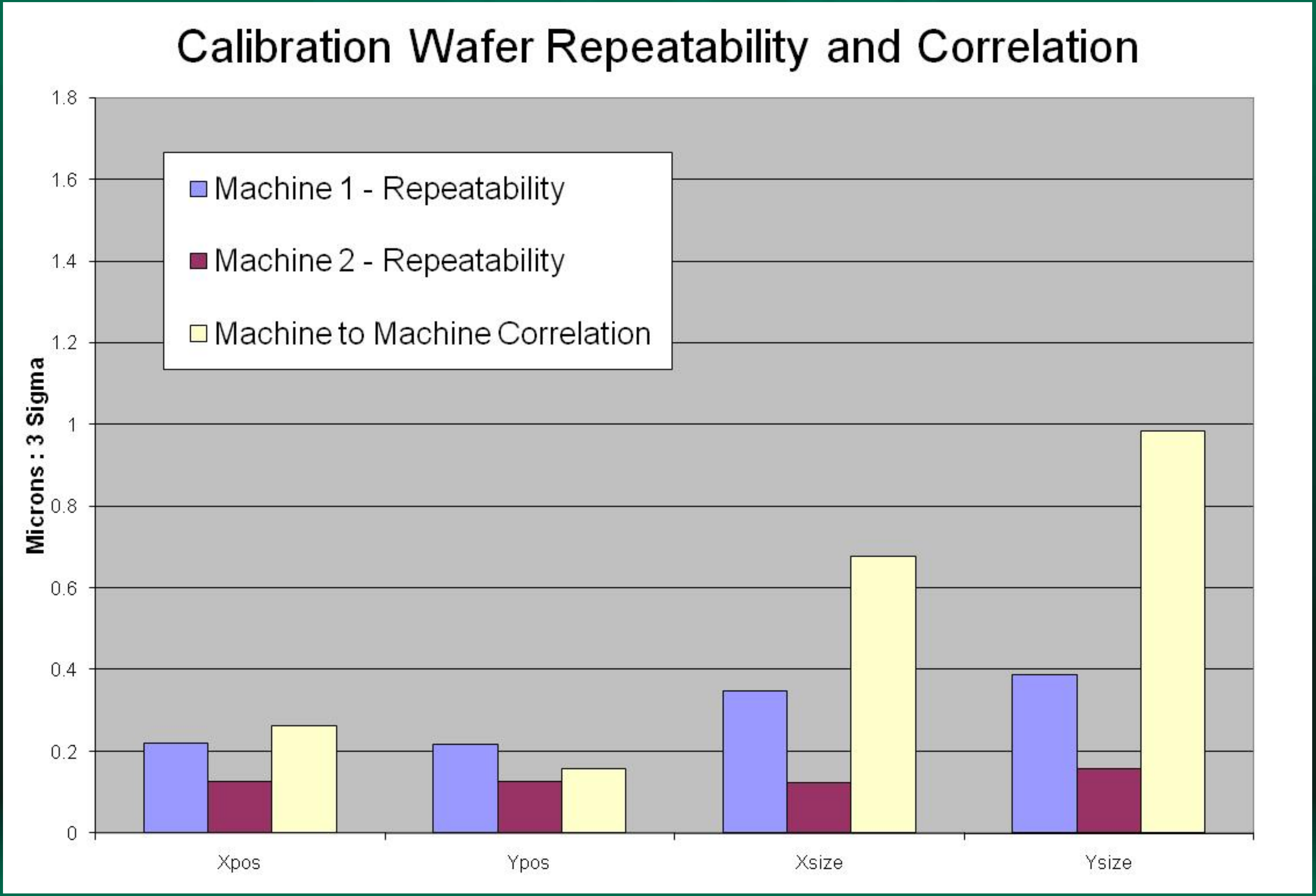
Case Study1 – WWX300 Tool to Tool Correlation

