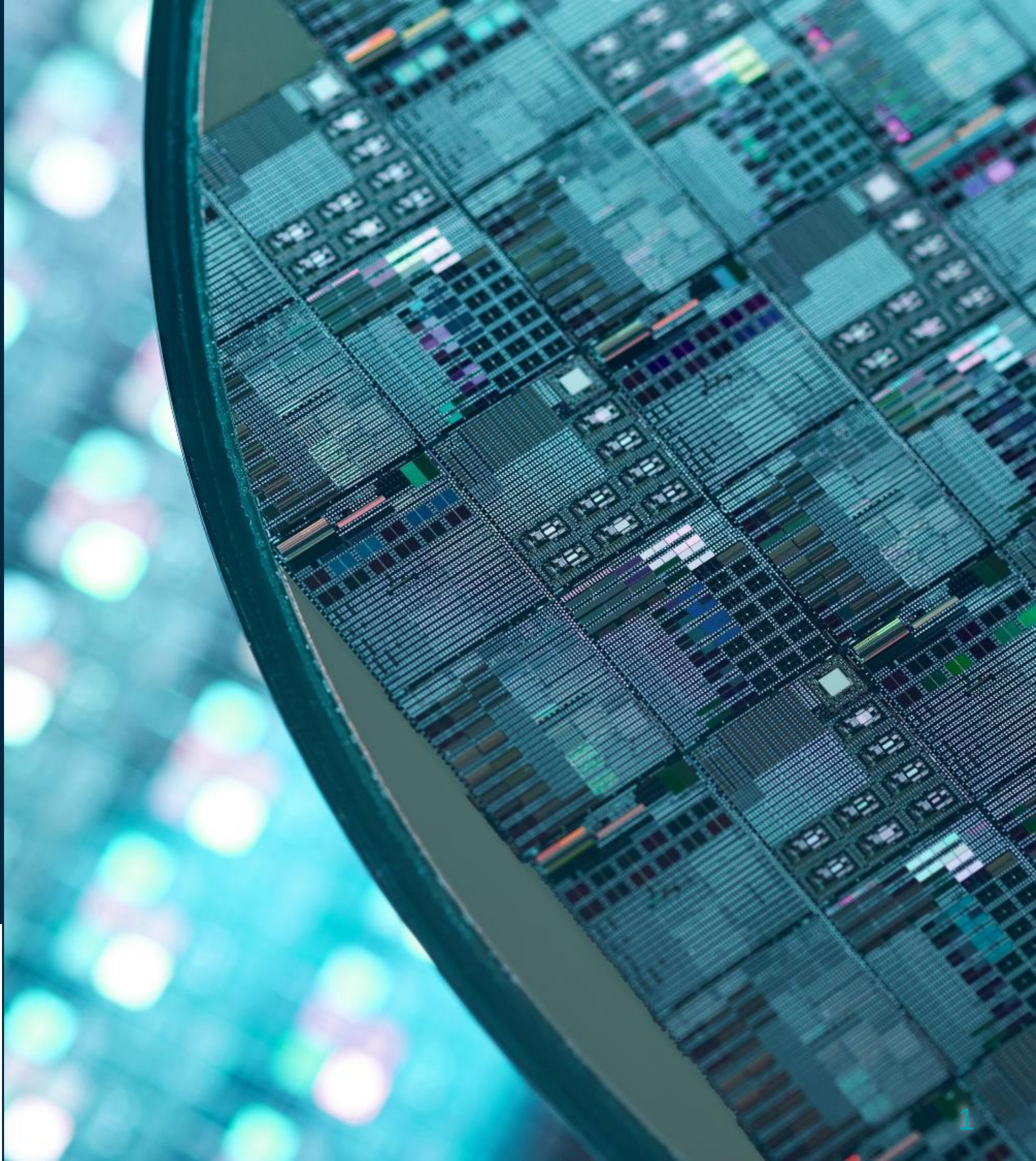
FormFactor™

Maximising return on investment for on-wafer over-temperature millimetre-wave characterisation

June 2023

Gavin Fisher

IMS
2023 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM
11–16 JUNE
CONVENTION CENTER
San Diego, California
The Coolest Ideas Under the Sun
SAN DIEGO 2023
IEEE
MTT-S IEEE MICROWAVE THEORY & TECHNOLOGY SOCIETY



Abstract

- Speaker: Gavin Fisher
- Speaker organization: FormFactor
- Location: Hall F Booth 843 The talk will show the best methods for setting up, calibrating, and evaluating measurement performance for measurements spanning WR15 (75 GHz) to WR1 (1100 GHz) over a broad (-40 to 125c) temperature range. This includes approaches to conveniently swap waveguide bands.
- We will discuss test executive approaches for multi-wafer over-temperature testing, both using commercial test executives and programming examples using FormFactor WinCalXE and Velox software to automate on-wafer data measurement and analysis
- Single-sweep measurements from 900 Hz to 220 GHz will be highlighted along with measurements at elevated temperatures.
- Examples in WinCal itself and supporting video will be provided

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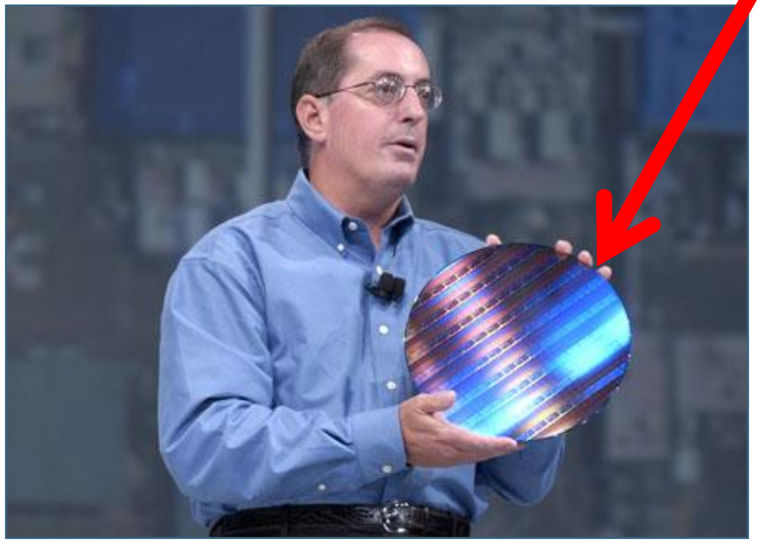
Acknowledgements :-

- DOMINION MICROPROBE
- VIRGINIA DIODES
- KEYSIGHT TECHNOLOGIES

Probing background

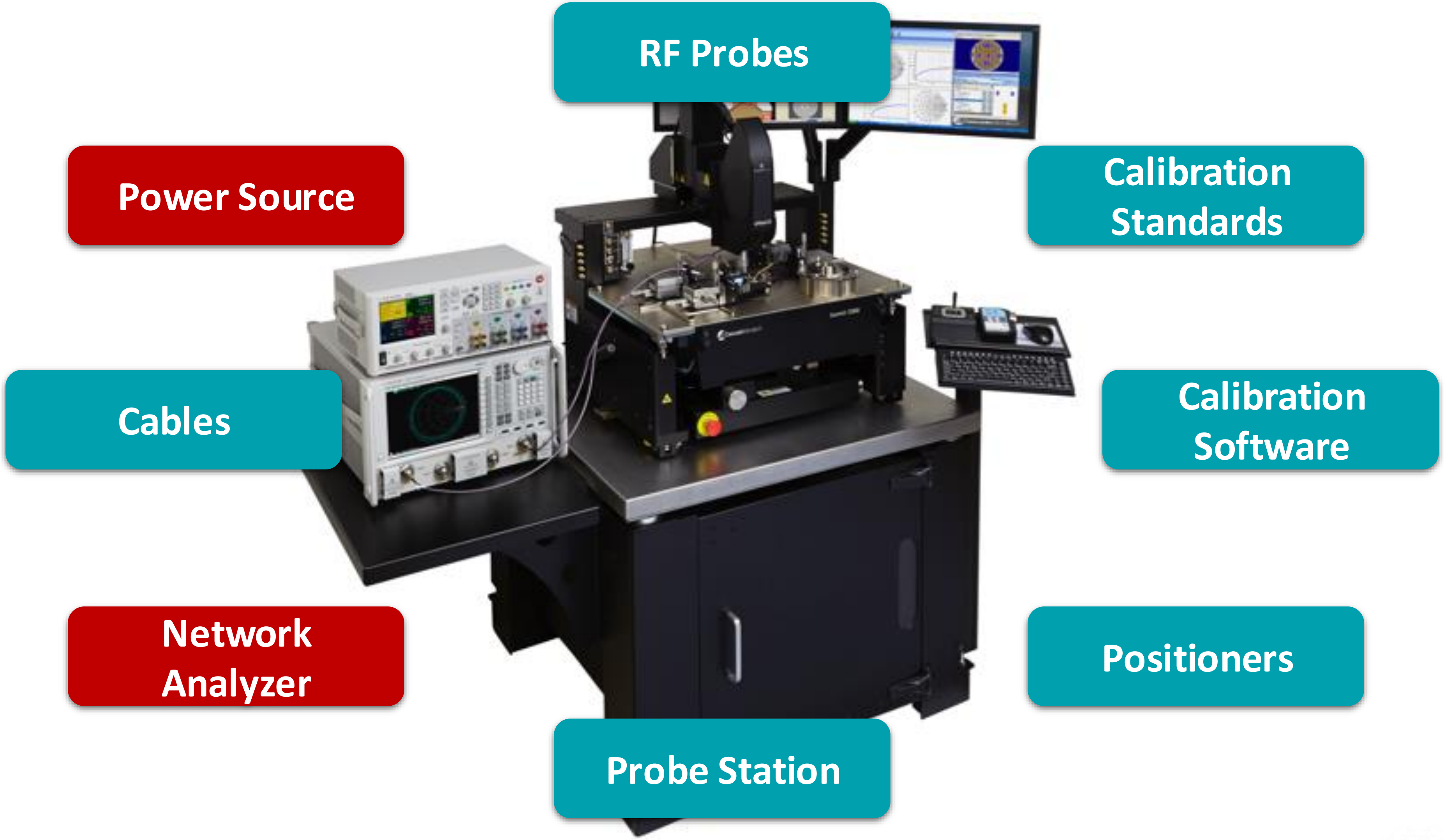
The Challenge We Address

- Simply put - We connect this to this



Our mission: to make our part of the system invisible in the DUT measurement results

Typical On-wafer RF Measurement Solution



Probe Station Essentials

Stage

Chuck

Thermal Controller

Software

Microscope

Chamber

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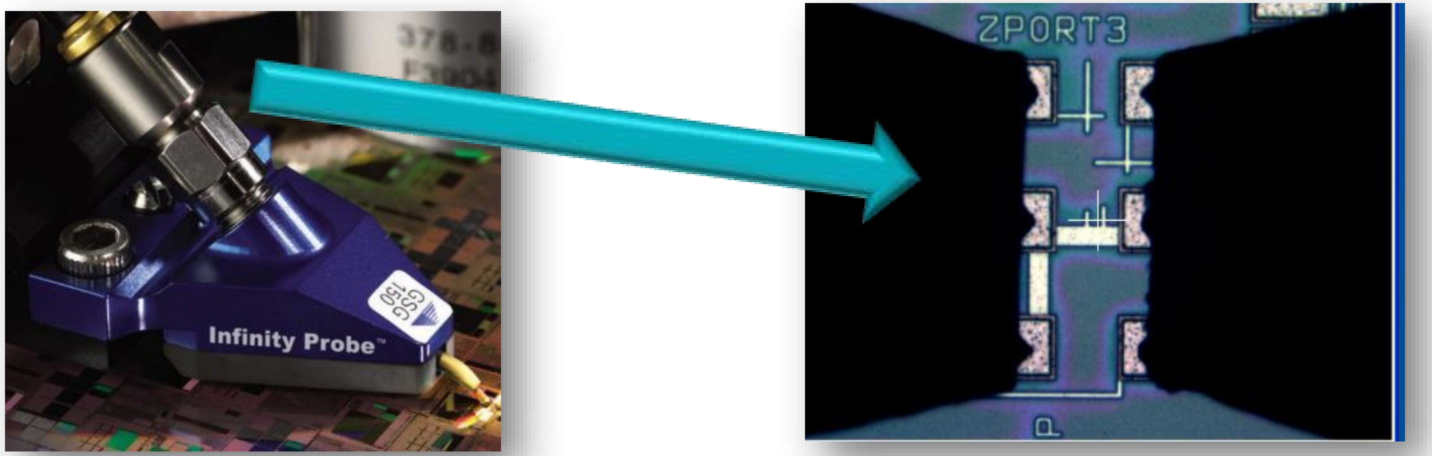
Probe station essentials - Microchamber

- Rollout chuck provides very easy access to wafer
- Auxiliary chucks allow 2 or more substrates additional to wafer
- Substrates from a few mm up to full wager can be tested on the same machine
- Velox software allows independent X,Y,Z, Theta for all 3 chucks for fast, effective and accurate wafer probing
- Thermal capability can be added at any time via upgrade to either -65 to 300 or Ambient to 300 solutions

What is an RF probe?

- The probe transitions the signal from coaxial cable (or rectangular waveguide) to a co-planar waveguide
  - The co-planar probe tips contact the pads of the device
- The transition is 50 ohms
  - Offers good match and insertion loss
- A ground (preferably symmetrical) is located close to the signal contact



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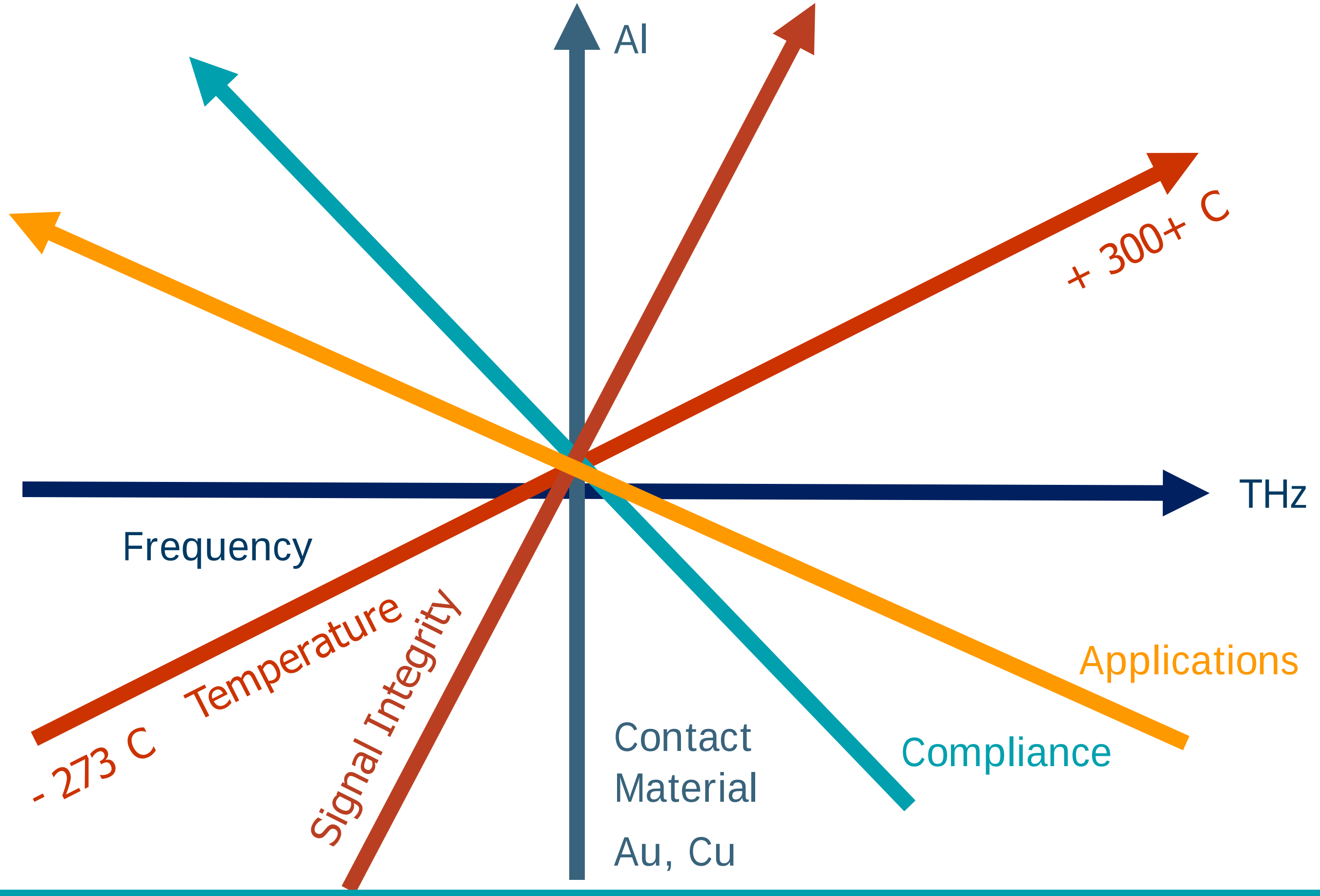
RF Probing



…is a multidimensional challenge!