Calibration Wafer

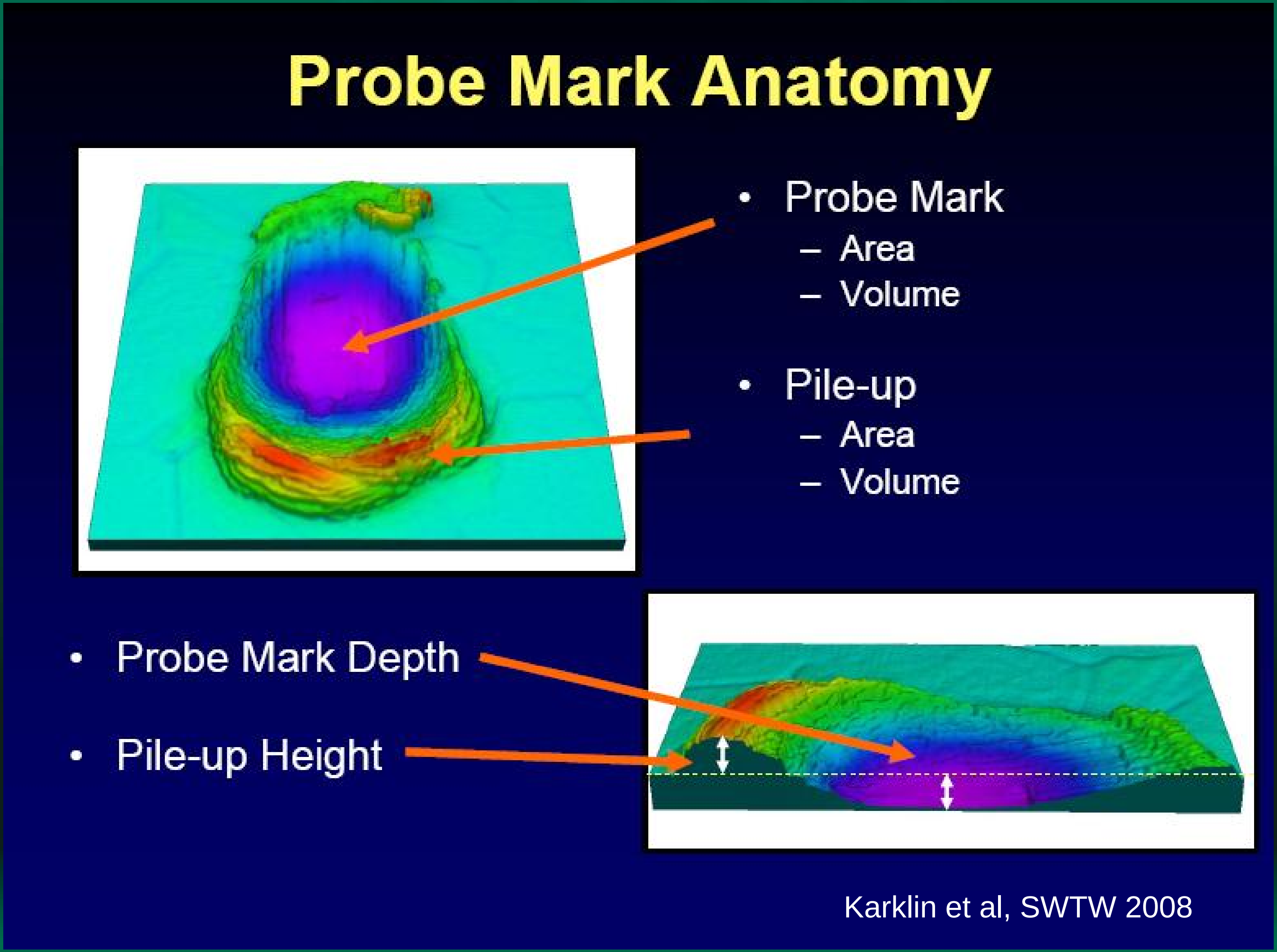


Case Study1 – WWX300 Tool to Tool Correlation

- Calibration wafer results



Case Study1 – WWX300 Tool to Tool Correlation



Probe Mark Anatomy

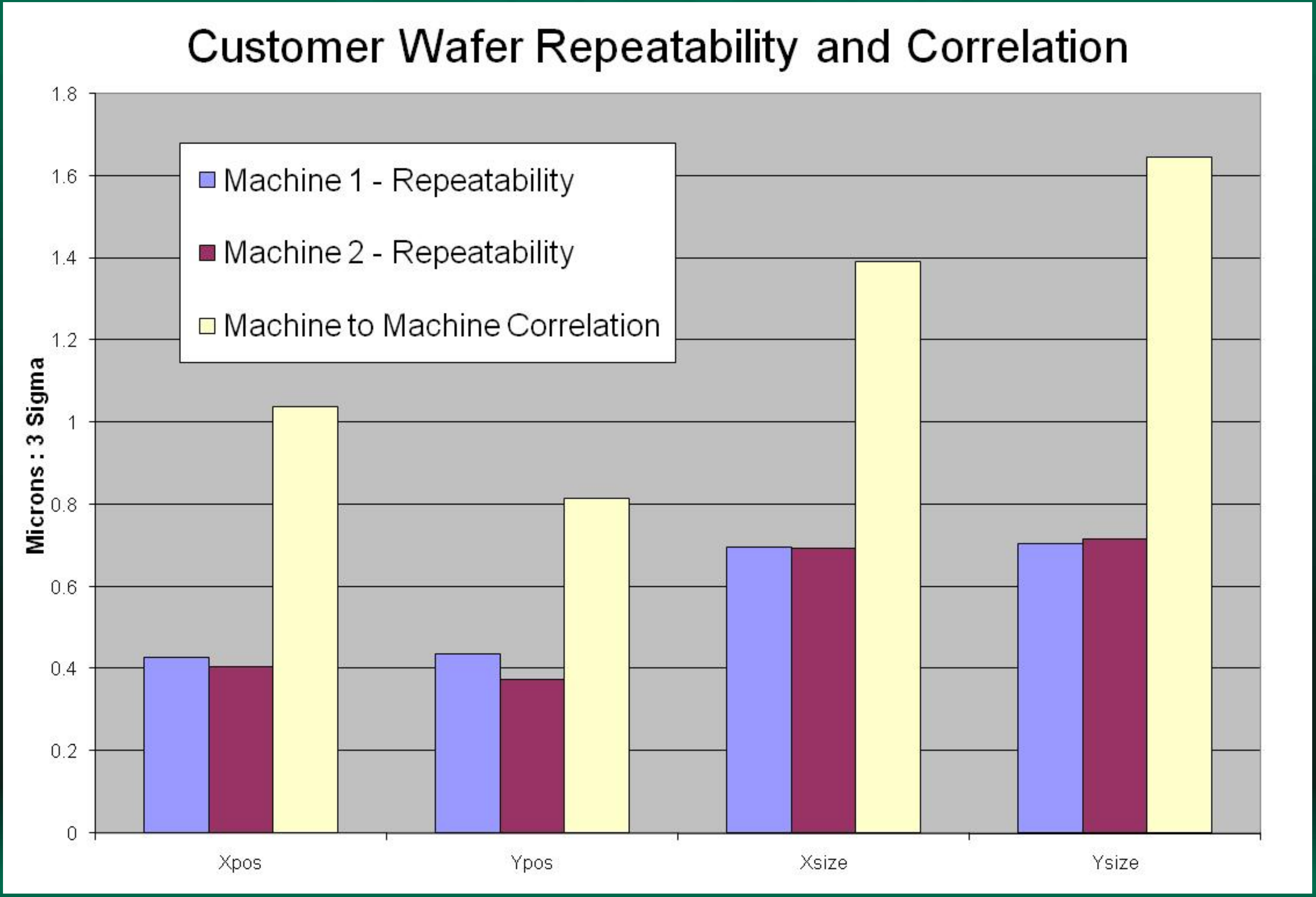
- Probe Mark
  - Area
  - Volume
- Pile-up
  - Area
  - Volume

- Probe Mark Depth
- Pile-up Height

Karklin et al, SWTW 2008

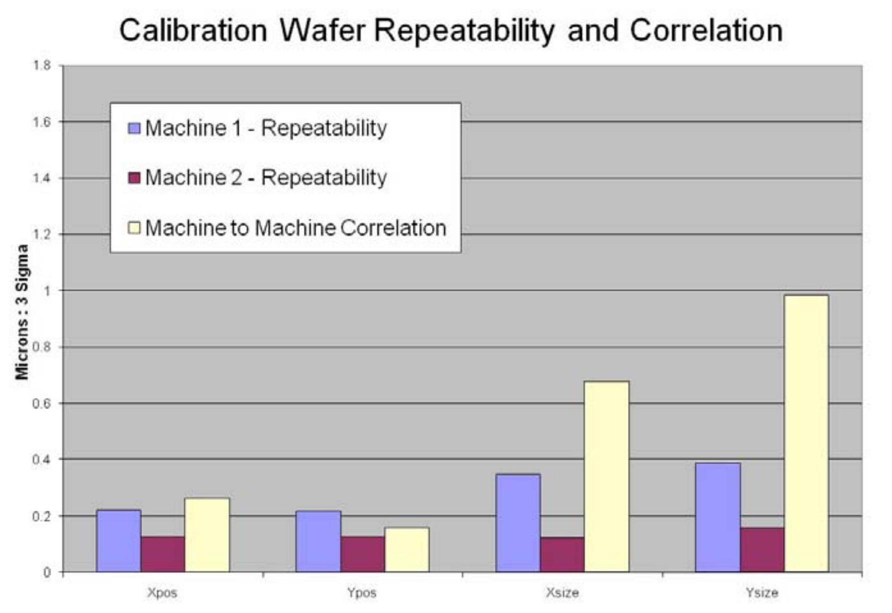
Case Study1 – WWX300 Tool to Tool Correlation

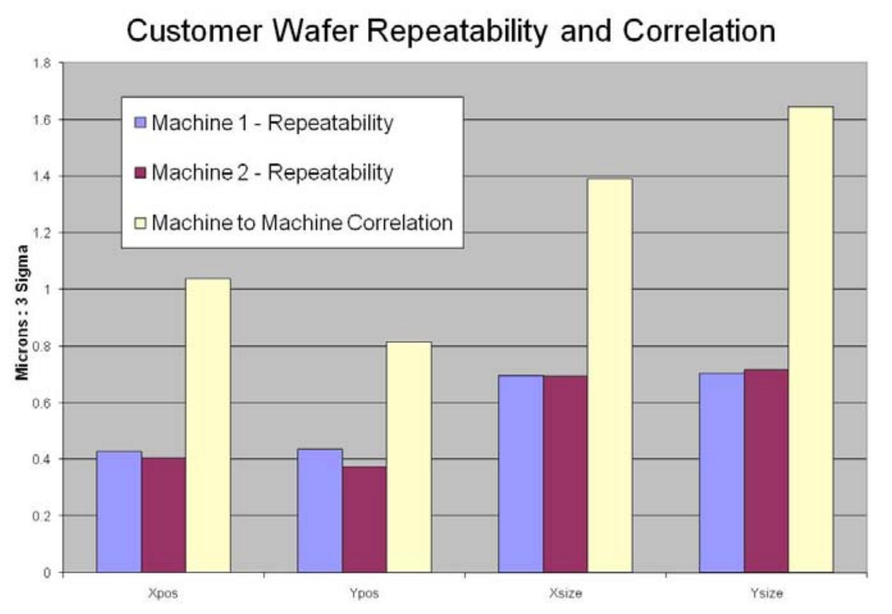
- Customer wafer results



Case Study1 – WWX300 Tool to Tool Correlation

- **Conclusions**
  - Repeatability and tool to tool correlation are best with calibration wafer
  - As scrub mark variability increases (customer wafer) GRR results are impacted