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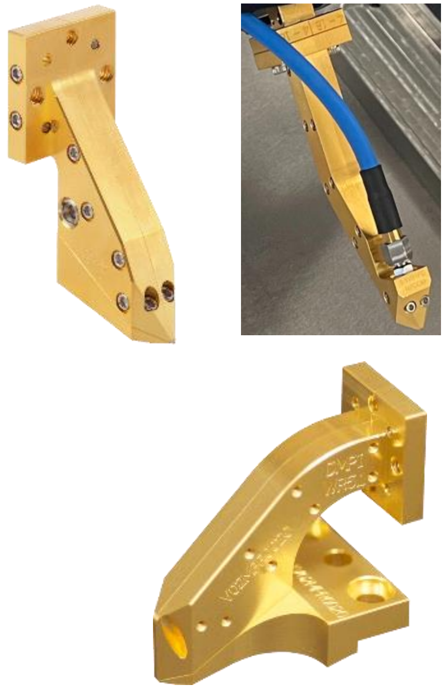
RF Probe Families

T-Wave Probe



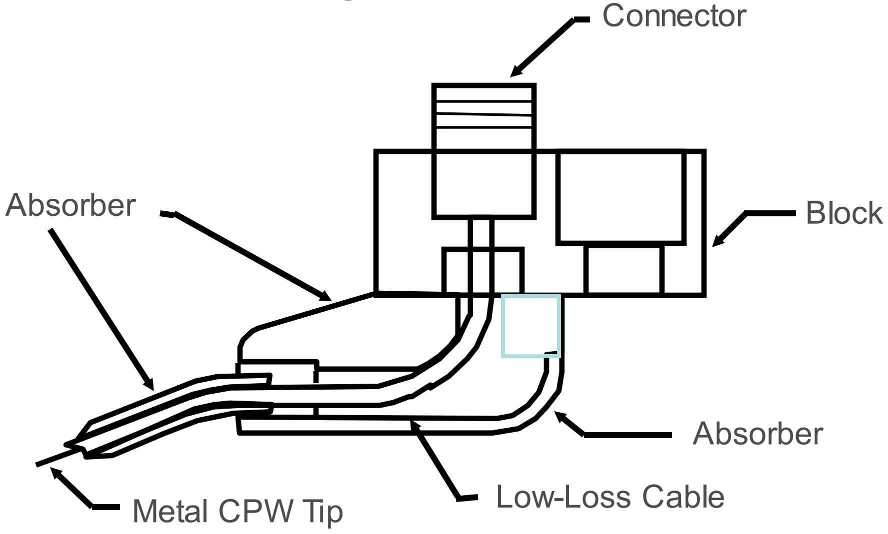
Infinity Probe ®

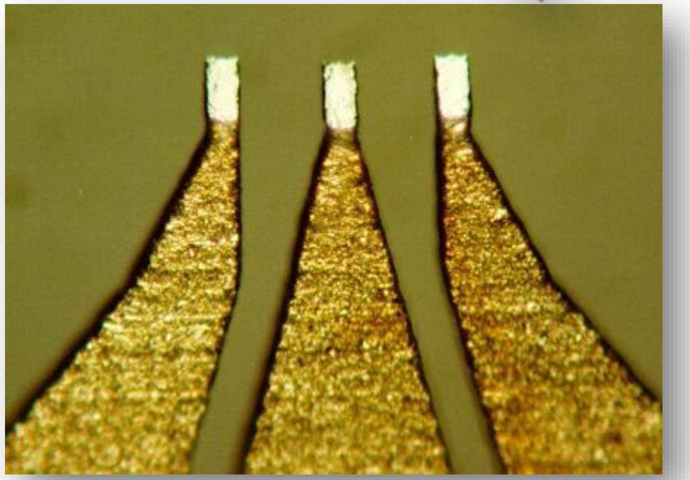
ACP Probe

|Z| Probe®

Air Coplanar Probe (ACP)

- Air dielectric between tips
- Ideal for High Power - 15 W CW at 10 GHz
- 5 A DC current
- Measurements from -65ºC to 200ºC
- 25 µm compliance
- Low pad damage





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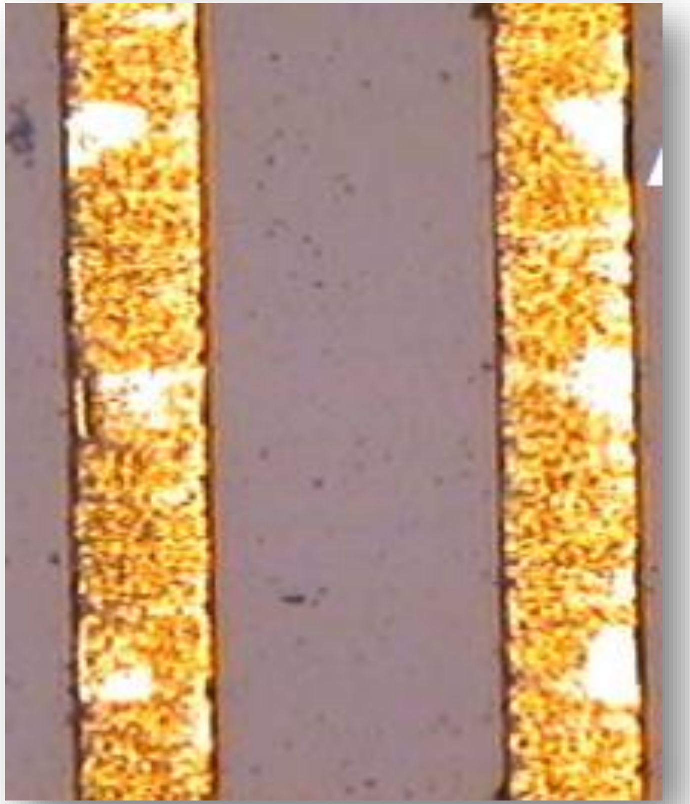
ACP Probe – Minimise pad damage on Au

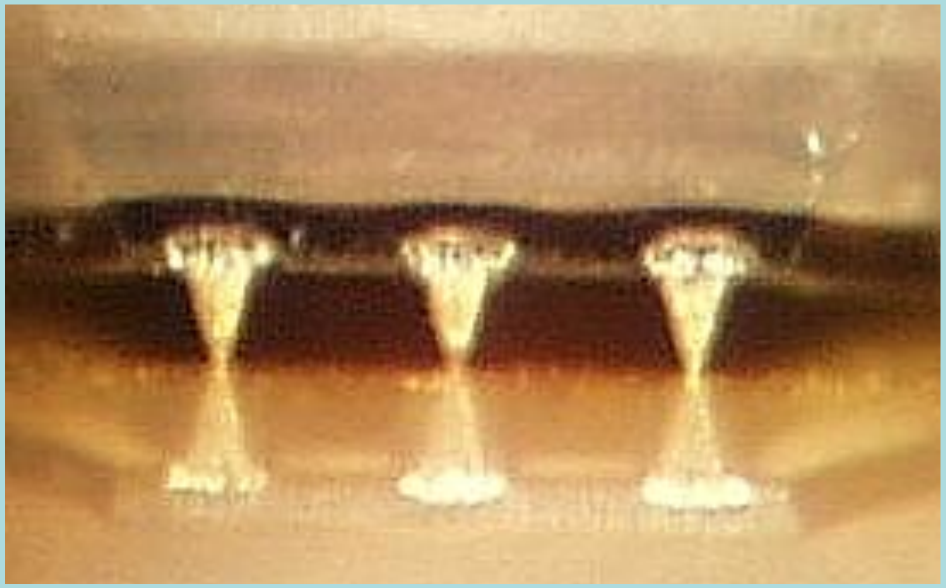
Formfactor ACP probe marks

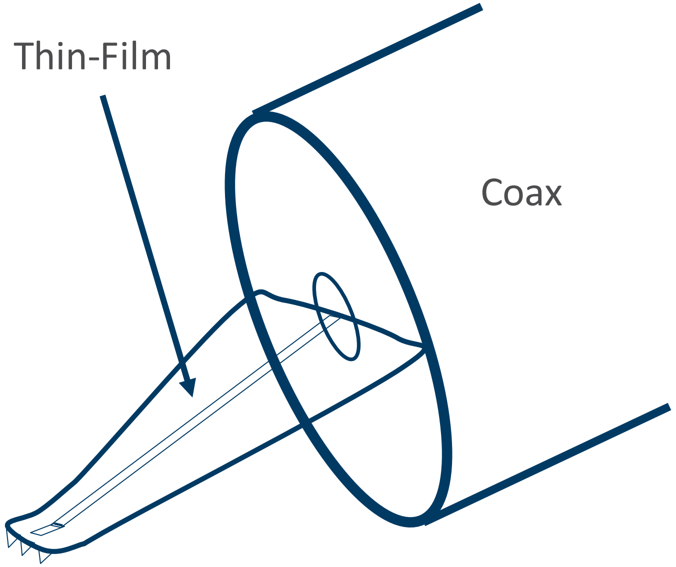


Other manufacturer probe marks

Infinity Probe®

- Best Electrical Performing Probe
- Ultra Low Contact Resistance (30 mΩ)
- Small Contact Area (12 μm)
- Improved Unsymmetrical Ground Performance





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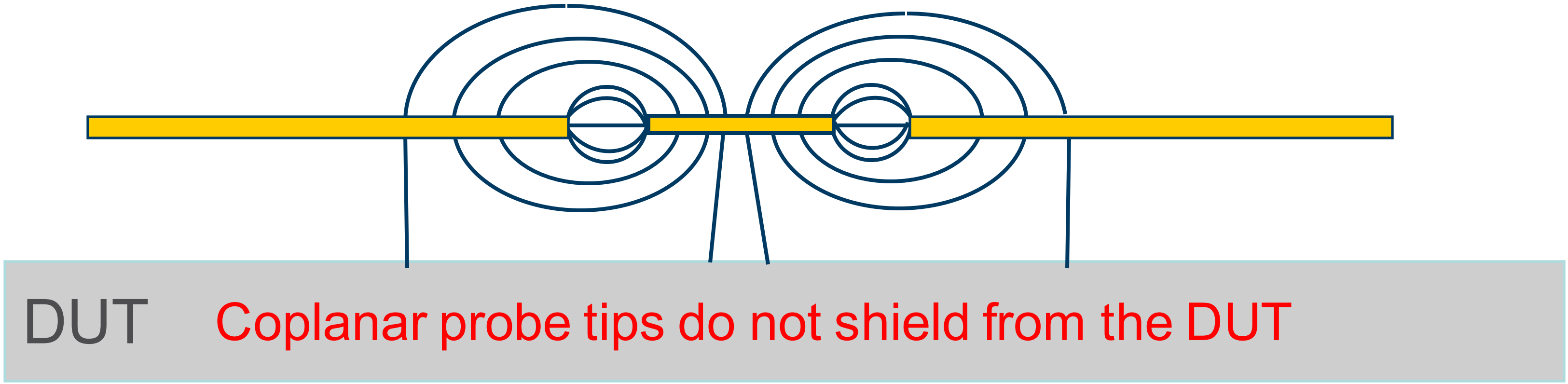
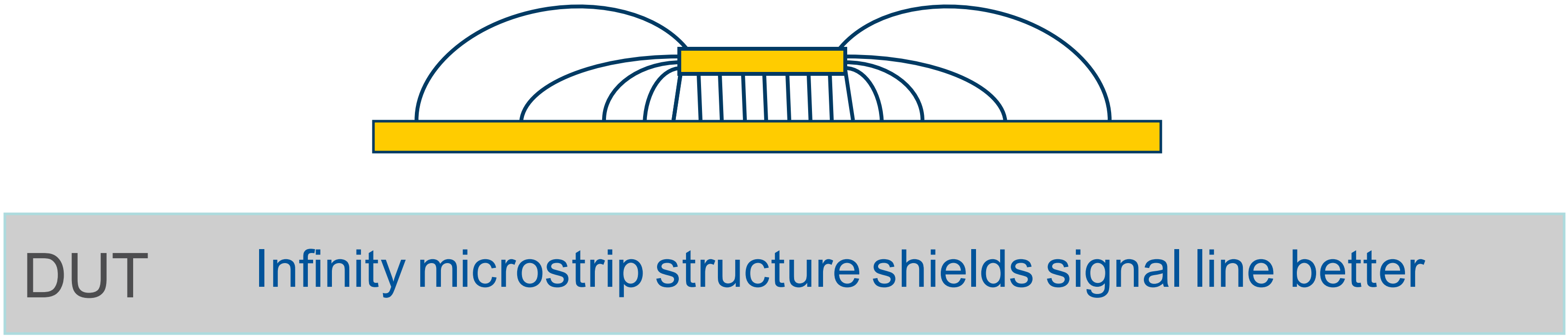
Infinity Adjacent structure Shielding

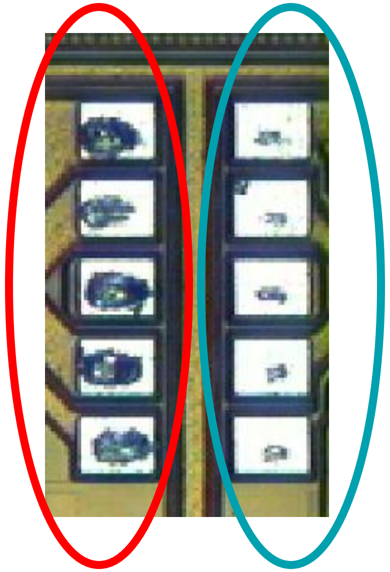




- Fringing fields are confined in the Infinity microstrip probe tip

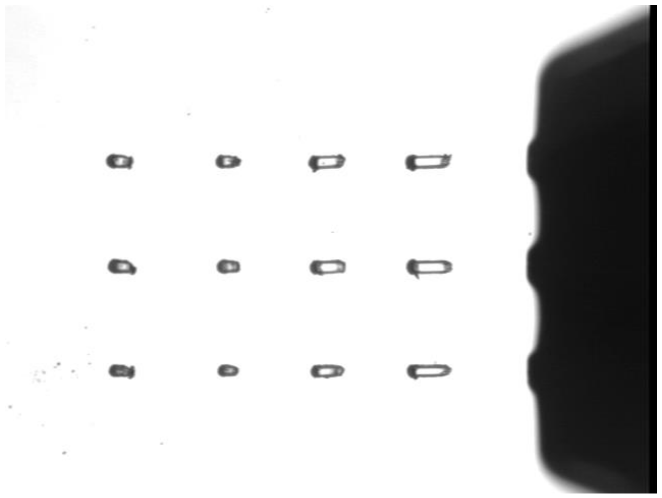
Infinity probes Small Pads

- Contact area of probe tip 12 µm x 12 µm
- Typical scrub is 25 µm
- Reduced pad damage
- Pad geometries can be shrunk to 25 x 35 µm
- Pad parasitic effects can be minimized



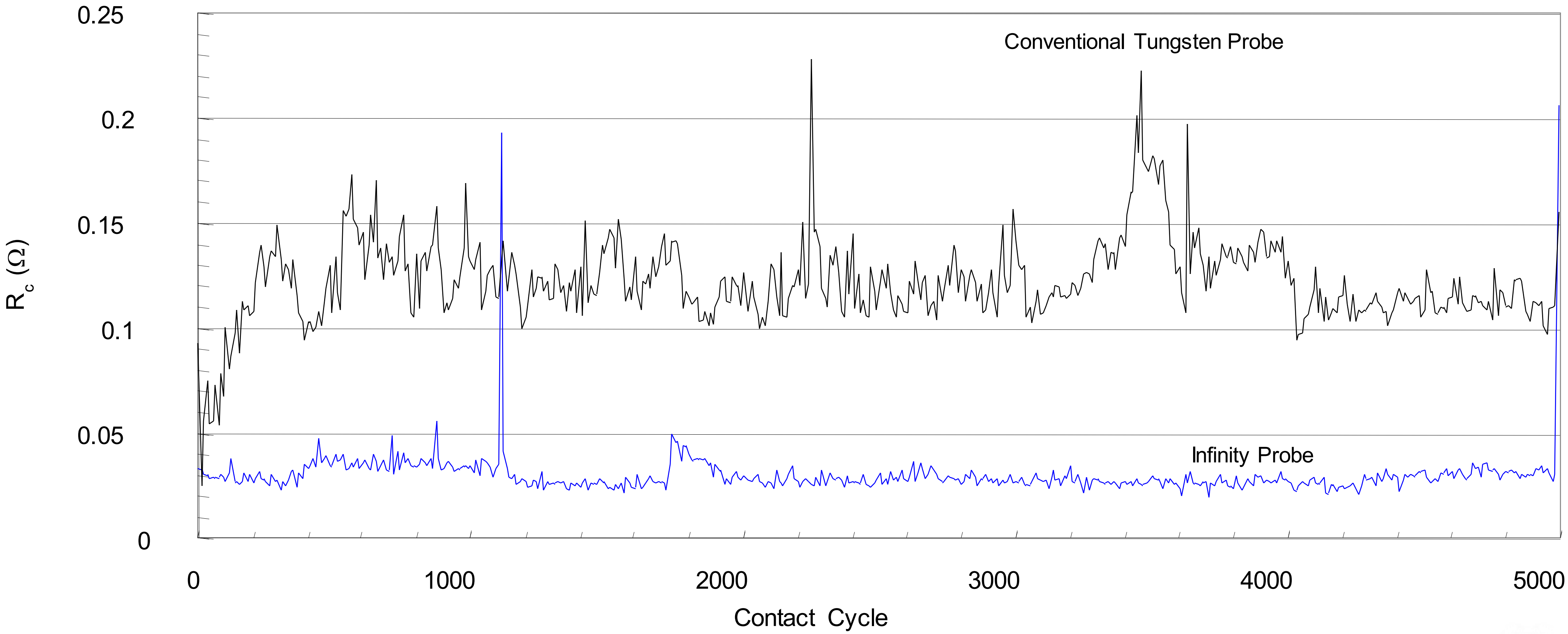
Conventional probes

Infinity probes

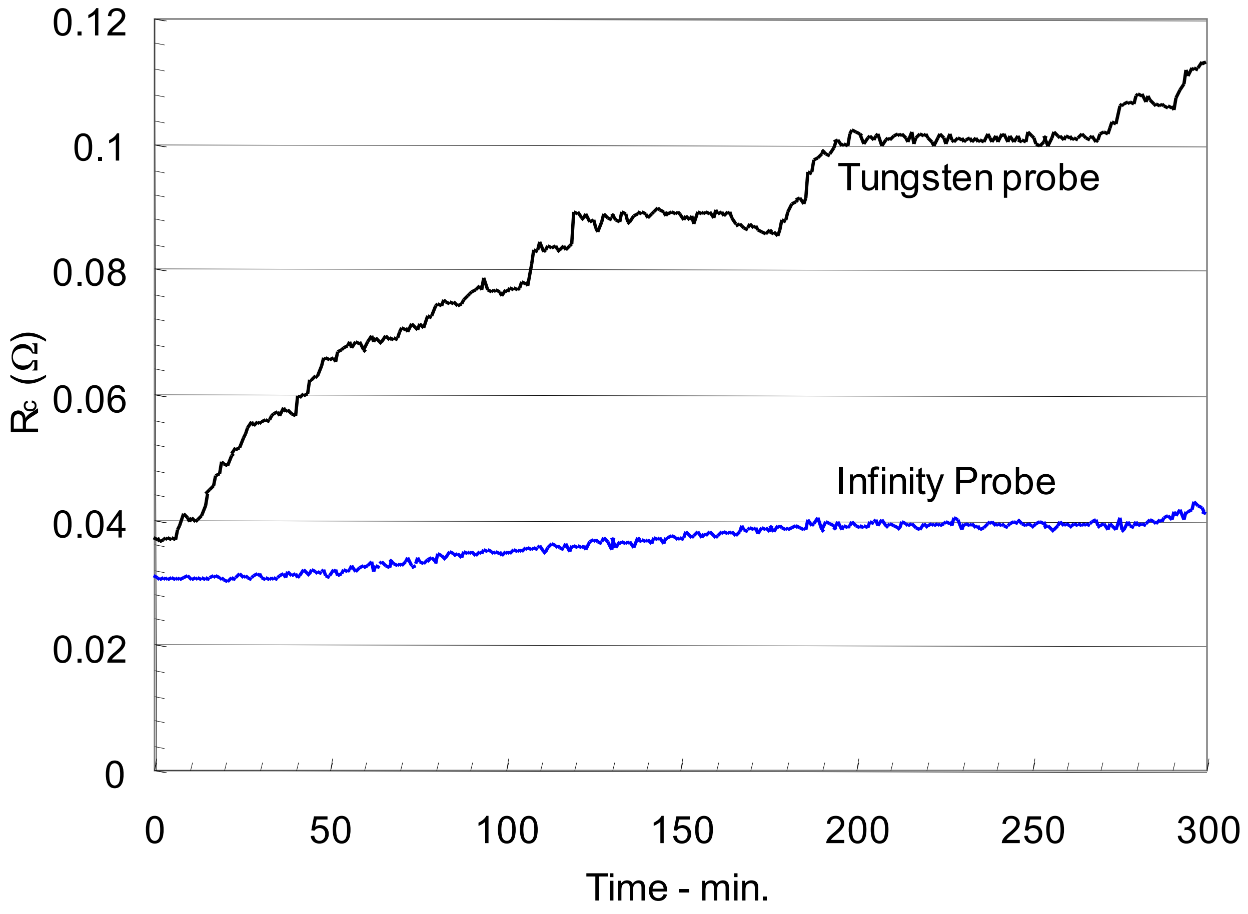


Infinity Contact resistance Repeatability

Contact resistance on un-patterned aluminum averages about 30 mΩ over 5000 contact cycles at ambient



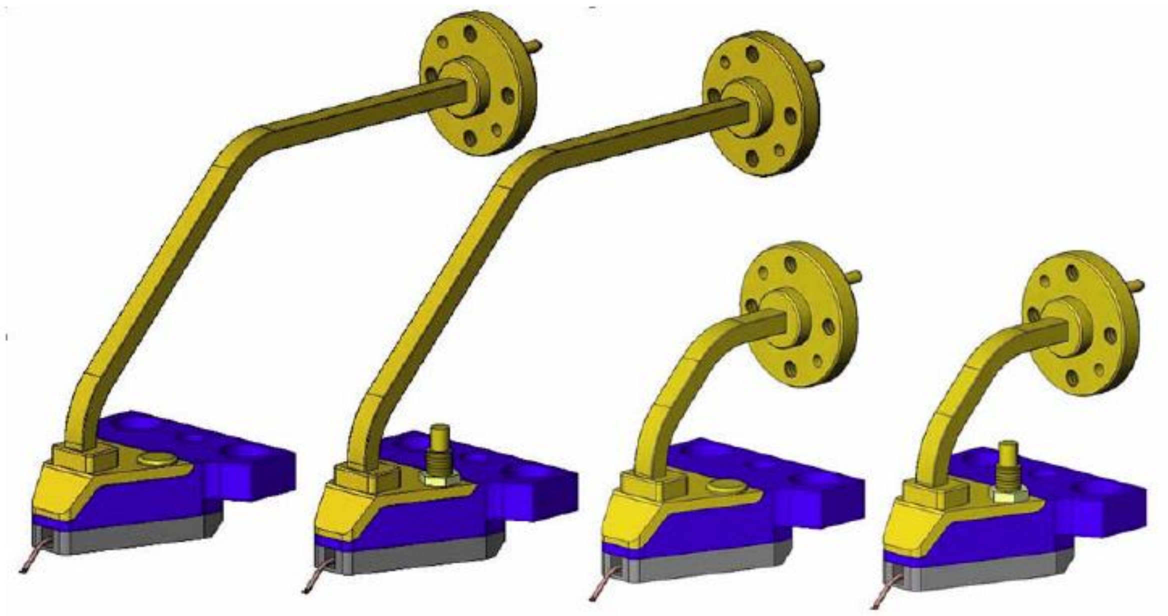
Infinity probe - Contact resistance over time



- Contact made on aluminum bare wafer
- Only 10 mΩ variation was observed during a 5-hour continuous contact cycle @ 100 mA

Infinity Waveguide Probes

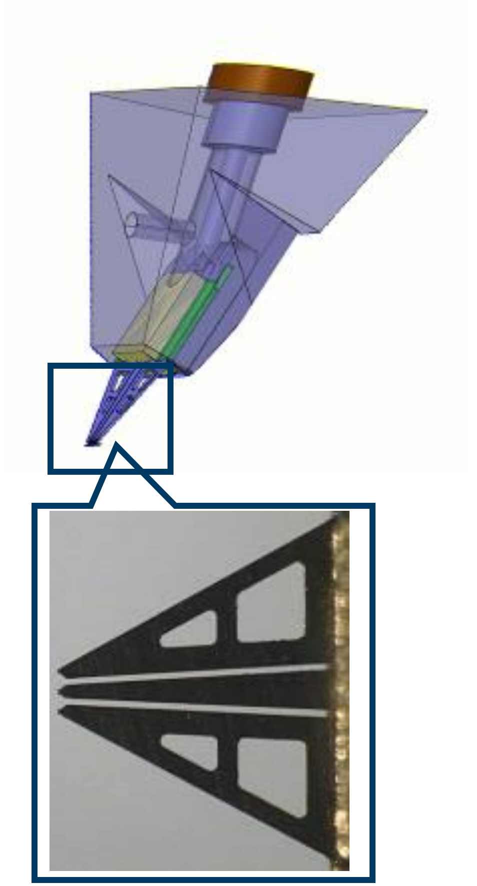
- i75 WR-15 (50-75 GHz)
- i90 WR-12 (60-90 GHz)
- i110 WR-10 (75-110 GHz)
- i140 WR-8 (90-140 GHz)
- i170 WR-6 (110-170 GHz)
- i220 WR-5 (140-220 GHz)
- i325 WR-3 (220-325 GHz)



- 0.5 Amp Bias Tee Standard
  - Option w/o Bias Tee available

IZI Probe Technology

- Long CPW
  - Long lifetime
  - High power
  - Compliance
- No micro-coax cable
  - Direct control of the contact force
  - Shielded transmission to CPW
  - Thermal stability and higher temperature capability



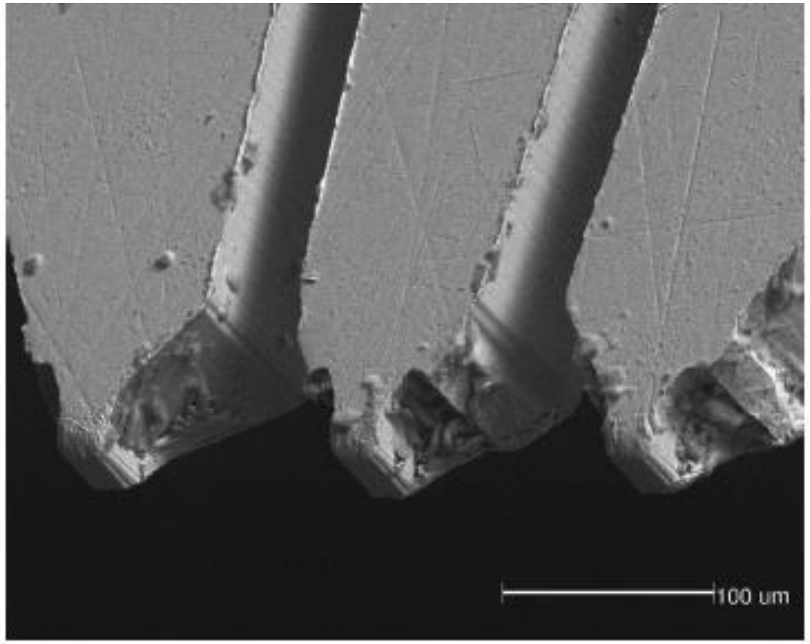
MEMS CPW

|Z| Probe Technology Value

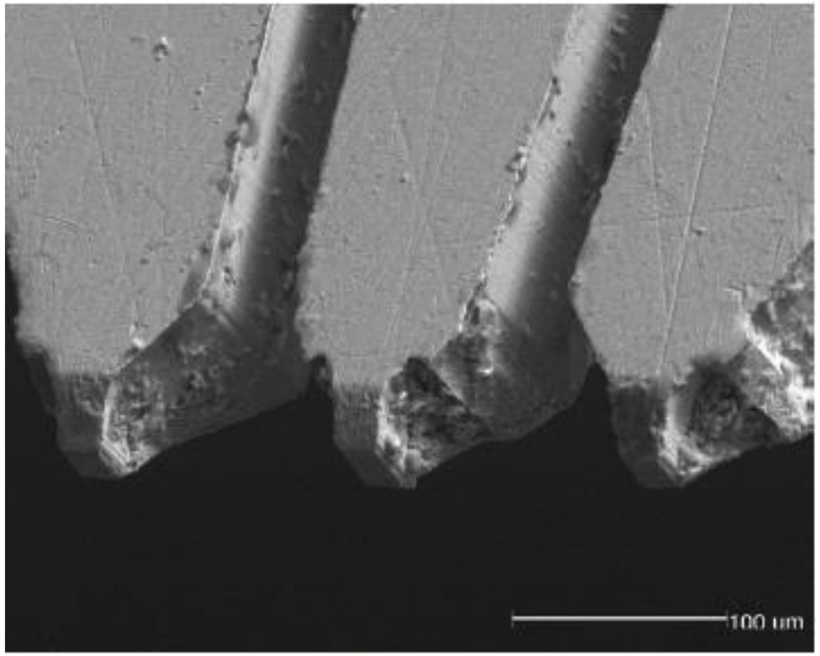
- Longest lifetime
  - 1+ million touchdowns (on AL!)
- The best contact repeatability and compliance
- The best for automated testing
- Widest temperature and RF power range
- Very good electrical characteristics

|Z| Probe Lifetime

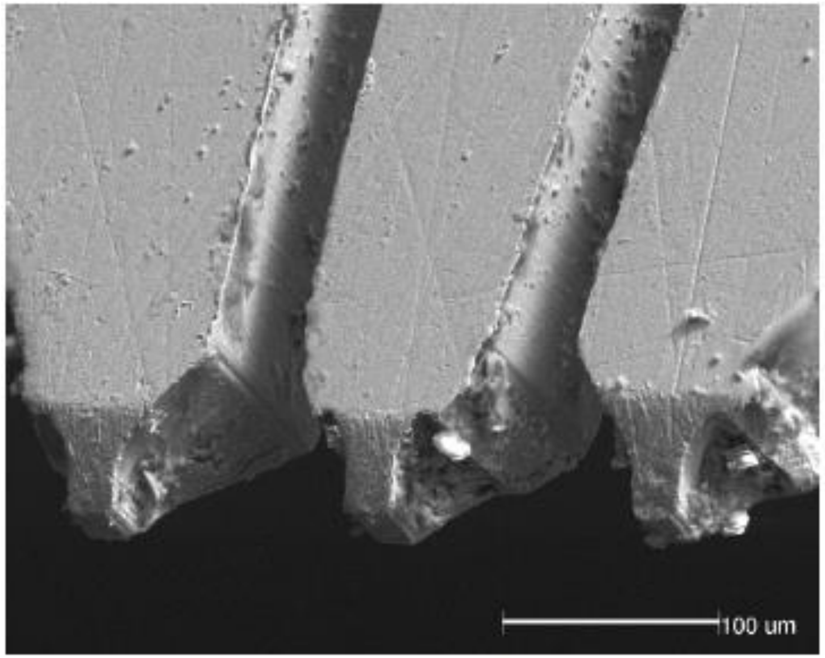
- Probe still functional after 3 Million touchdowns with 1Mx



New |Z| Probe (upside-down).



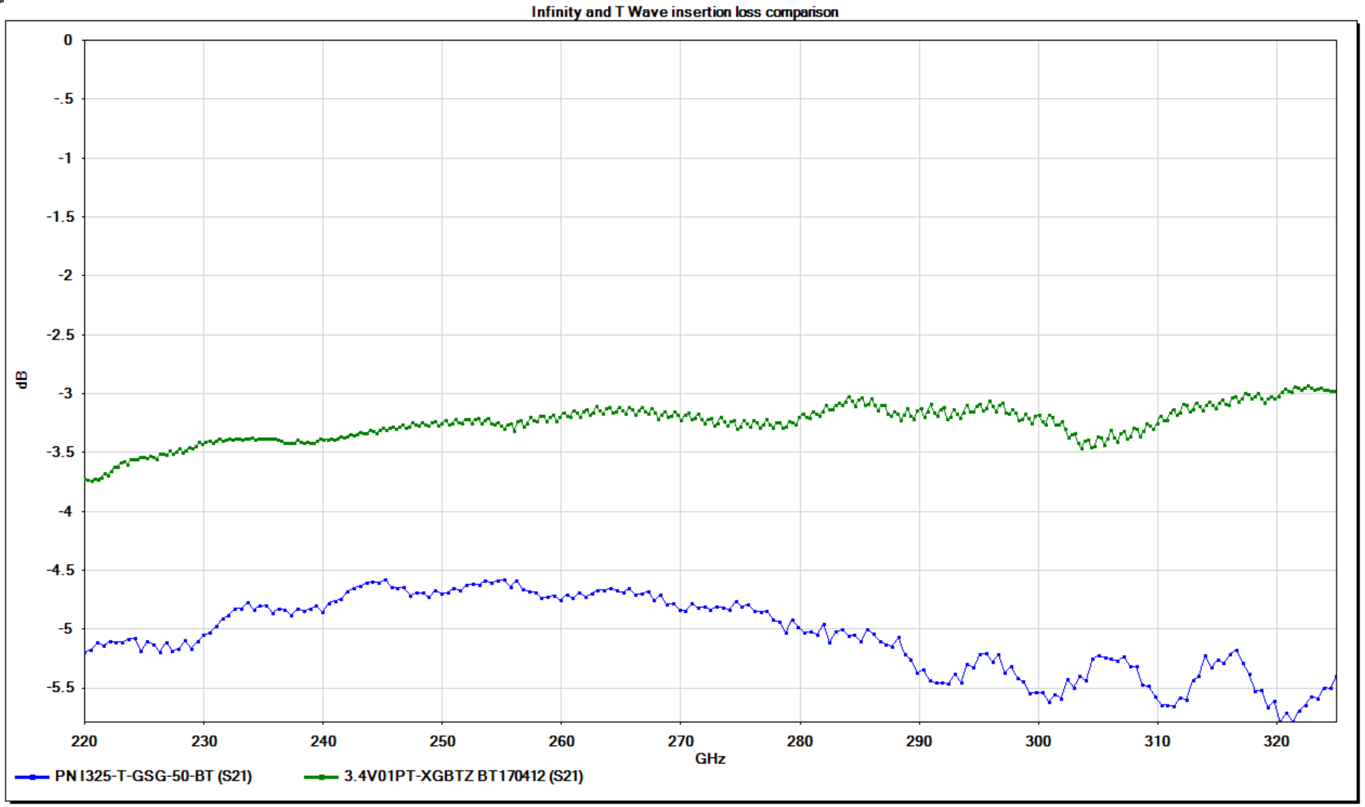
The same probe after 1.5 million touchdowns.



The same probe after three million touchdowns.

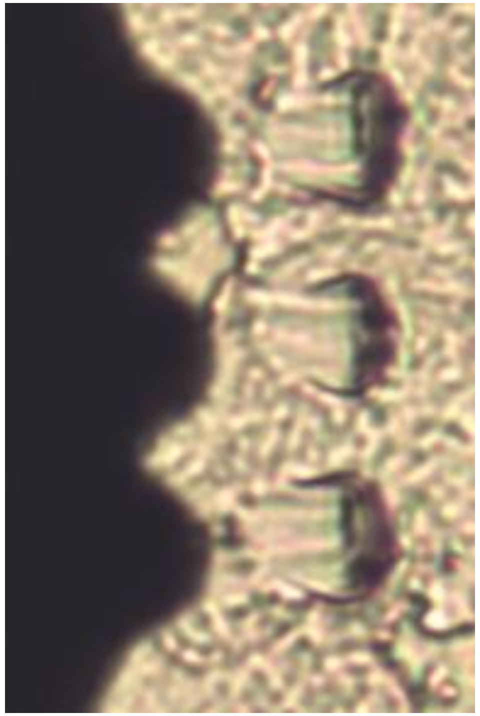
T-Wave Probe

- **Industry-leading performance for on-wafer measurement of millimeter and sub-millimeter wavelength devices**
- T-Wave Probes set the industry performance standard for characterization of mm-Wave & THz devices
- Low insertion loss, excellent visibility and low contact resistance when probing gold pads.
- Available in Standard T and S probe geometries as Infinity
- Solid waveguide allows unsupported mounting even for Taller probes

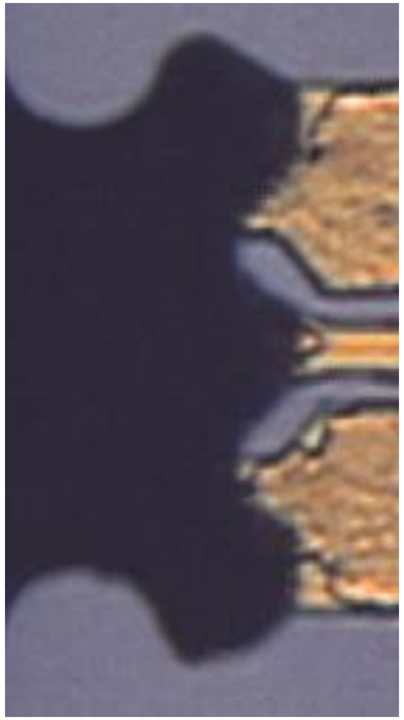


T-Wave Probe

- Accurate characterization of devices in the mmWave and sub-mmWave spectrum
- Very low insertion loss and low contact resistance
- Integrated DC bias-T network
- Tip is a replaceable silicon substrate – good as new on every repair
- Excellent tip visibility
- Low cost of ownership driven by long tip life and probe repair program
- Can address very small pad sizes
  - 15 µm x15 µm (on Gold Pads with no passivation)
  - 25 µm x 25 µm (Typical pad area)



25 µm 1100GHz



50 µm 325 GHz

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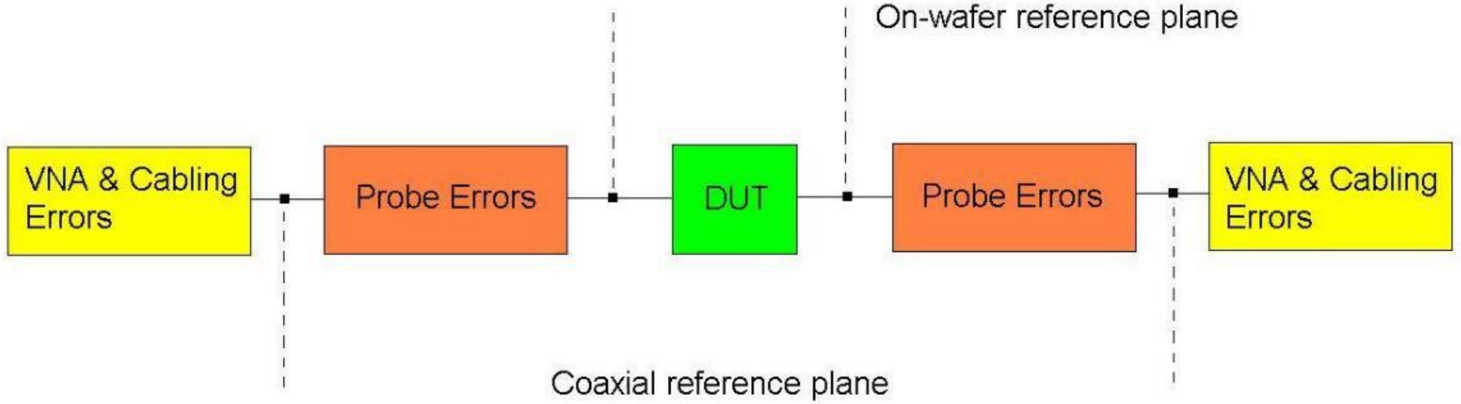
Calibration and WinCal XE™

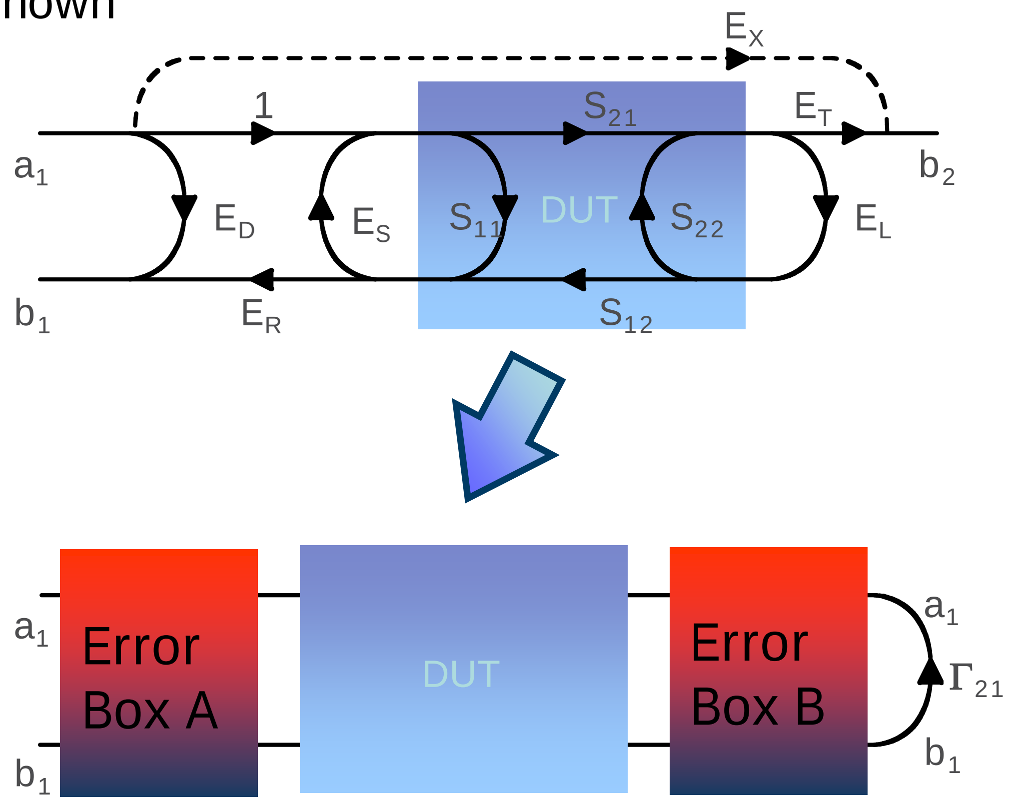
Calibration



- All errors up to the probe tip must be removed for accurate measurements
- Includes internal VNA errors after the sampler, the cables and probes
- Coaxial calibration removes errors to the end of the coax cable
- On-wafer measurements need to correct for the errors in the probes
- Calibration standards are required at the probe tip BUT a single calibration can be done which includes repeatable systemic errors