Assessing Metrology Tool Capability

Case Study #2

Case Study2 – ProbeWoRx300 Tool Capability

- Used a stable probe card technology
  - 10,000 probes, array size 100mm x 100mm
- Used 1-touch measurement system that minimizes touchdown effects on probe card
- DOE attempts to isolate probe card docking effects from metrology measurement capability
- Measured across two ProbeWoRx300 tools

- Step1: Gather undisturbed P&A data (repeatability)
- Step2: Gather disturbed P&A data removing card after each run
- Step3: Gather fully-disturbed data removing PCI after each run
- Step4: Analyze results to determine tool performance

Case Study2 – ProbeWoRx300 Tool Capability

- A more complete story…

$$GRR = \sqrt{\begin{array}{l}(GRR^2{}_{TOOL} + GRR^2{}_{PROBECARD}) + \\ (GRR^2{}_{PROBECARD\ /\ PCI\ :\ Tilt} + GRR^2{}_{PROBECARD\ /\ PCI\ :\ Intrinsic}) \\ + GRR^2{}_{PCI}\end{array}}$$

- There are more contributors to the error budget including:
  - Baseline tool measurement variability
  - Probe Card variability
  - PCI – Probe Card interaction variability
  - PCI variability

Case Study2 – ProbeWoRx300 Tool Capability

- Step1: Gather undisturbed P&A data (repeatability)
- Used 2 different tool modes (standard/precision) to evaluate test time vs. performance trade-offs

Mode	Planarity Repeatability @ 3 Sigma	X Position Repeatability @ 3 Sigma	Y Position Repeatability @ 3 Sigma	Test Time
Standard	1.15 um	0.30 um	0.34 um	16 min
Precision	0.63 um	0.23 um	0.24 um	31 min

Case Study2 – ProbeWoRx300 Tool Capability

- Step2: Gather disturbed P&A data removing card after each run
- Improvements when using Precision mode are not as significant as with the undisturbed data

Mode	Planarity Repeatability @ 3 Sigma	X Position Repeatability @ 3 Sigma	Y Position Repeatability @ 3 Sigma	Test Time
Standard	2.39 um	0.78 um	0.63 um	16 min
Precision	1.90 um	0.67 um	0.50 um	31 min

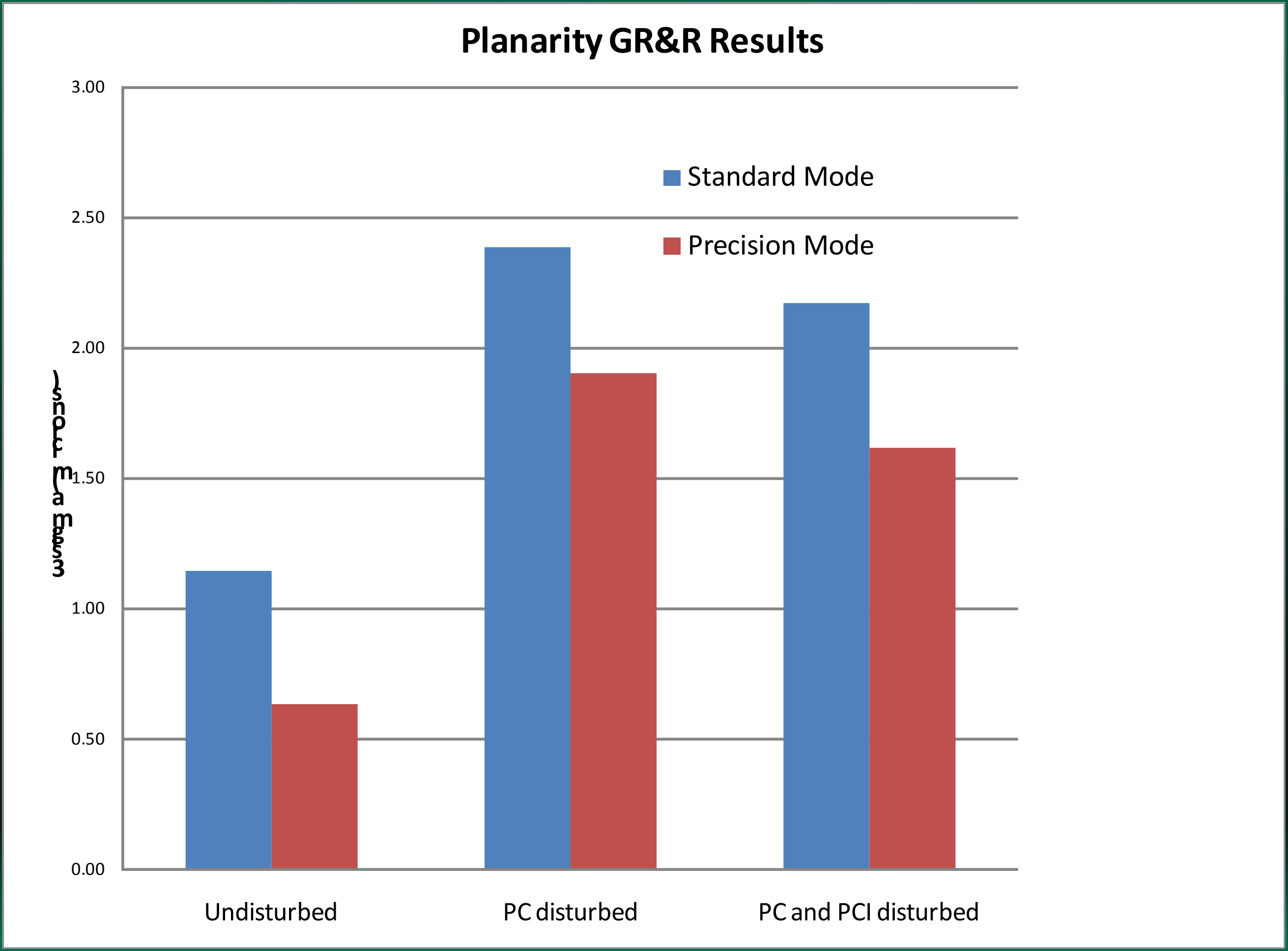
Case Study2 - ProbeWoRx300 Tool Capability