Two-port error model reduction

12-term error model – forward half shown



8-term error model –with forward switch reflection

Reflection terms:

- Directivity, E_D
- Source match, E_S
- Reflection tracking, E_R

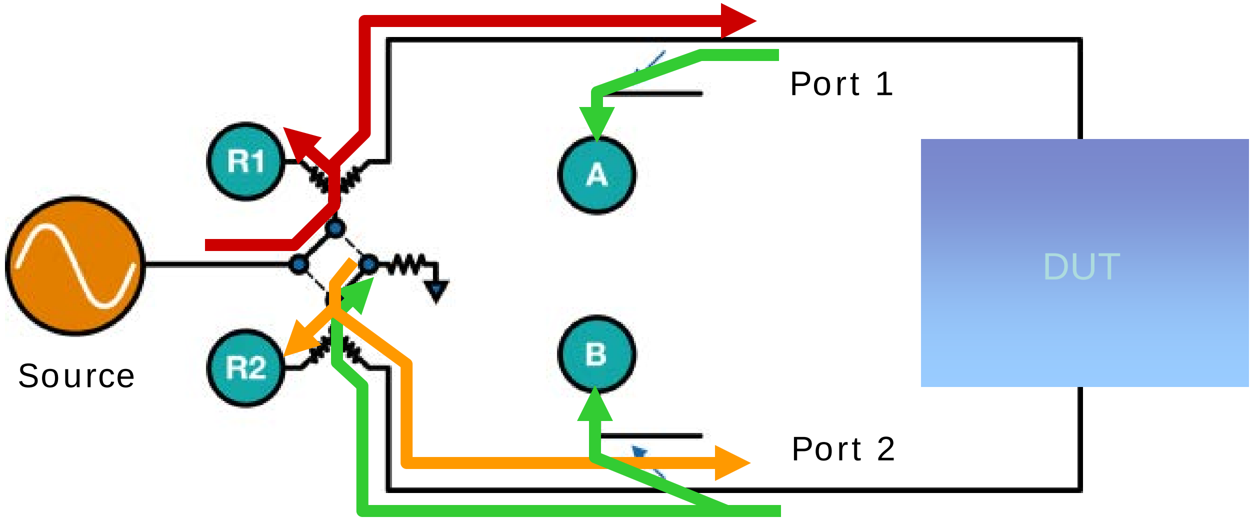
Transmission terms:

- Transmission tracking, ET
- Load match, EL
- Crosstalk, EX (OFTEN NEGLECTED)

- Omit or pre-correct isolation
- Pre-correct switching Γ
- Common forward/reverse error boxes
- Enables advanced calibration
  - TRL, SOLR, LRM, LRRM, etc
- Cal method regardless most VNA's are expecting to receive a 12 Term error model for correction

Two-port PNA switch corrections

Port 1 excited



R1, R2 – reference receivers

A, B – response receivers

Raw S_{11} = A/R1
Raw S_{21} = B/R1
Γ_{21} = R2/B (ports connected)

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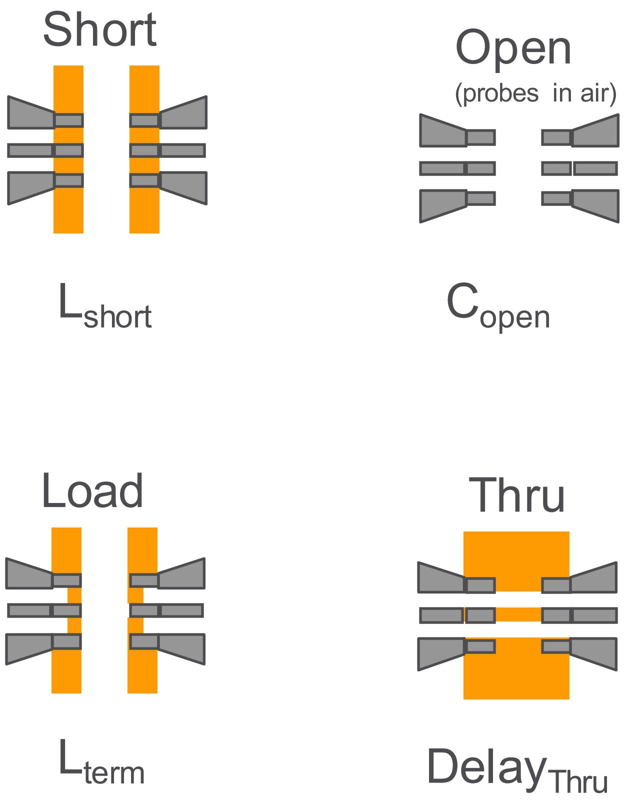
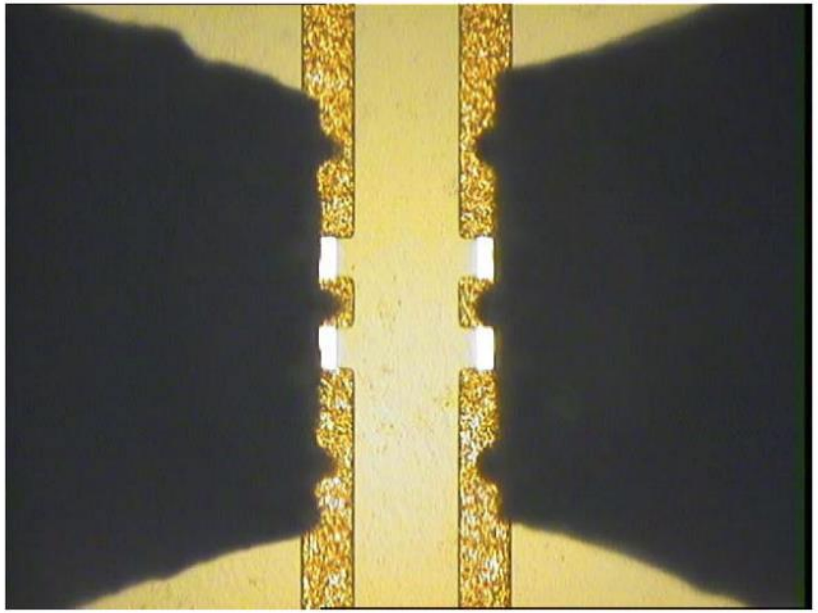
SOLT Calibration

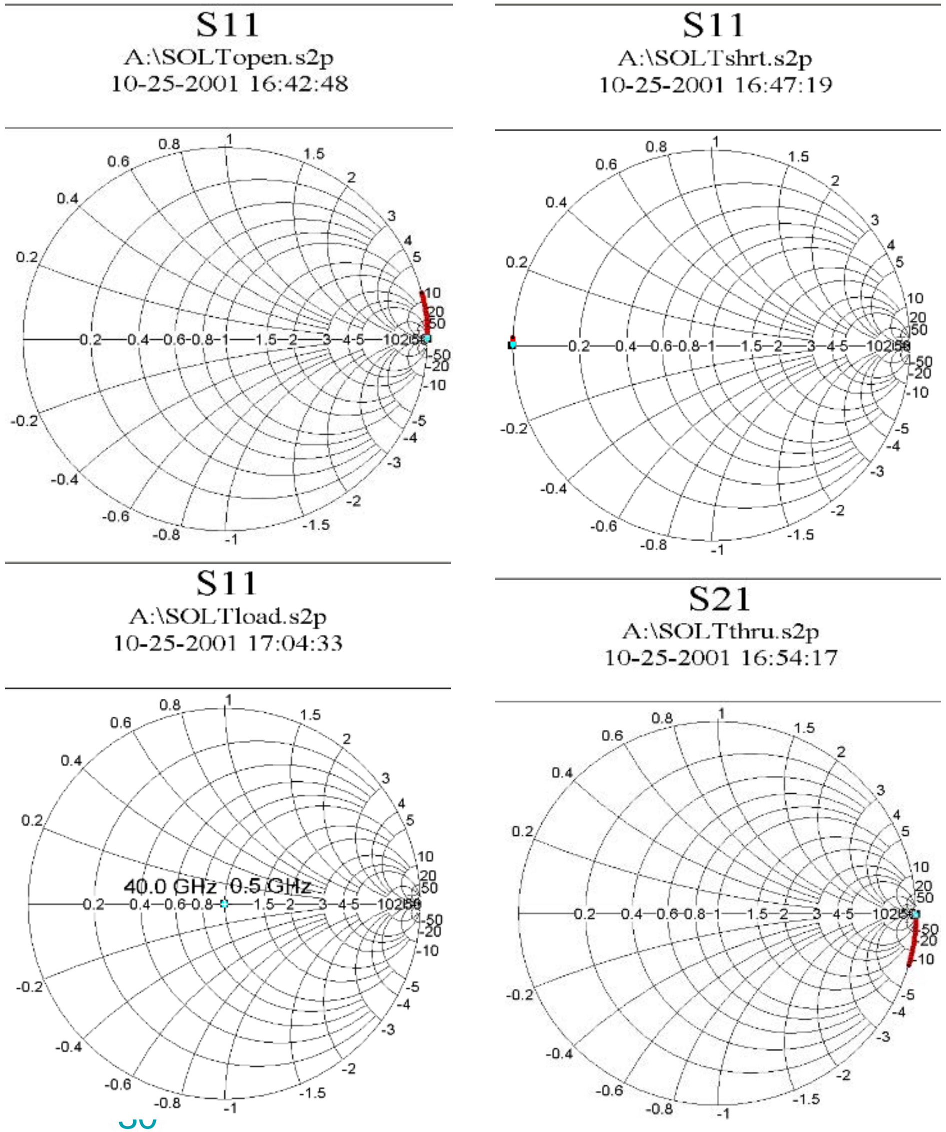


- Oldest calibration technique
- Doesn't need 2n sampler vna
- All standards must be fully known
- Available in every vector network analyzer (CalKit definition required)
- Open has capacitance (often negative) dependent if using air or on substrate
- Short and load have inductance
- Actual standard definitions vary due to probe placement
- Mathematically over-determined

SOLT Calibration Validation

- All standards match their cal kit definitions EXACTLY by default
- Even bad standards will look good remeasured if contact is consistent
- Independent Validation required!

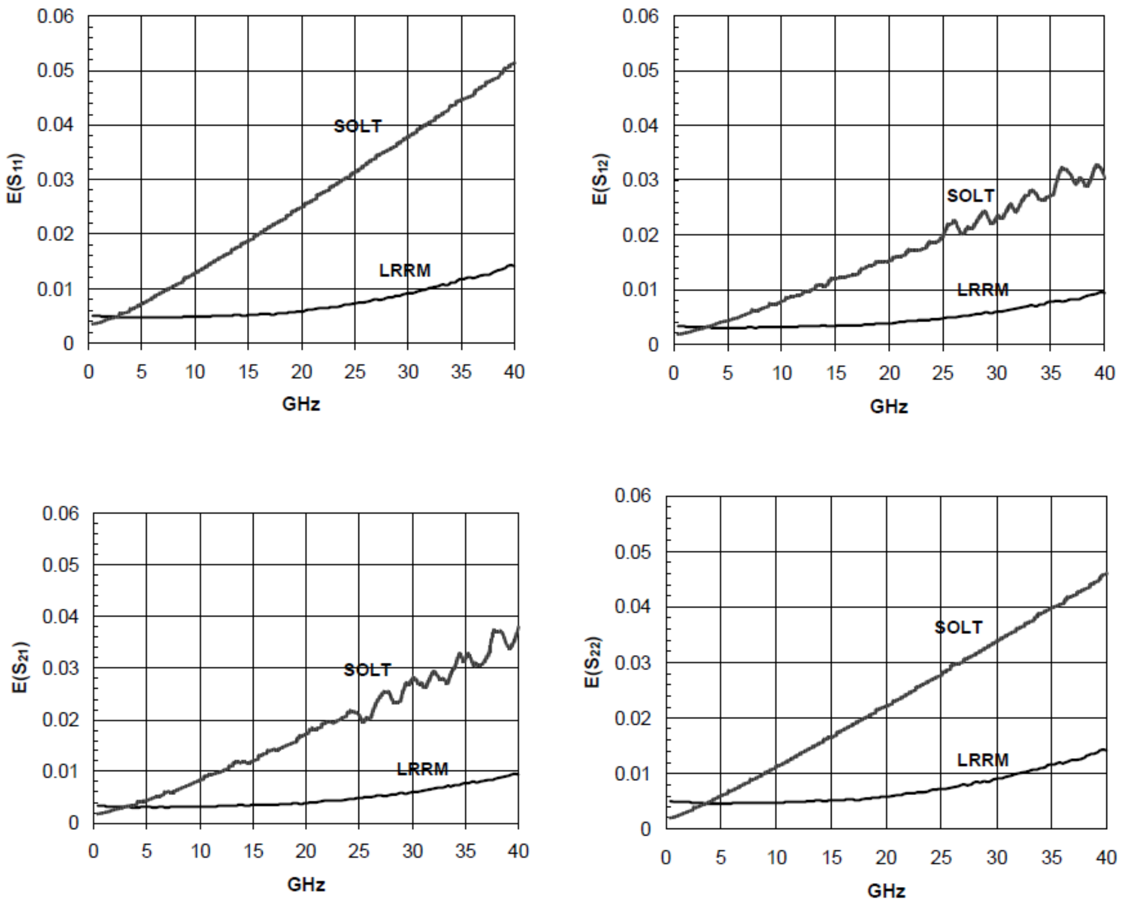




Paper SOLT v LRRM

(a) (b)

Fig. 3 Probe Placement: Two positions of the probe relative to the load and short standards were used. a) The middle of the standard. b) The end of the standard.



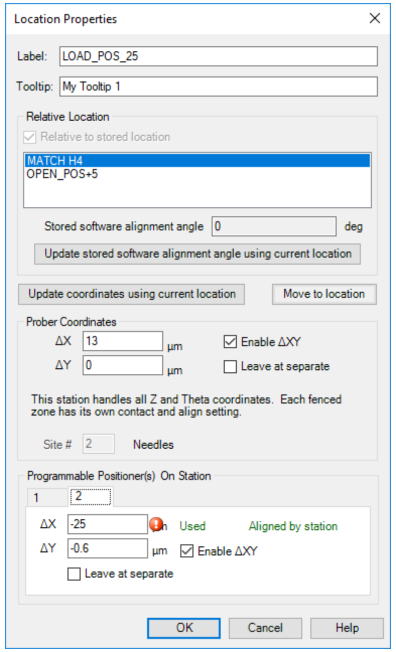
- From paper the probes on the Load were offset by approximately 25 um per probe on the load standards Short Standards and Thru standard
- Results opposition show delta in error terms between original and offset positioning for both LRRM and SOLT

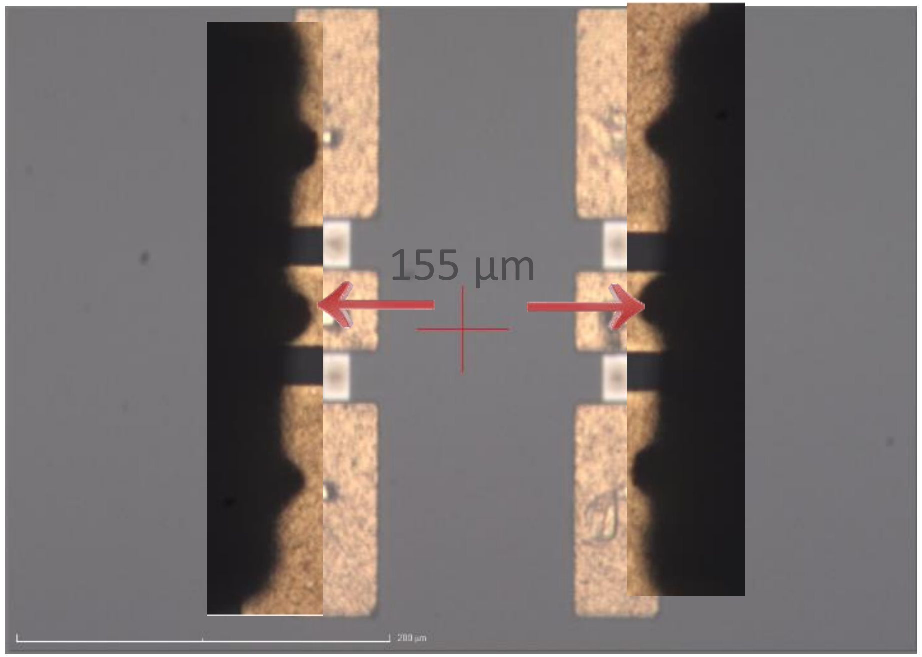
SENSITIVITY ANALYSIS OF CALIBRATION STANDARDS FOR SOLT AND LRRM

Amr M. E. Safwat, and Leonard Hayden

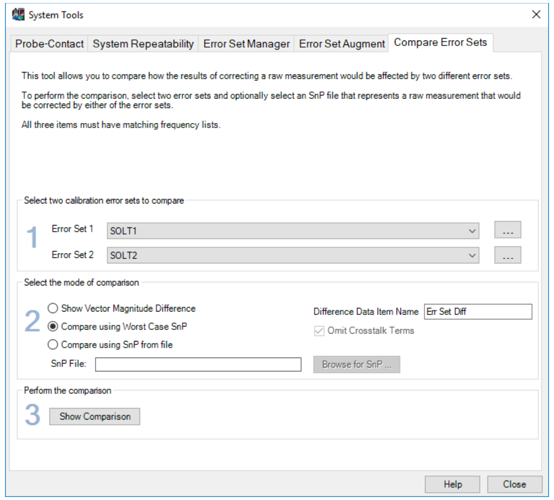
Cascade Microtech Inc., 2430 NW 206th Avenue, Beaverton OR 97006, USA