- Step3: Gather fully-disturbed data removing Probe Card and PCI after each run
- Results are similar to previous step with only probe card removed (removing PCI has minimal impact)

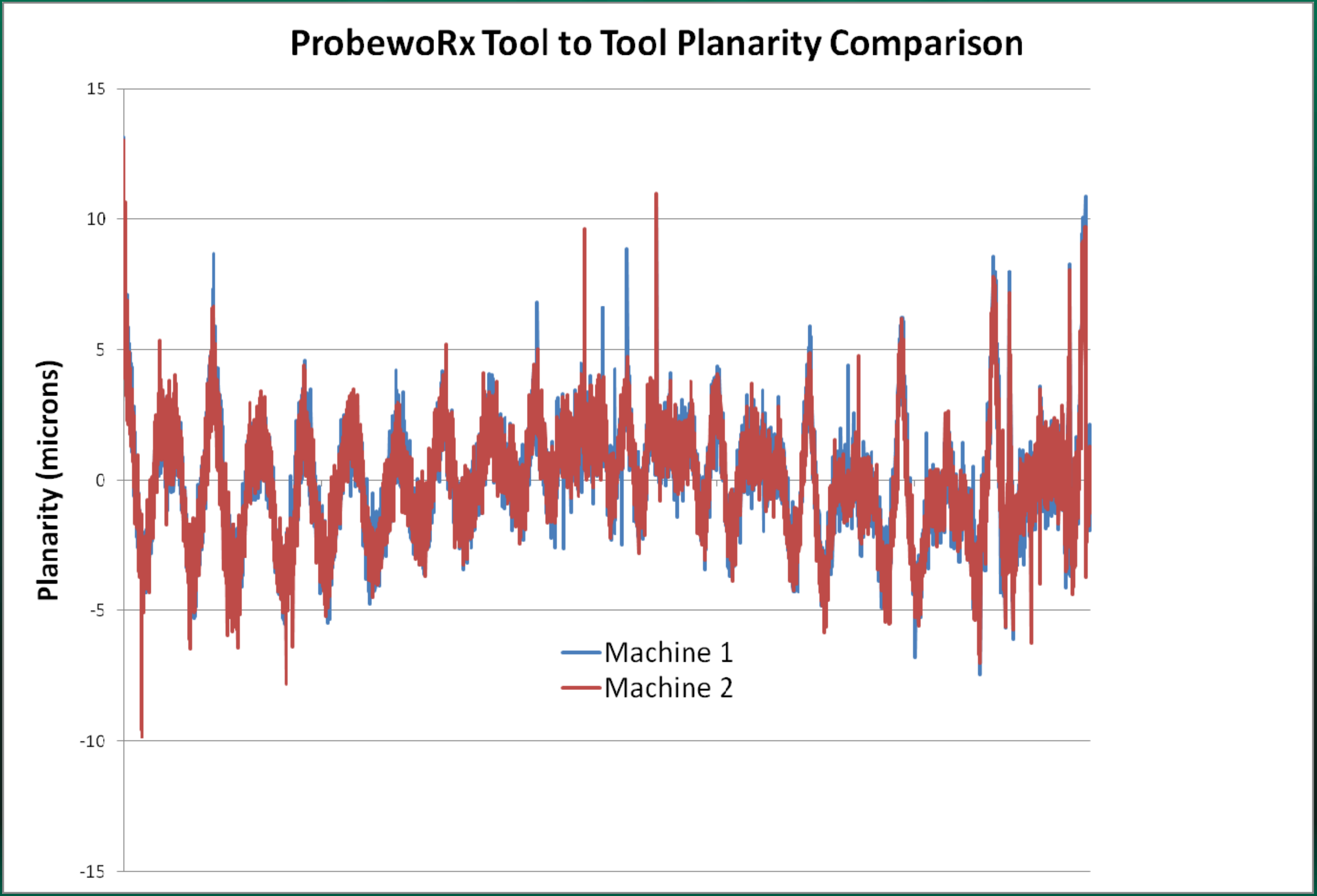
Mode	Planarity Repeatability @ 3 Sigma	X Position Repeatability @ 3 Sigma	Y Position Repeatability @ 3 Sigma	Test Time
Standard	2.17 um	0.71 um	0.55 um	16 min
Precision	1.62 um	0.67 um	0.46 um	31 min