More recent experiments

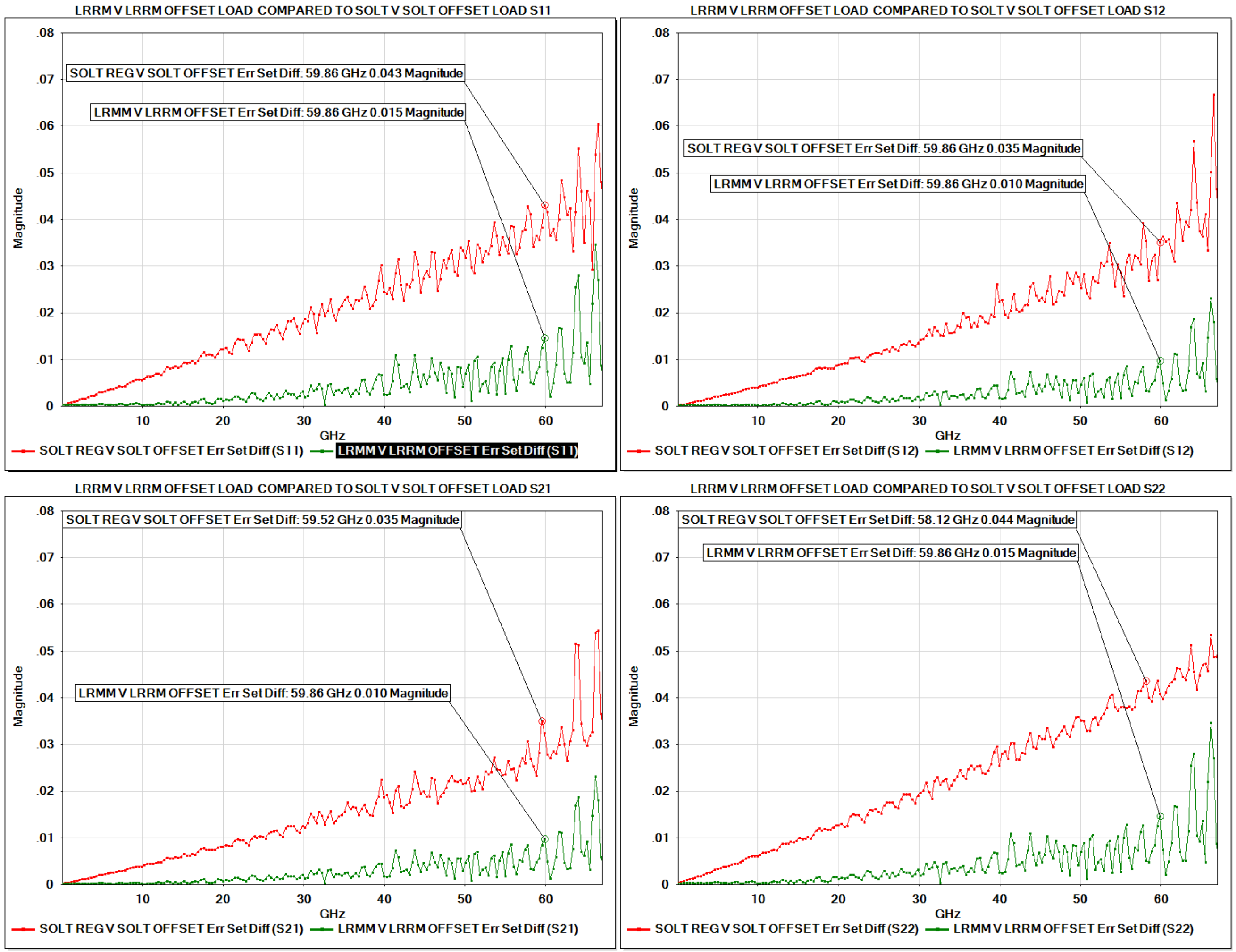




- Location manager to move right hand probe 25 um further out
- Stage offset by 13 um to the left resulting in both probes ~ 12.5 um offset from the load centre outwards
- This was done for all standards in the run but cals built sequentially here from component measurements
- Comparison for error bounds using WinCal error set comparison tool

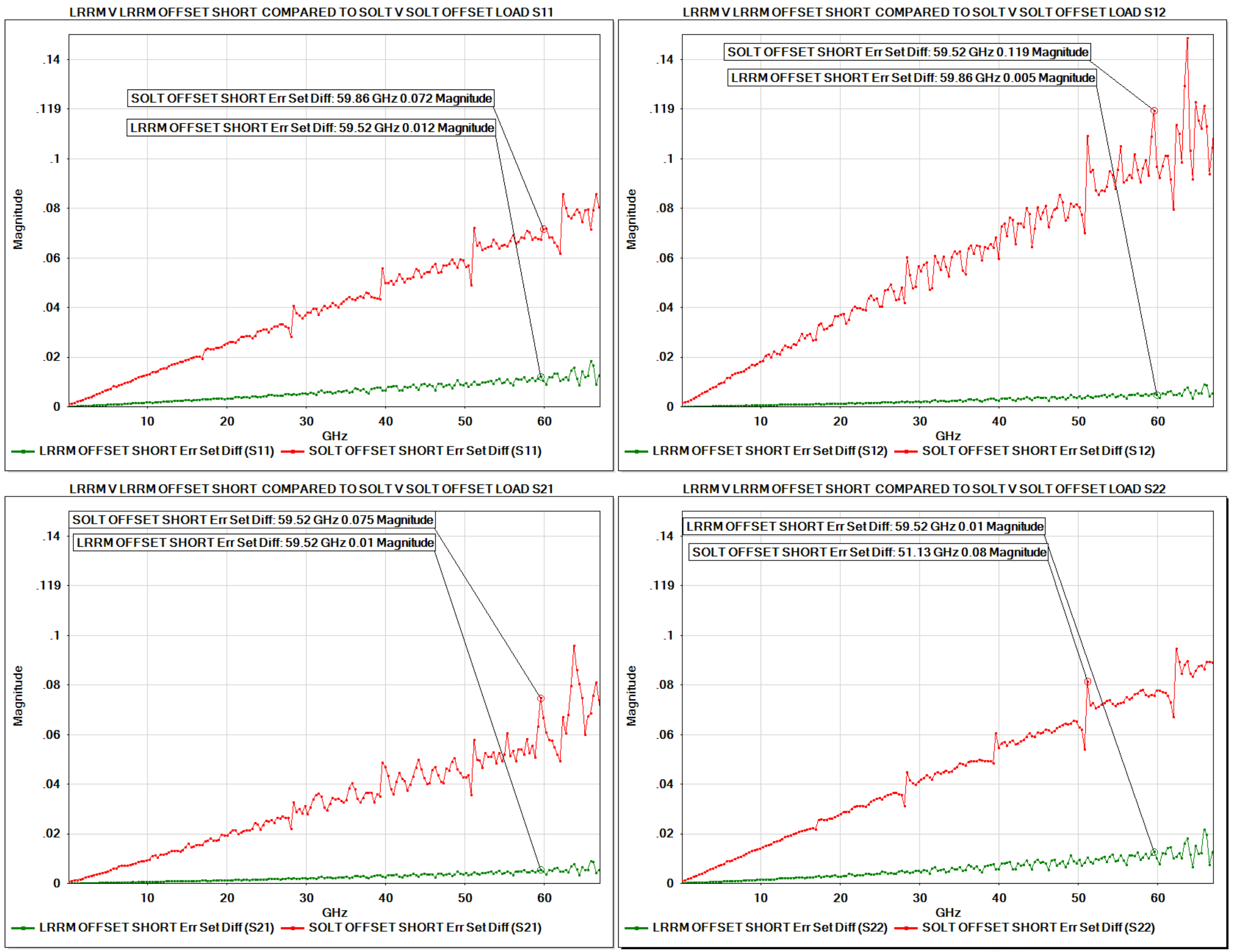


Offset load only error set comparison



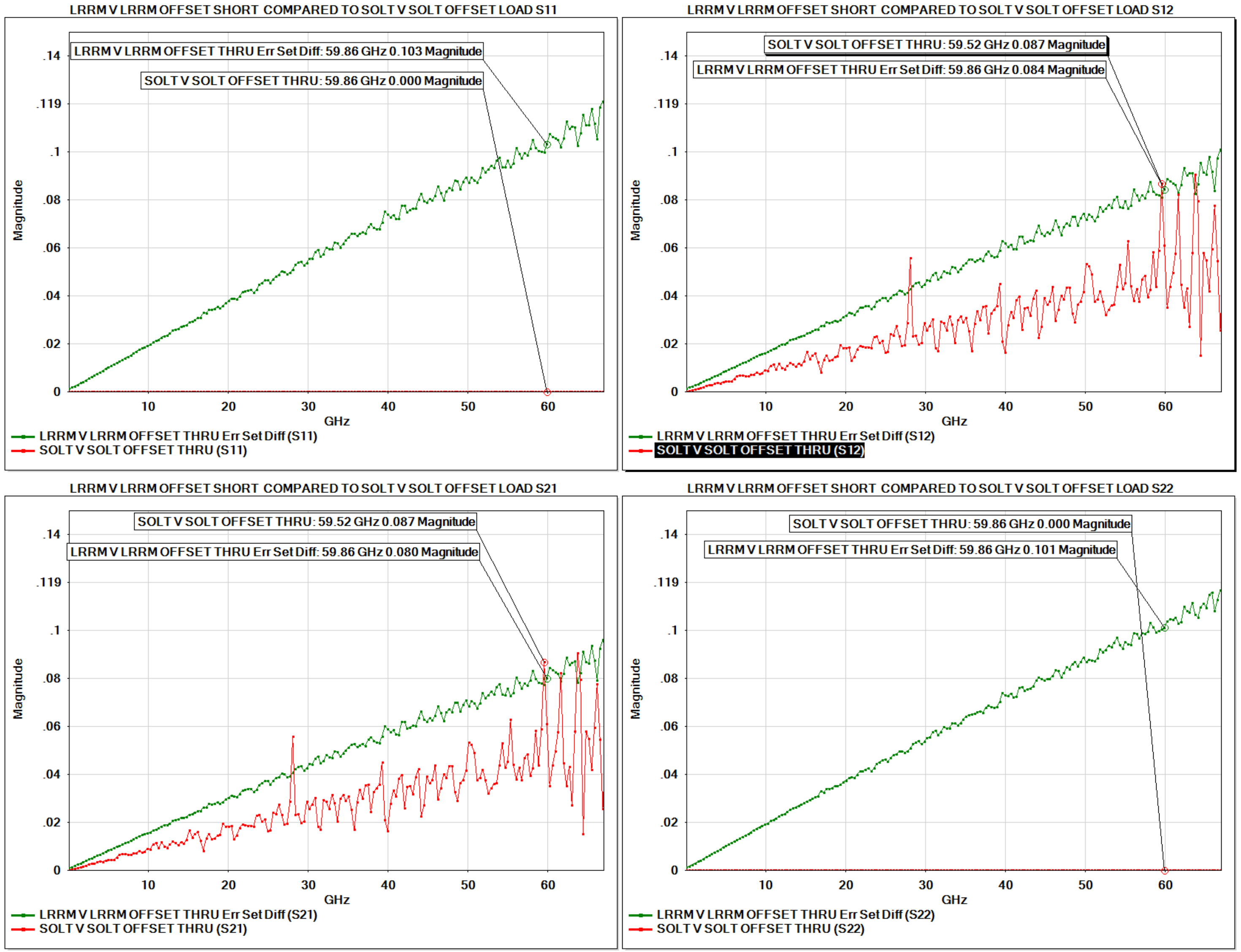
- 0.044 S22 delta SOLT compares to 0.015 for LRRM

Offset Short only error set comparison



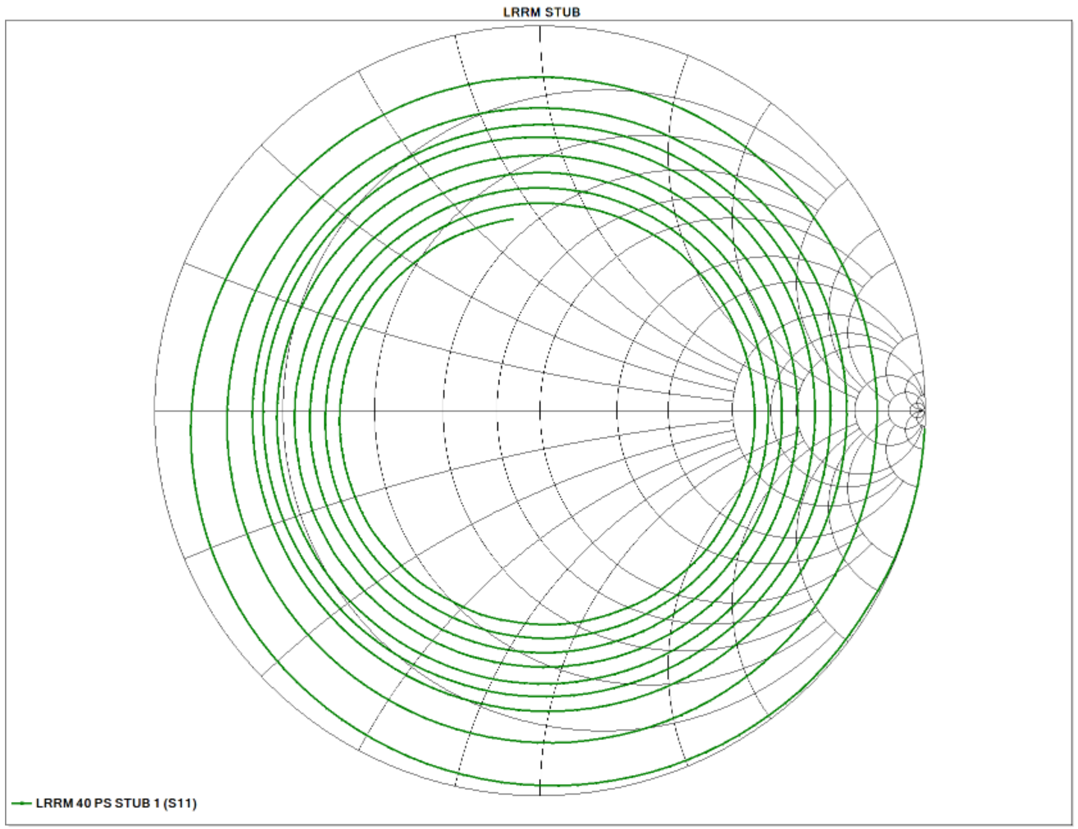
- Note change in scale 0.15 full scale compared to 0.08
- SOLT seems very sensitive to variation in Short (0.119 worst case below 60 GHz compared to 0.005 for LRRM)

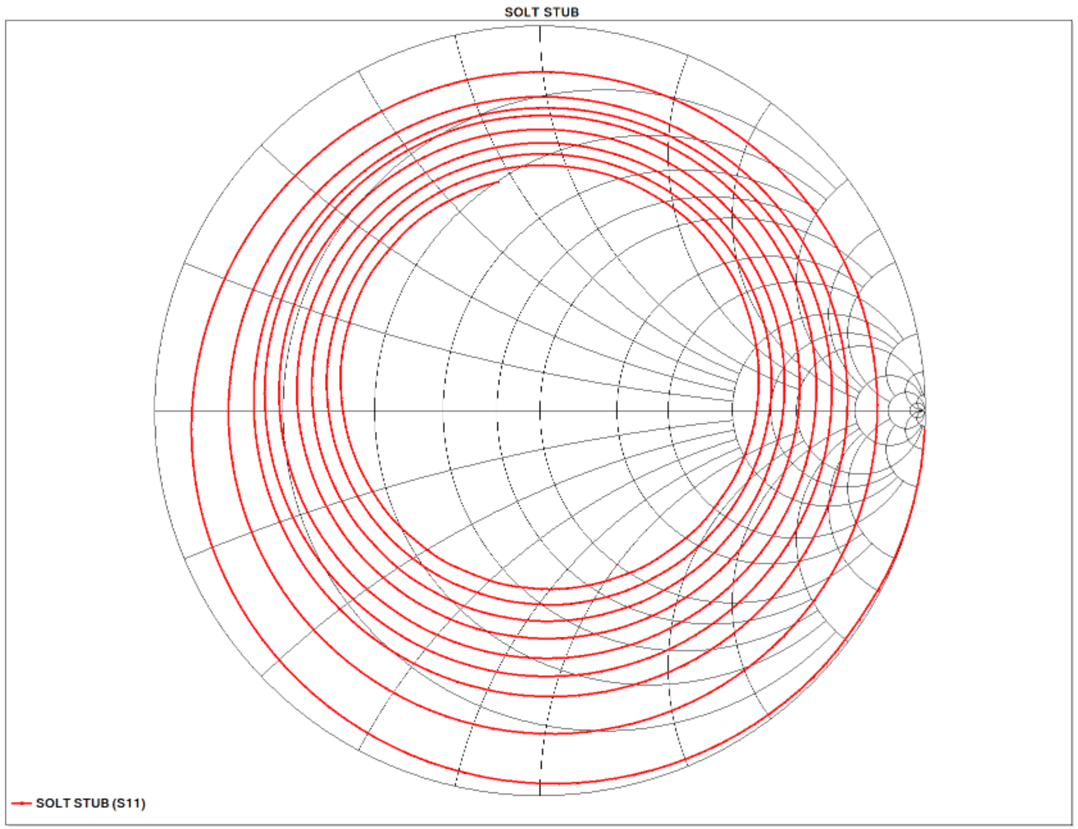
Offset Thru only error set comparison



- Thru for LRRM is used to shift reference plane so deltas seen on all 4 S Parameters
- SOLT has similar sensitivity for the Thru
- SOLT unaffected for the reflects for this case where the Reflect position is the same as in the Cal

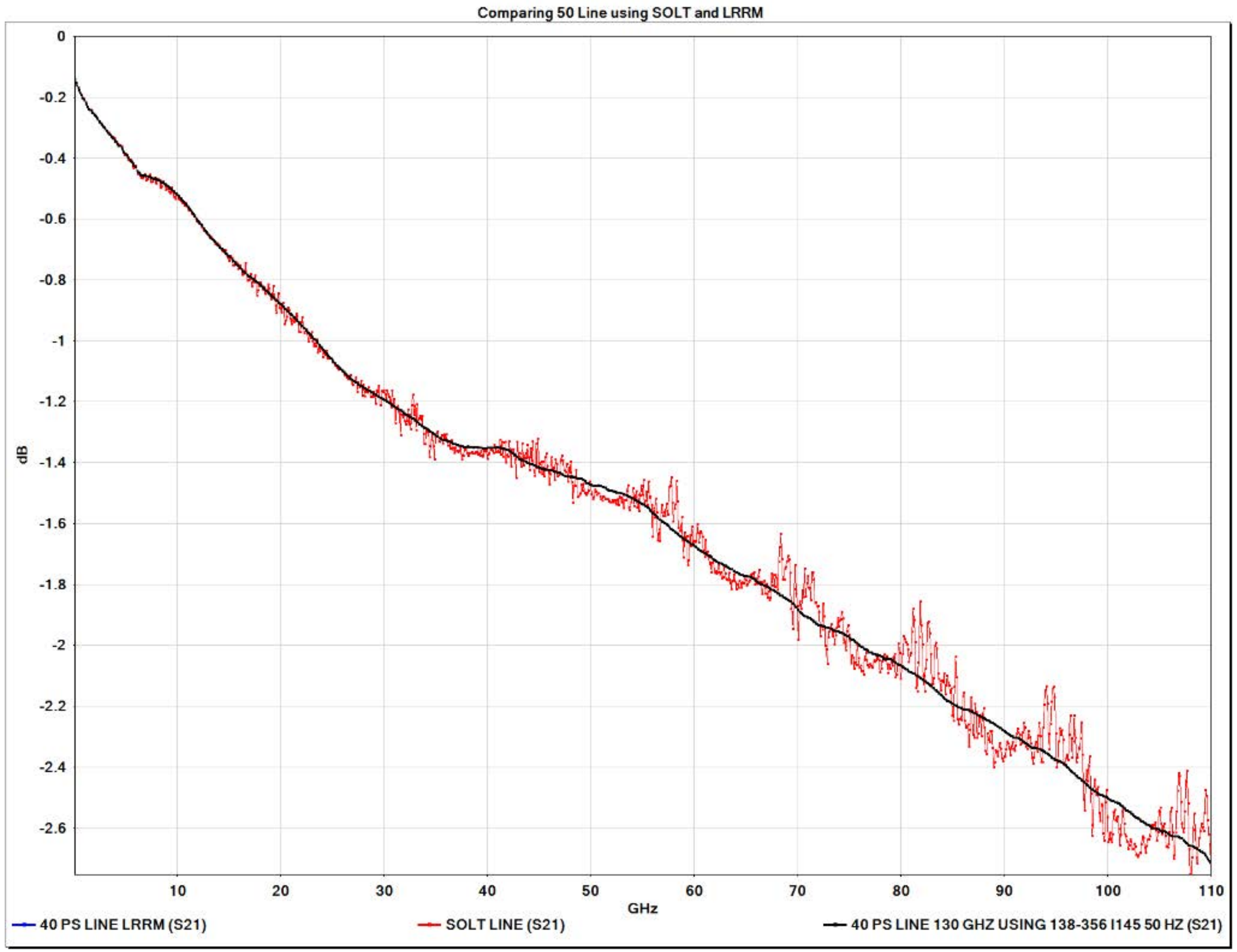
SOLT (Right) Calibration Results Compared to LRRM (Left)





- 40 Ps Open stub SOLT
  - Not centered on the Smith chart
  - Sometimes lines can cross
  - This affect relates in part to the reality of standard definitions not matching their definition

SOLT Calibration Results Compared to LRRM

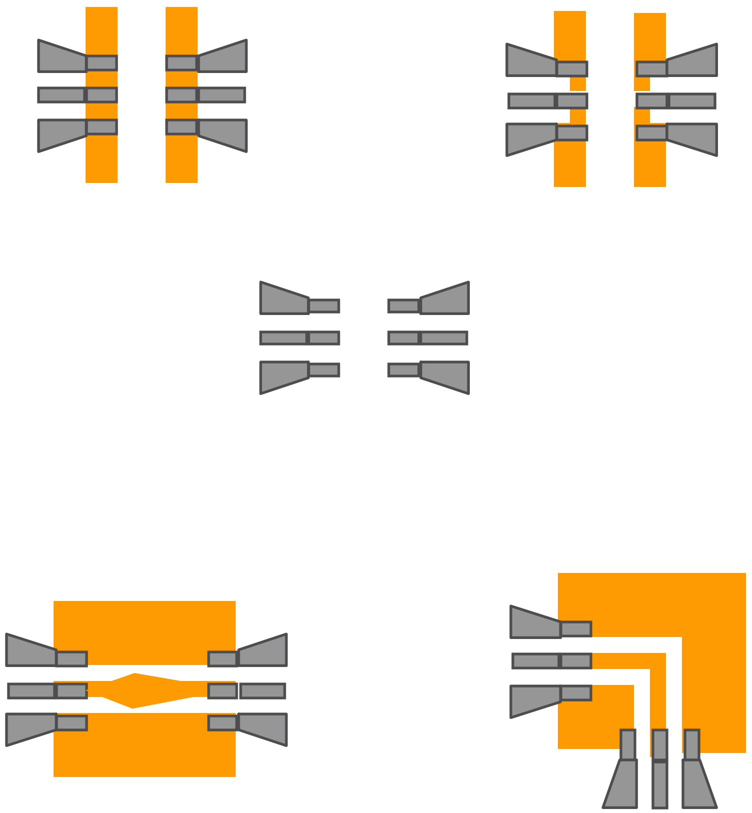


- Fine grain ripple on transmission is a typical artefact of SOLR

SOL-R 2-Port Calibration

- Works on PNAs
- WinCal supported
- Requires no THRU definition
- Recommended for dual probes, right angle probes & probe cards

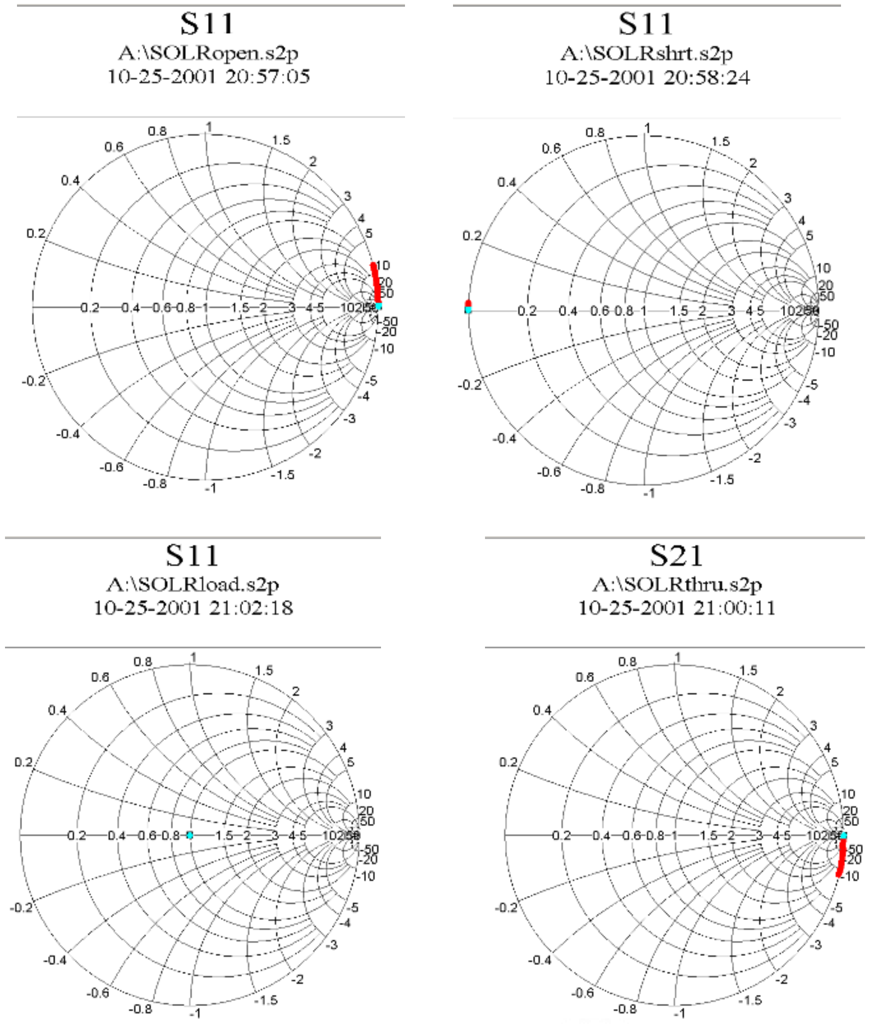
SOL-R Calibration



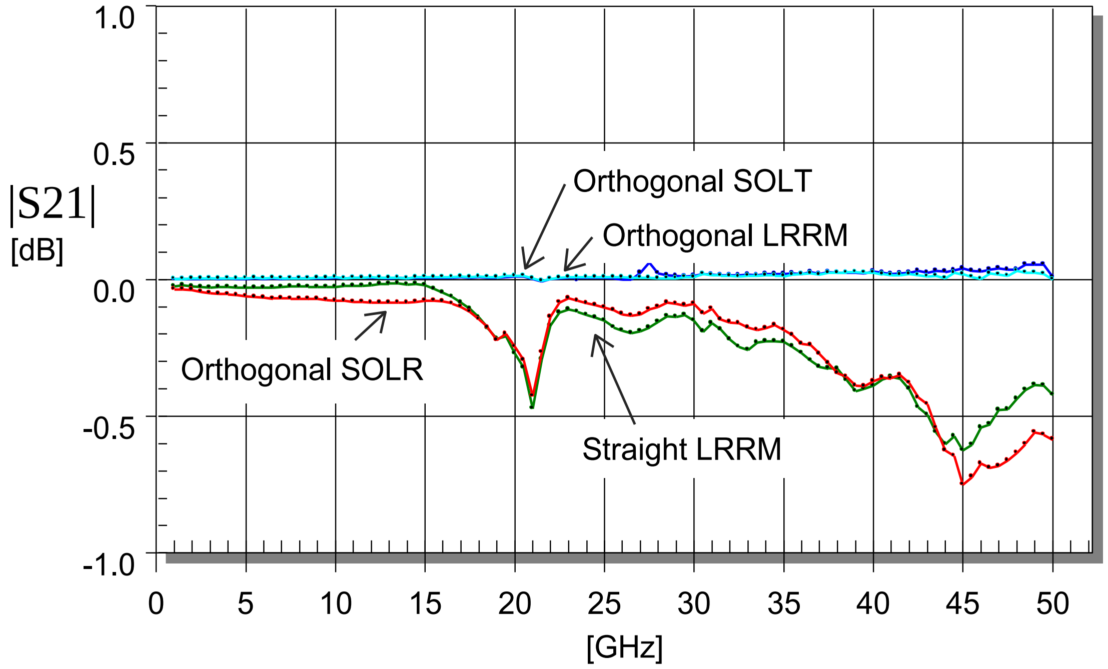
- Short-Open-Load-Reciprocal Thru
  - Reciprocal Thru requires only S12 = S21
  - Tolerant to lossy or highly reactive insertion standard
  - Convenient for use with fixed probe spacing in probe cards
  - Does not require a custom Thru
  - Convenient for use when DUT terminals are orientated at 90°
  - Available in WinCal, PNA

SOL-R Calibration Results

- Short, Open & Load match the SOL definitions (just like SOLT)
- Highly probe position dependency on the standards



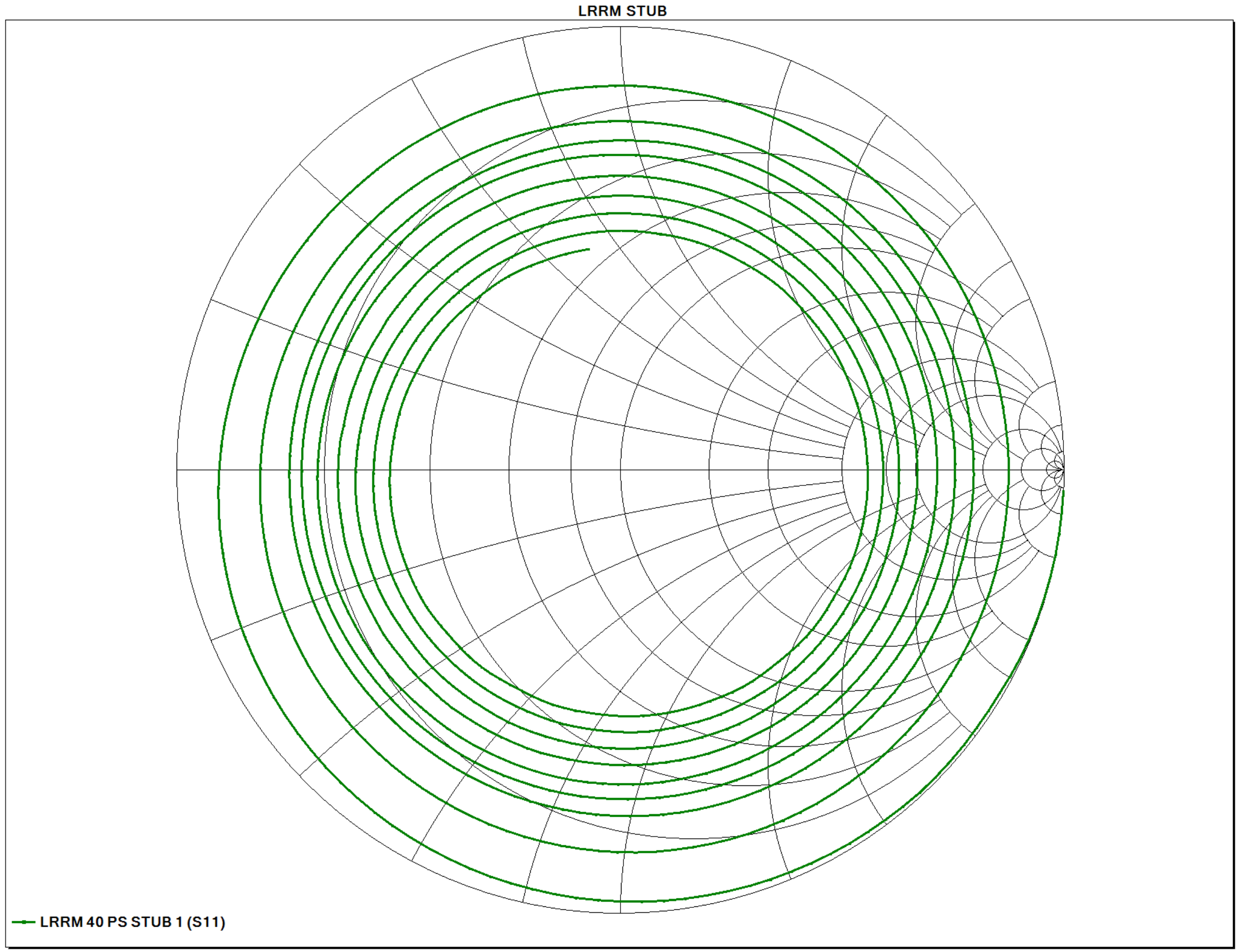
Right Angle Measurements

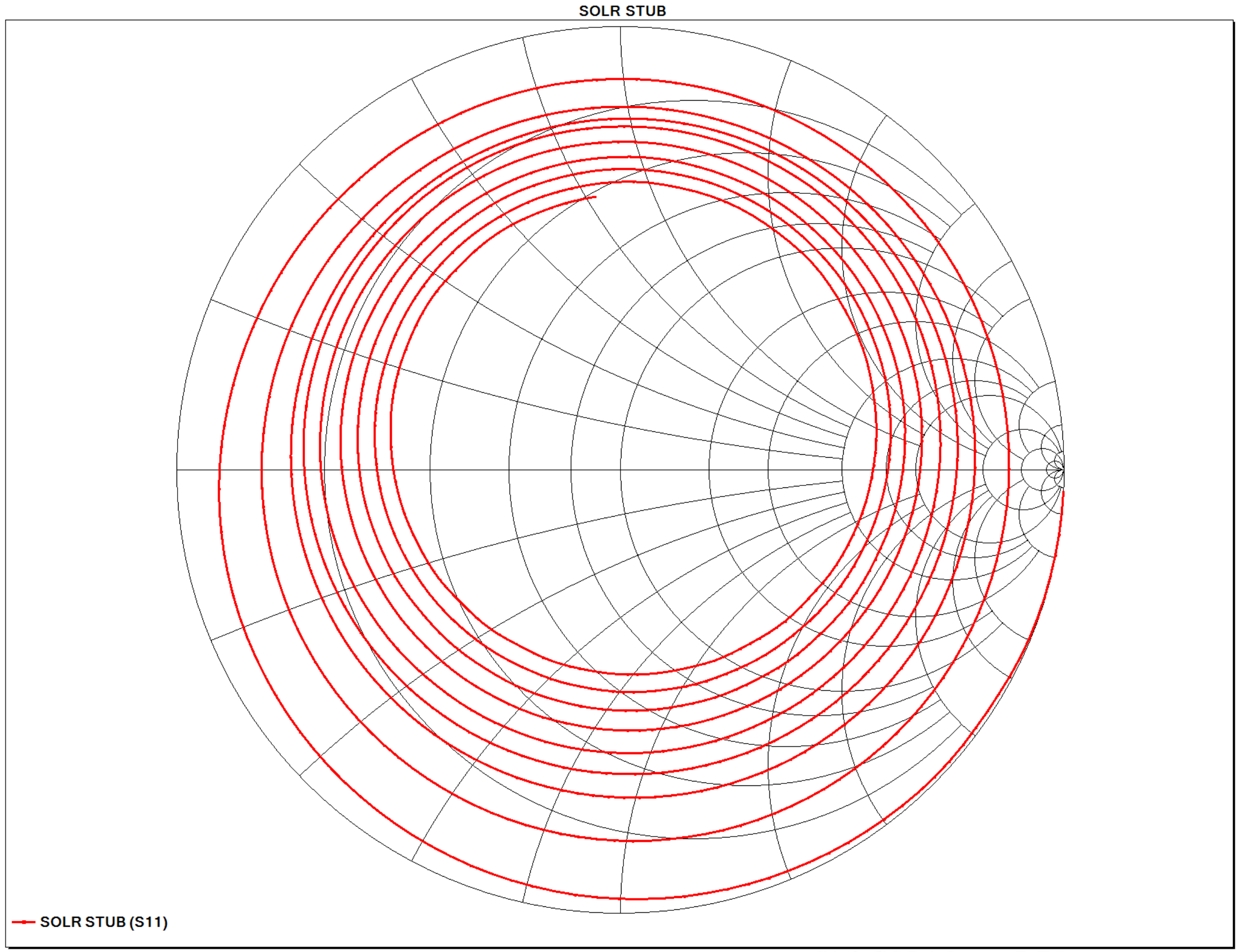


- Carefully constructed right angle 'Thru' standard
- Thru is non-ideal, large dip at 20 GHz
- Errors in standard cal's
- SOLR largely immune to Thru errors
- LRRM and SOLT using even best effort definition of the thru don't show thru real characteristics (which has a dip)
- LRRM done straight and then with one probe rotated (dangerous) do show the dip and this tallies with SOLR done rotated

SOL-R Calibration Results compared to LRRM

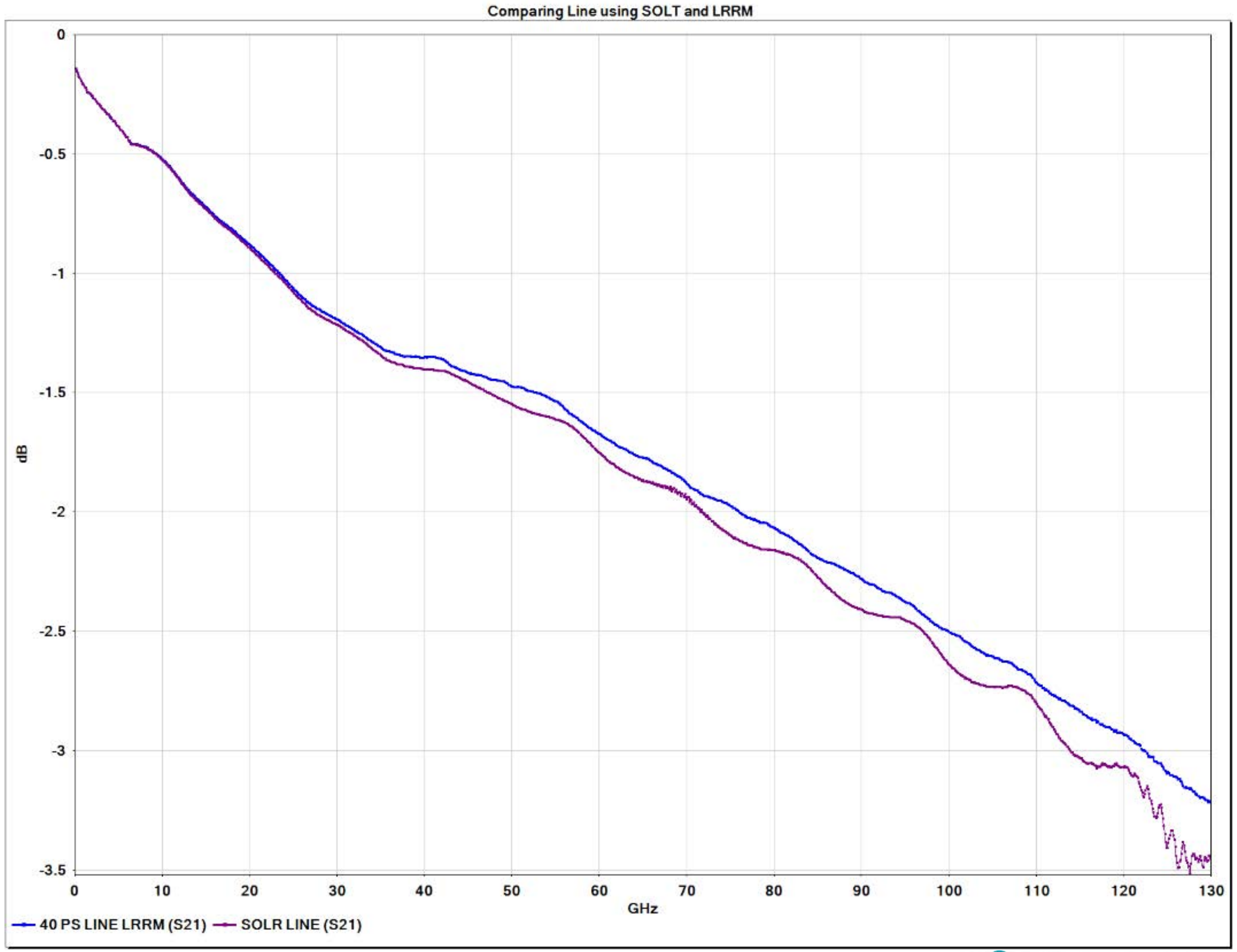
- Open Stub - Not centered on the Smith chart. Similar standard definition issues to SOLT