Case Study2 - ProbeWoRx300 Tool Capability

- Results summary



Case Study2 – ProbeWoRx300 Tool Capability



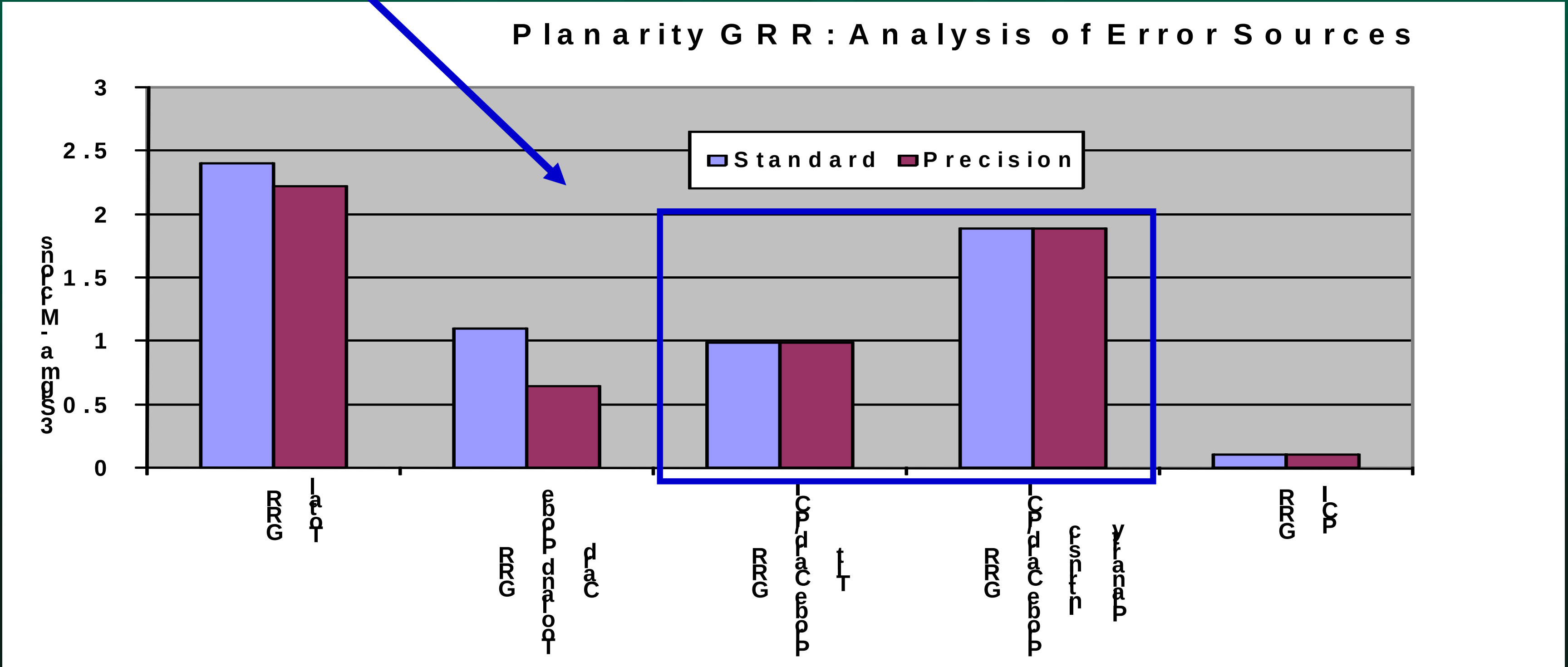
Case Study2 – ProbeWoRx300 Tool Capability

- Step4: Analyze results
- Try to determine contributions of the various error sources
  - Could not separate tool and probe card errors
  - Able to separate effect of PCI/Probe Card interaction (loading/unloading card) into tilt and intrinsic planarity components by analyzing with a best-fit plane
  - Effect of PCI load/unload is minimal

$$GRR = \sqrt{\begin{array}{l}\left(GRR^2{}_{TOOL} + GRR^2{}_{PROBECARD}\right) + \\ \left(GRR^2{}_{PROBECARD\,/\,PCI\ :\ Tilt} + GRR^2{}_{PROBECARD\,/\,PCI\ :\ Intrinsic}\right) \\ + GRR^2{}_{PCI}\end{array}}$$

Case Study2 - ProbeWoRx300 Tool Capability

- Conclusion: Probe Card disturbance (load/unload) is the largest error contributor to GRR results



$$GRR = \sqrt{\begin{aligned}&(GRR^2{}_{TOOL} + GRR^2{}_{PROBECARD}) + \\ &(GRR^2{}_{PCI\ /\ PROBECARD\ :\ Tilt} + GRR^2{}_{PCI\ /\ PROBECARD\ :\ Intrinsic}) \\ &+ GRR^2{}_{PCI}\end{aligned}}$$

Assessing Metrology Tool Capability

Case Study #3

Case Study3 - PWX Tool Qualification

- Real-world Customer Tool Qualification Case Study:
  - Undisturbed repeatability assessment
    - Sequence of P&A tests
    - **Results P&A results well within desired P/T spec**

  - Semi-disturbed repeatability assessment
    - Sequence of P&A and Contact Resistance (CRES) tests
    - Results: Planarity is outside desired P/T spec

  - What happened?