SOL-R Calibration Results

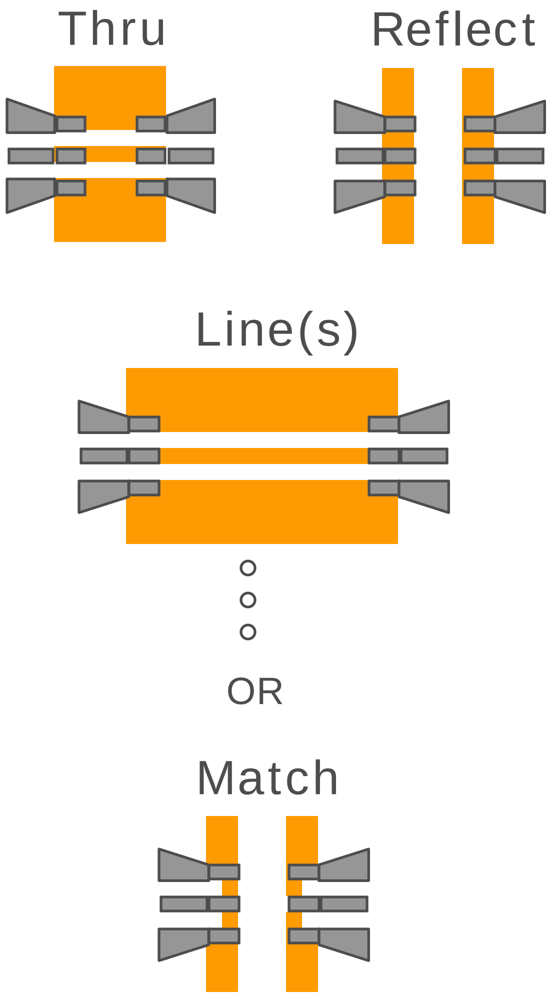
- Thru is least accurate of all calibration types (by product of unknown thru)
  - Main use for SOL is for right angle probing and probe cards or anything when a good thru is hard to achieve



TRL 2-Port Calibration

- Preferred by engineers for on-wafer micro-strip embedded devices
  - Cannot realize 50 Ohm lines exactly
- Most popular for GaAs, and THz frequencies
- Reference plane can be left at Thru center thus removing the pad parasitics and getting closer to the device
- Hard to get broadband standards
  - Dispersive at low frequencies
  - Long lines require too much wafer real estate for low frequency work

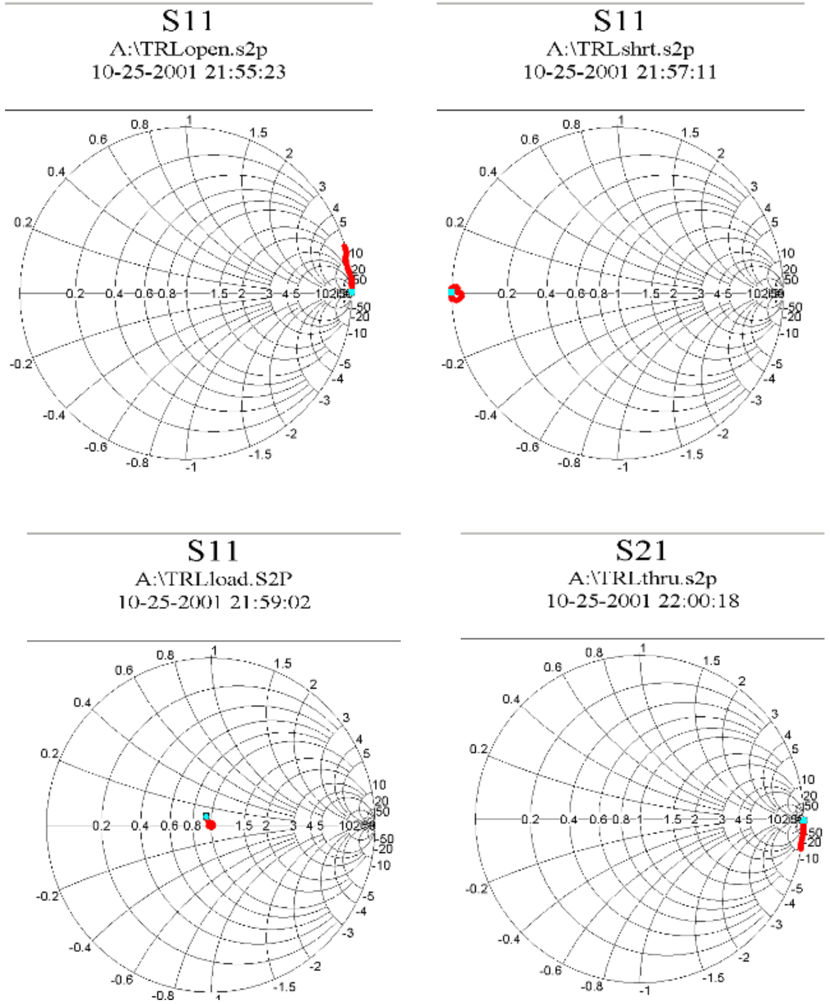
TRL/LRM Calibration



- Thru-Reflect-Line
  - Requires least info about standards
  - S-parameters referenced to line Zo
  - Reference plane at center of Thru
  - Requires multiple probe spacings
  - Zo is inherently complex at low frequencies
  - Not suitable for fixed spacing probes (e.g., probe card)
  - Line standards need to be known to ¼ Wavelength dimensionally but probe position is still essential to maintain the same launch
  - Moving probe tips can be awkward and error prone
  - Line should be between 20 and 160 degrees of Thru delay
  - MLTRL gives best results
- Line-Reflect-Match
  - Referenced to Zmatch

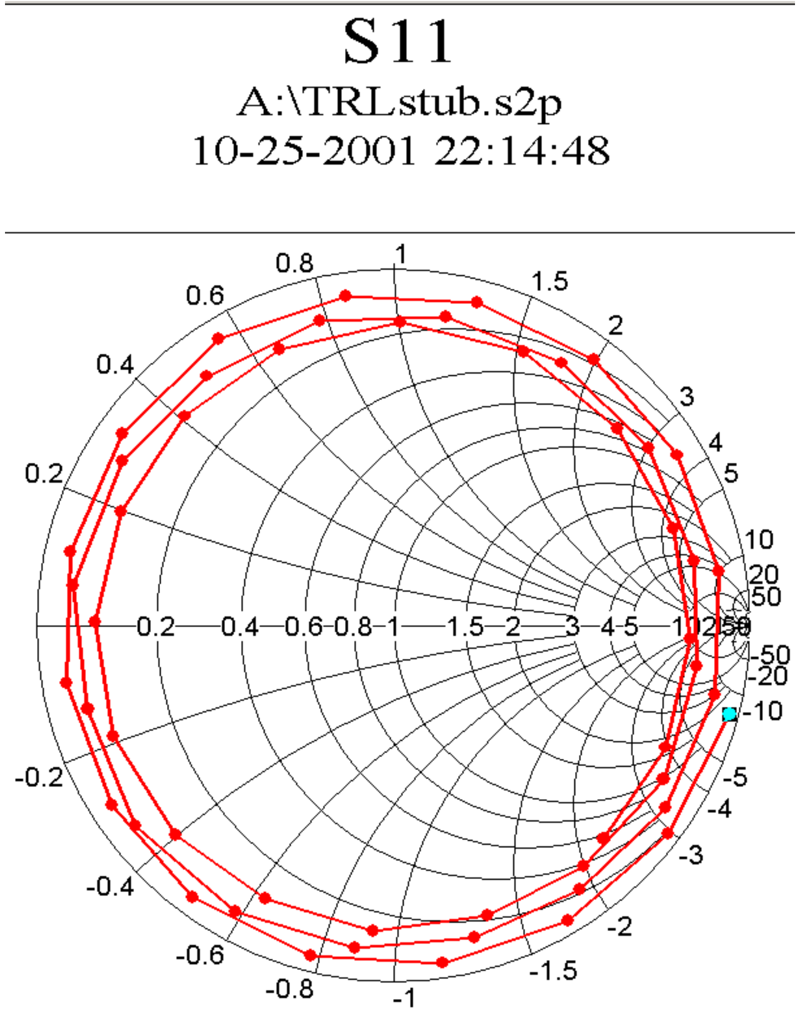
TRL Calibration Results

All standards other than Thru exhibit anomalies as the lumped element definitions for these is not defined in cal



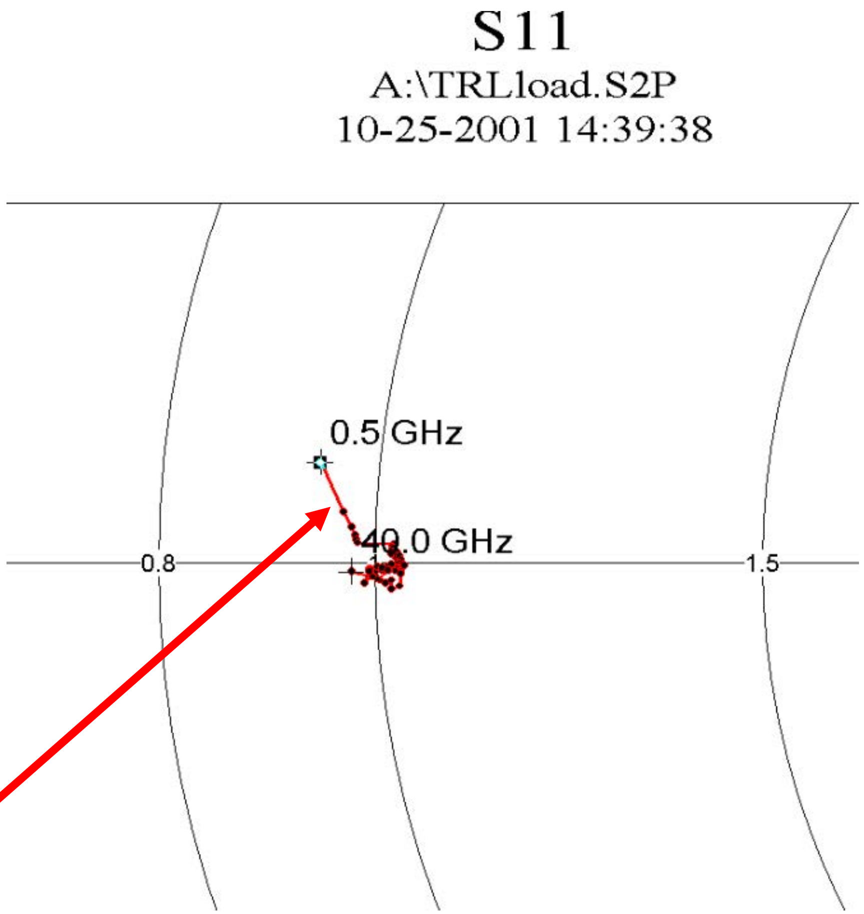
TRL Calibration Results

- Open stub is well centered on the Smith chart
- No lines are crossing



TRL Measurement Problems

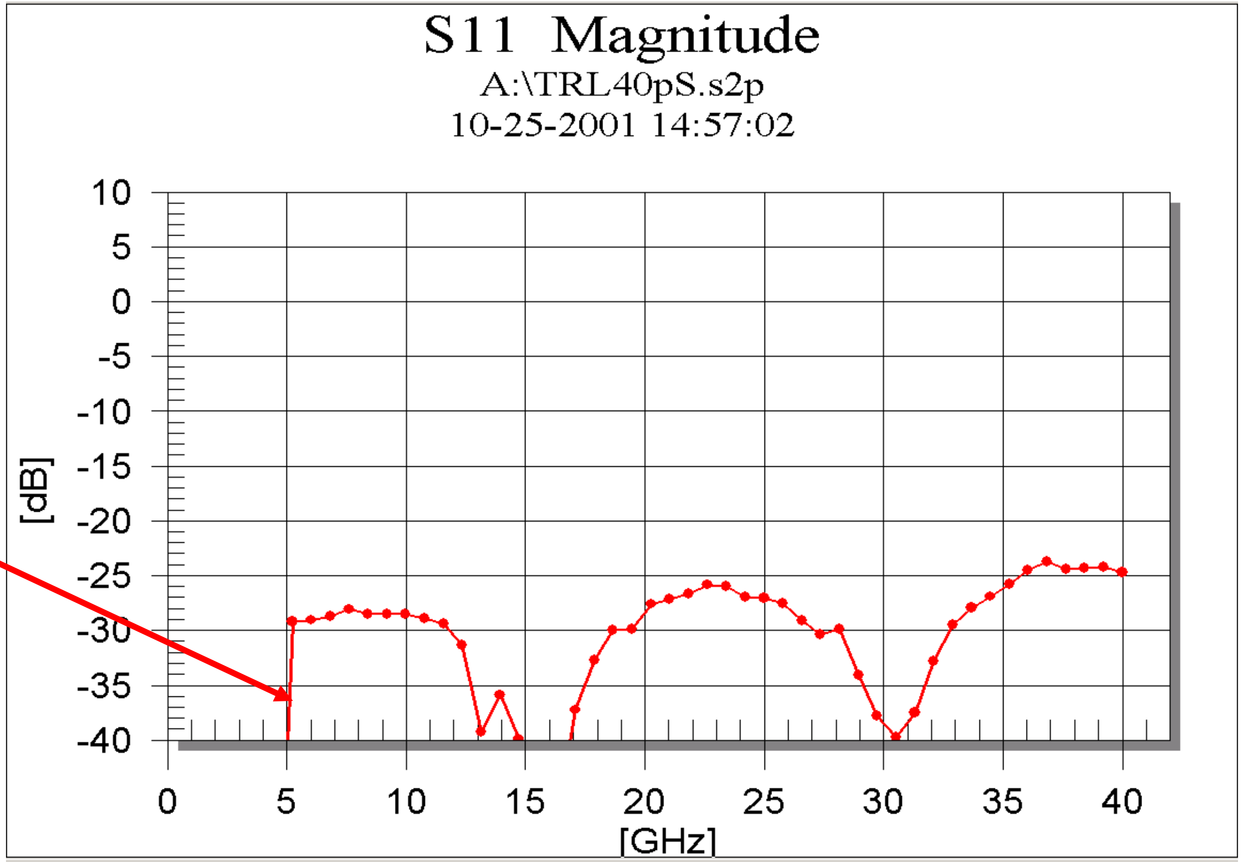
- Typically, poor below 5 GHz
- Propagation not constant for thin film structures



Apparent dispersion of a lumped element

TRL Measurement Problems (solved by MLTRL)

Discontinuities
at the delay line
definitions



What is Multi-line TRL?

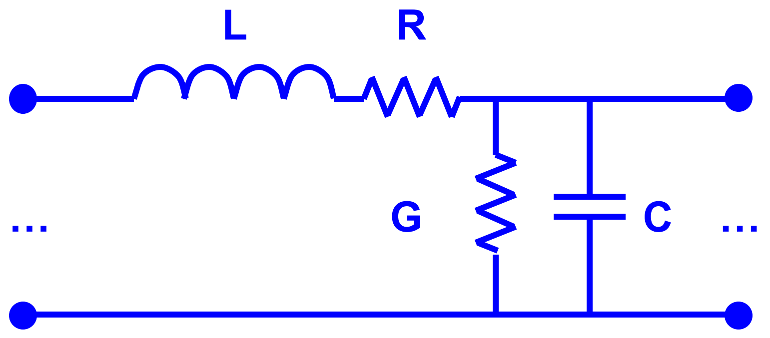
- Uses all lines at all frequencies
  - not banded
- Optimally weights data from line pairs according to how distinguishable they are
  - 90 degree differences maximally weighted
  - 0 or 180 degree differences minimally weighted
- No data discontinuities due to band breaks
- Provides the ability to:
  - Position the reference plane locations to a specific physical offset distance from the center of the thru
  - Renormalize the reference impedance to 50 ohms

A Multiline Method of Network Analyzer Calibration

Roger B. Marks, *Member, IEEE*

Characteristic Impedance - Normalisation

$$Z_o = \sqrt{\frac{(r + j\omega l)}{(g + j\omega c)}} = \frac{\gamma}{(g + j\omega c)}$$



When $g << \omega c \rightarrow Z_o = \gamma / (j\omega c)$

- True for low-loss lines on Alumina, SiO_2, GaAs, Quartz...
    - And the capacitance, c, is constant with frequency, $c(f) = c_{dc}$
- Not true for Silicon, Polyimide, Epoxy...

- With known Zo, the S-parameters may be renormalized to 50 ohms

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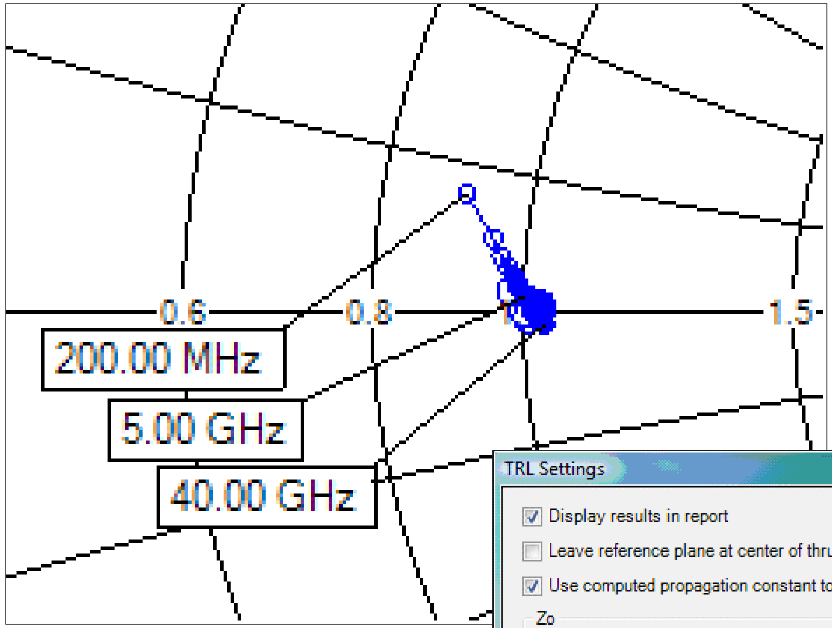
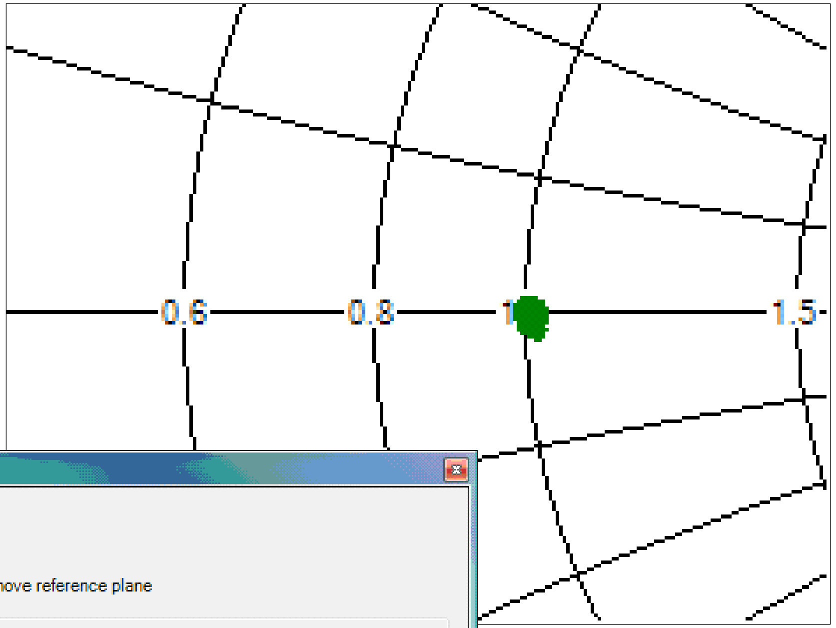
Characteristic Impedance Correction

- With known Zo, the S-parameters may be renormalized to 50 ohms
- Below - 50 Ohm Load S-Parameter