Case Study3 - PWX Tool Qualification

- Need DOE to isolate root cause of performance degradation
  - Determine major differences between semi-disturbed and undisturbed tests:
    1. Movement of MB/Probe card assembly (dock/undock to change measurement surfaces
    2. Change of measurement surfaces (fiducial plate and CRES plate)
    3. Probe contact with CRES plate
    4. CRES measurement

Case Study3 – PWX Tool Qualification

- DOE to understand semi-disturbed results
  - Move MB/Probe card assembly between each test
    - Dock/undock PCI/Probe assembly
    - Measure P&A
    - Repeat “n” times
  - Result: P&A results well with desired spec

  - Move MB/Probe card assembly and fiducial plate between each test
    - Undock PCI/Probe assembly
    - Remove and replace fiducial plate
    - Measure P&A
    - Repeat
  - Result: P&A results well with desired spec

  - Repeat original sequence of P & A test and CRES tests
    - Results: Planarity is outside desired spec

  - Why?
    - Poor results appear to be associated with CRES measurement

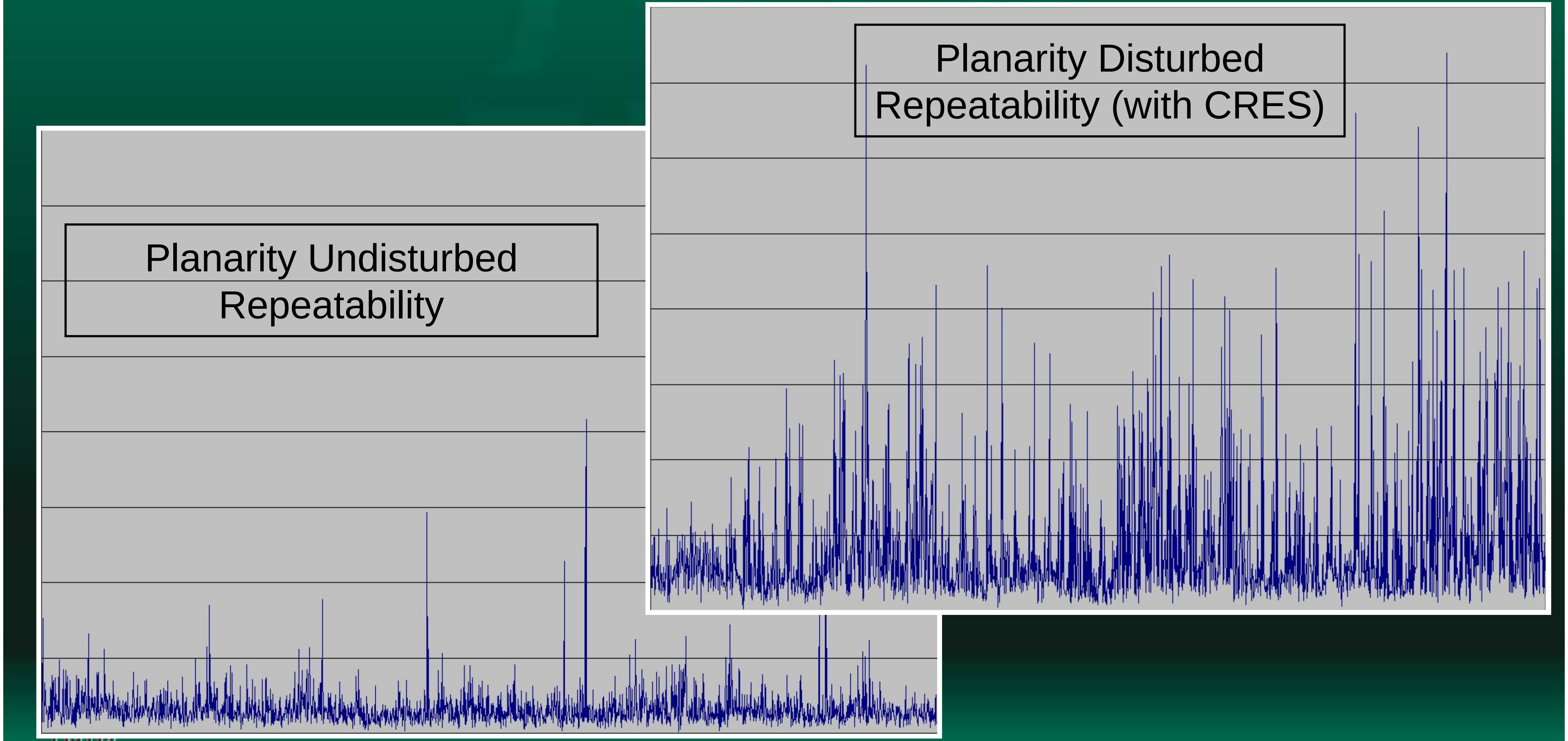
Case Study3 - PWX Tool Qualification

- DOE to understand semi-disturbed results
  - Poor results have been isolated to probe contact with CRES plate and/or CRES measurement
  - Need to analyze data and look for trends
  - Is the error source the tool or the probe card?

$$GRR_{Measured} = \sqrt{\overset{?}{GRR^{2}_{TOOL}} + \overset{?}{GRR^{2}_{PROBECARD}} + GRR^{2}_{OPERATOR}}$$

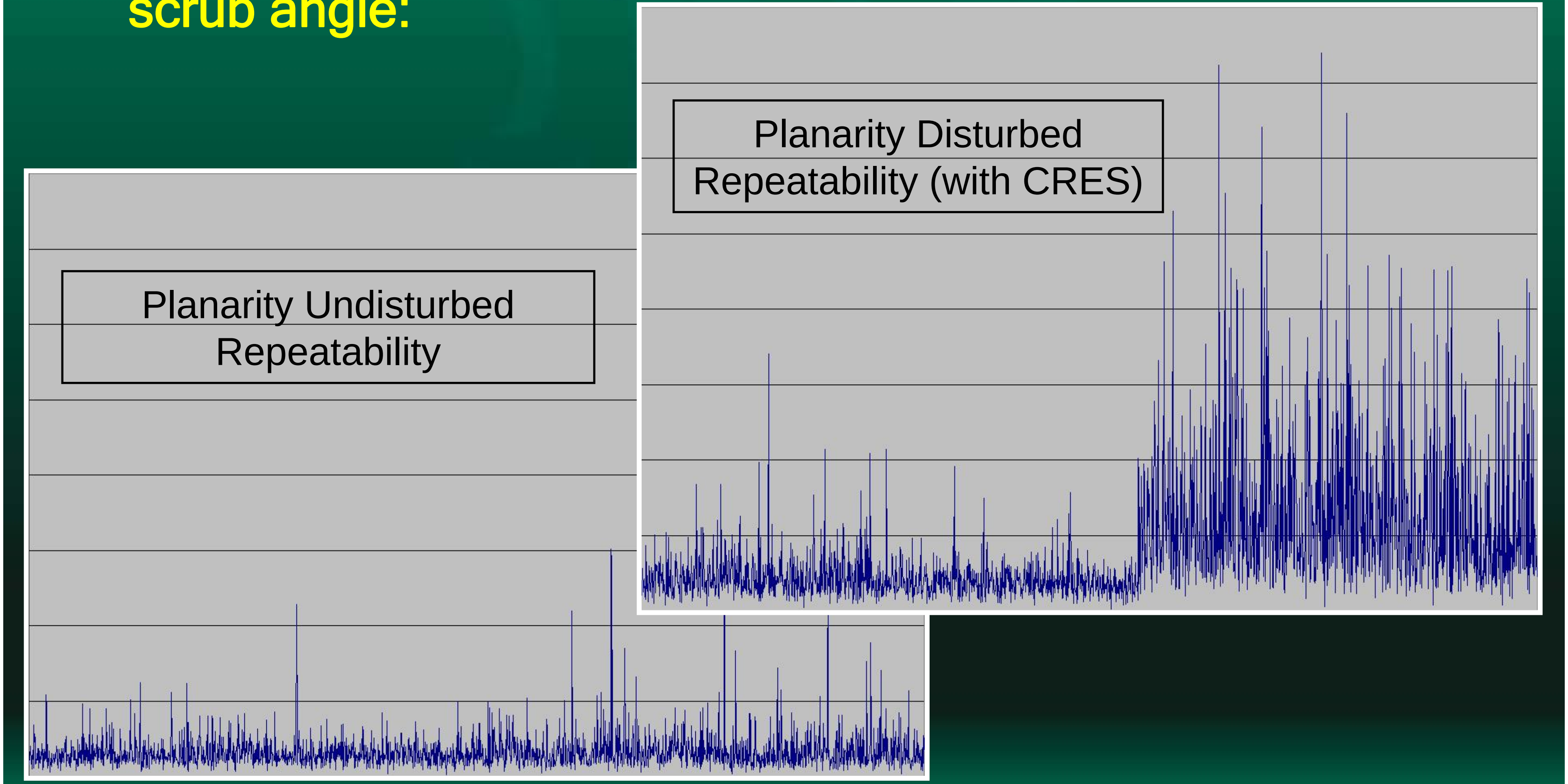
Case Study3 – PWX Tool Qualification

- Comparison of undisturbed/disturbed results shows no signature beyond increased noise (graphs at same scale)



Case Study3 – PWX Tool Qualification

- Pattern emerges from planarity repeatability sorted by scrub angle:



Case Study3 - PWX Tool Qualification

- What happened?
  - Probe tips picked up material from interaction with CRES plate
  - This was preferential based on scrub direction and left a clear signature
  - Probe tip contamination confirmed with optical inspection
- Conclusion
  - Metrology tool was reporting changes in tip planarity due to real changes to probe tip (observer effect rears its ugly head)

$$GRR_{Measured} = \sqrt{GRR^2_{TOOL} + GRR^2_{PROBECARD} + GRR^2_{OPERATOR}}$$

Probe Card was changing

- End result
  - Customer changed to a different material CRES plate that did not interact with probe tips and tool was qualified

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