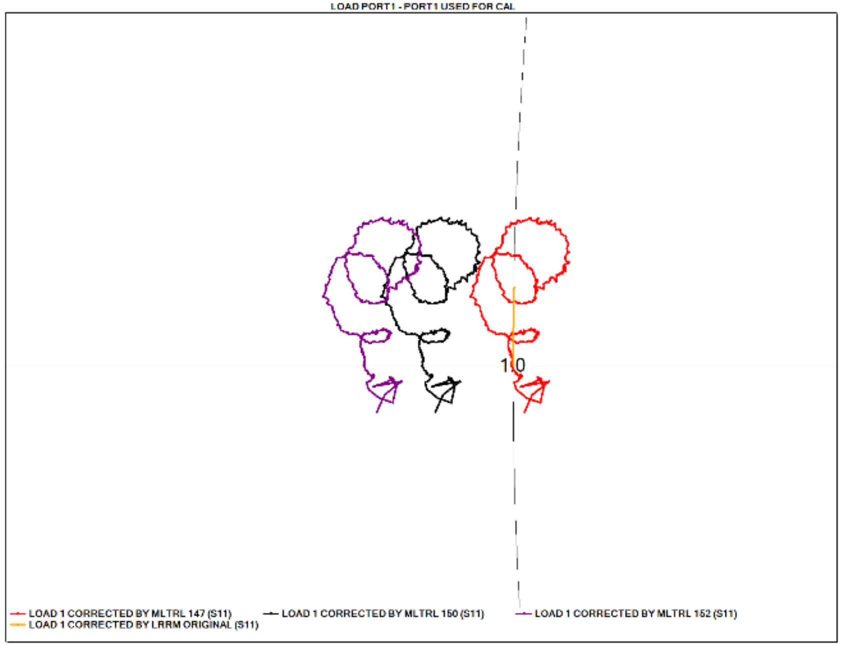
Normalized to Complex Line Zo

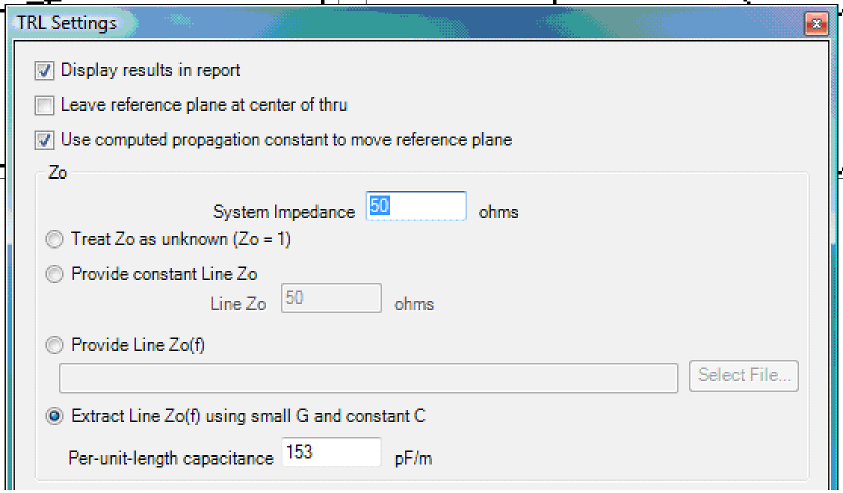


Normalized to 50 Ohms



Trialling different C values (67GHz)




TRL Settings

- [x] Display results in report
- [ ] Leave reference plane at center of thru
- [x] Use computed propagation constant to move reference plane

Zo

System Impedance 50 ohms

- ( ) Treat Zo as unknown (Zo = 1)
- ( ) Provide constant Line Zo
  Line Zo 50 ohms
- ( ) Provide Line Zo(f)
  Select File...
- (•) Extract Line Zo(f) using small G and constant C
  Per-unit-length capacitance 153 pF/m

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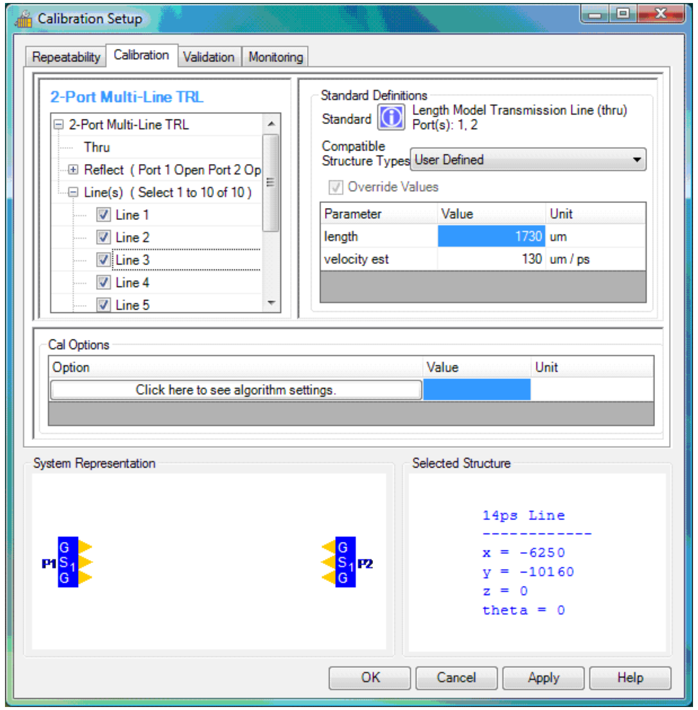
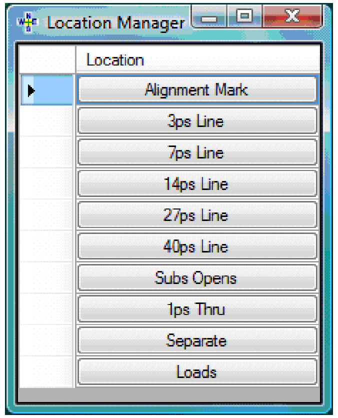
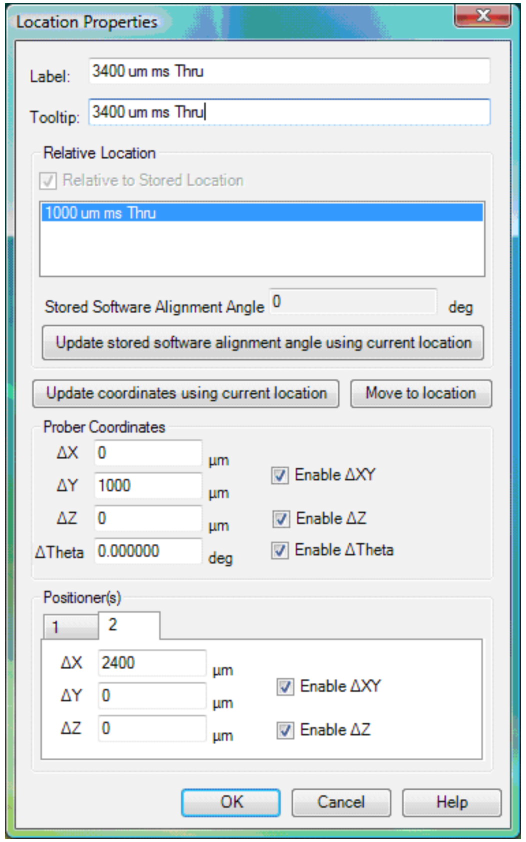
WinCal MLTRL Implementation

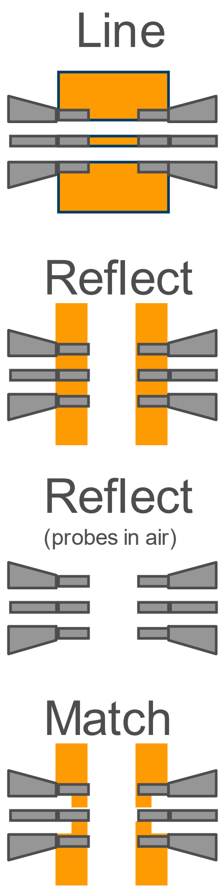






- TRL calibration standards are defined by physical dimensions
- The Location Manager tool provides a way to conveniently record a set of device locations including moves with probe position changes
- For ISS's known to WinCal lines can be selected from known validation lines on ISS bottom

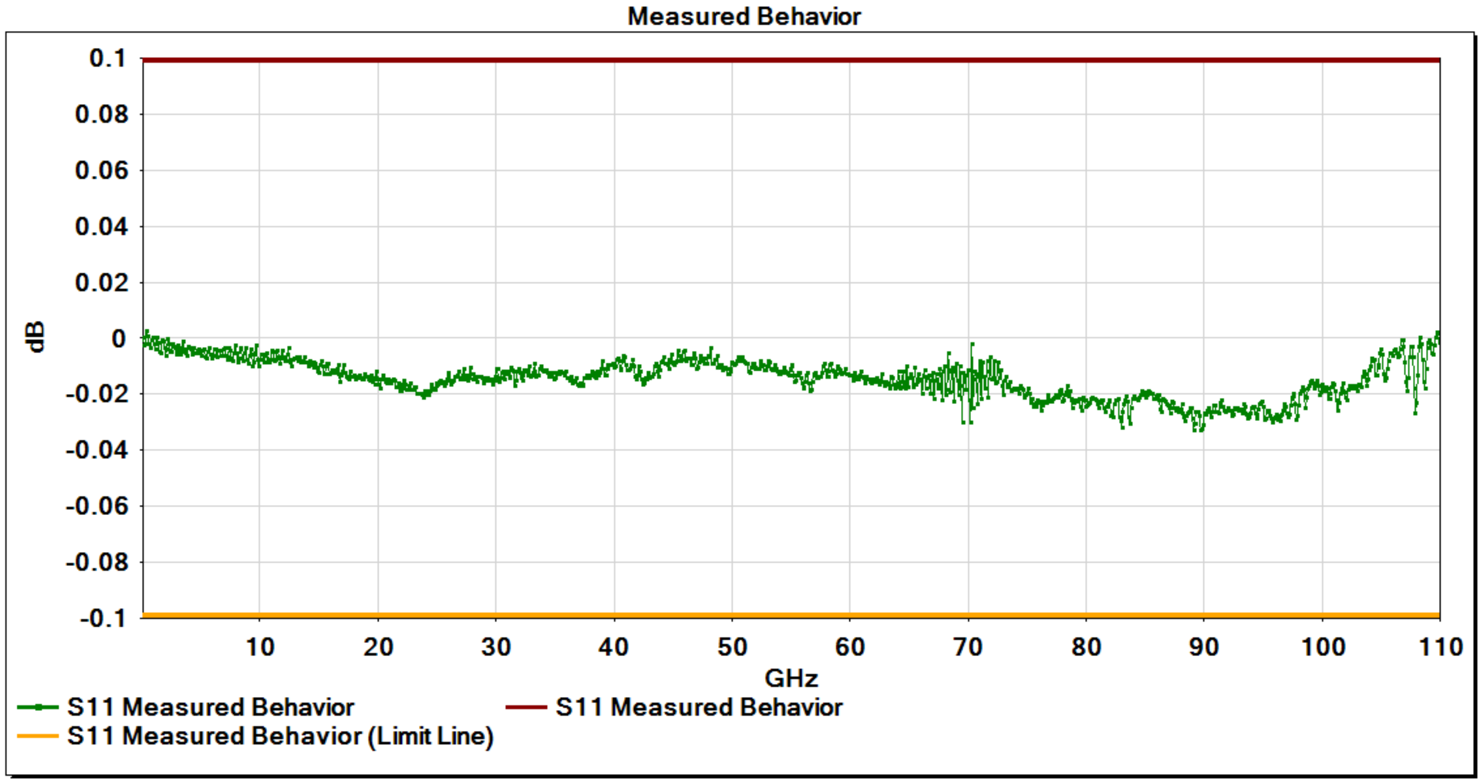
LRRM Calibration



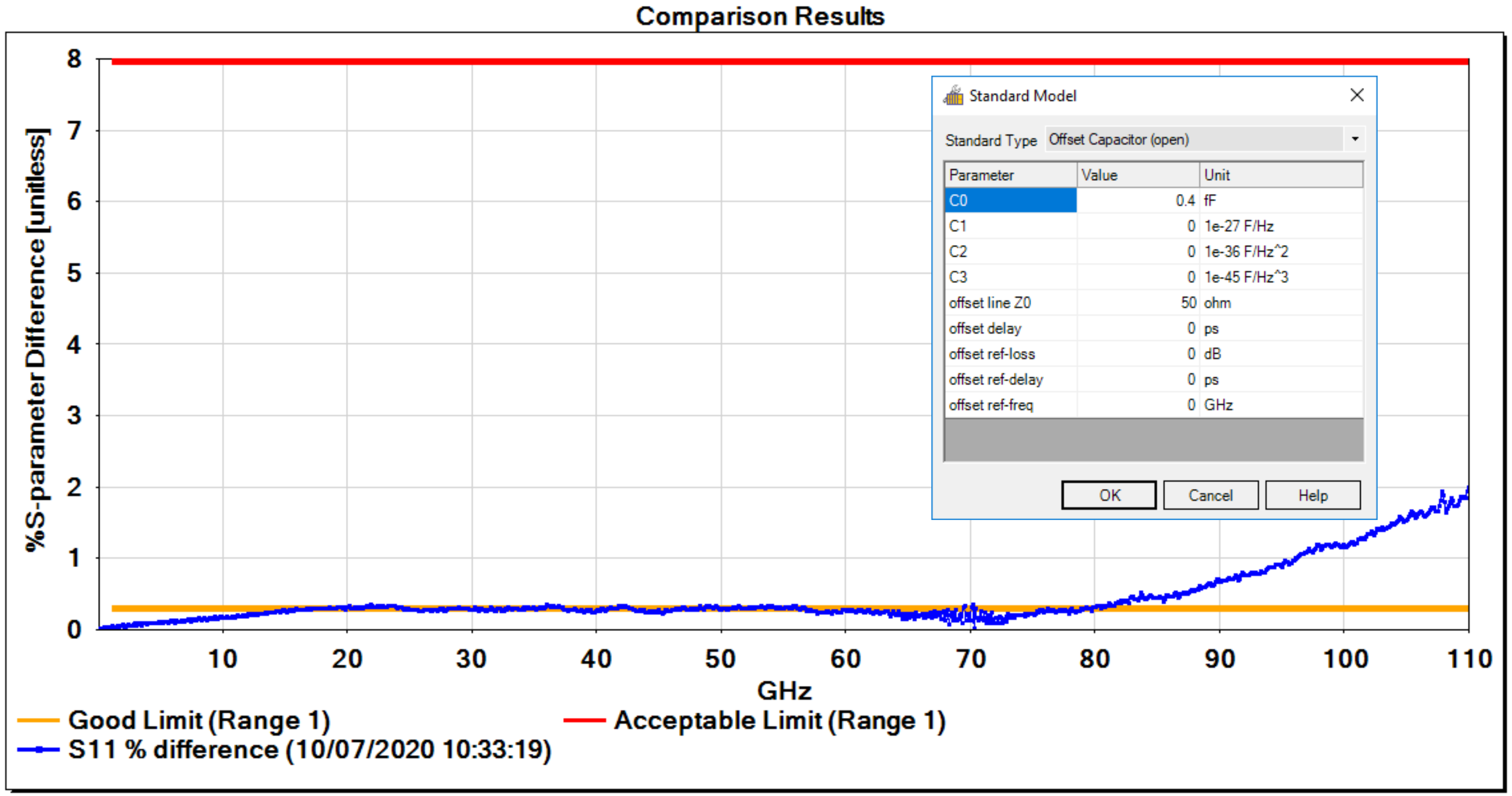
- Same Standards as SOLT
- Industry Standard verified by NIST
- Line-Reflect-Reflect-Match Calibration
  - Thru (line) delay, Match resistance must be known
  - Measurements referenced to trimmed resistor on one port only
  - Patented load inductance compensation
    - Minimize probe placement sensitivity, providing accurate load inductance extraction
    - Improves the accuracy of reference impedance
- Robust and Accurate
  - Less sensitive to probe placement errors
  - Requires less information about standards
- Available in WinCal only (not front panel)

Open Response After LRRM Calibration – Infinity

- Almost ideal
- 2 to 10 X better than other probes
- SOLT always yields perfect response but this does not reflect reality
- LRRM tries to adjust load inductance to adjust gradient but does nothing to flatness
- All that is known is S11=S22
- Post LRRM cal always S11=S22

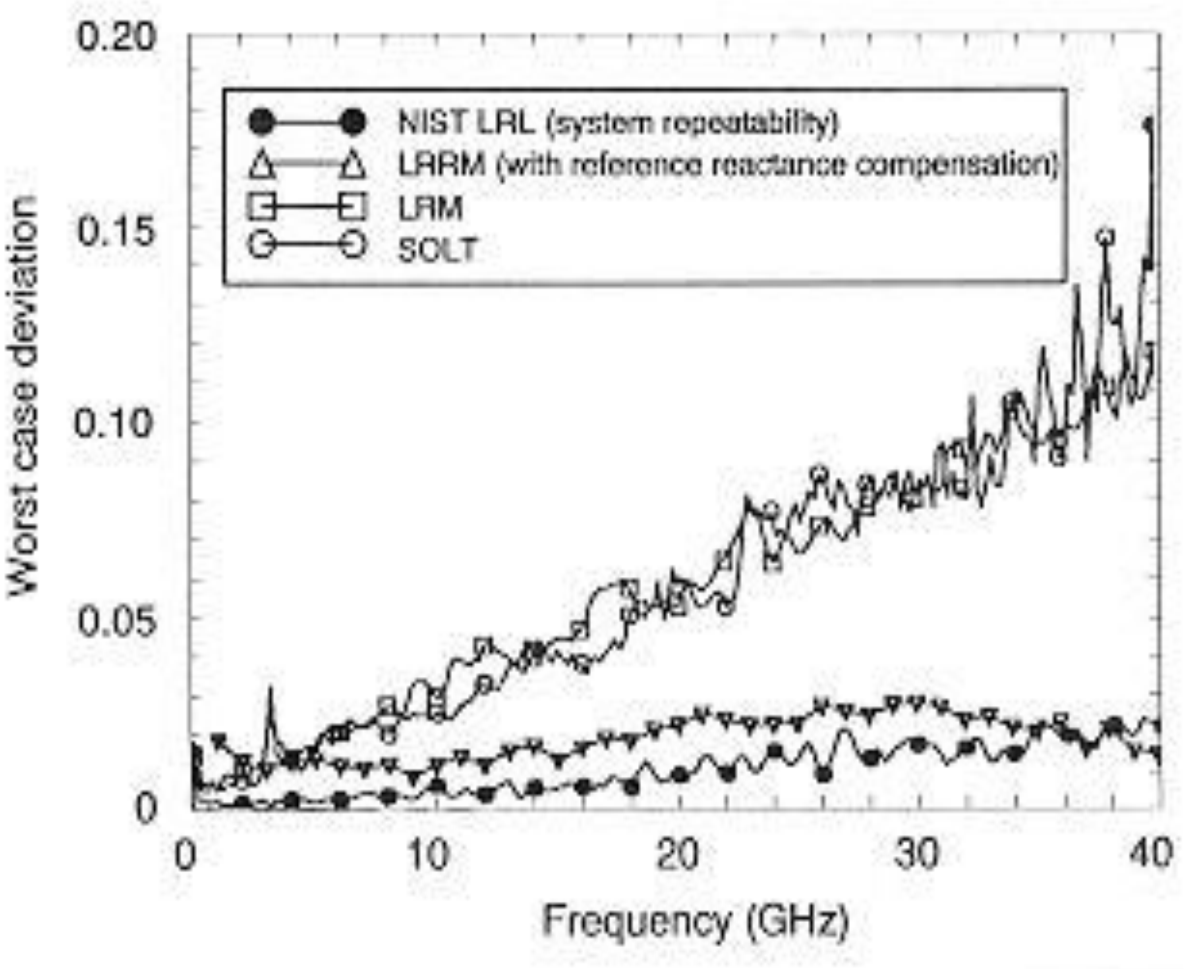


Open Validation in WinCal



- Default Open validation in WinCal XE compares the Vector between the model of the Open including Capacitance and the actual corrected Open (using Correction of raw data)
- In this case from 50 um probes using open on ISS

NIST Verification

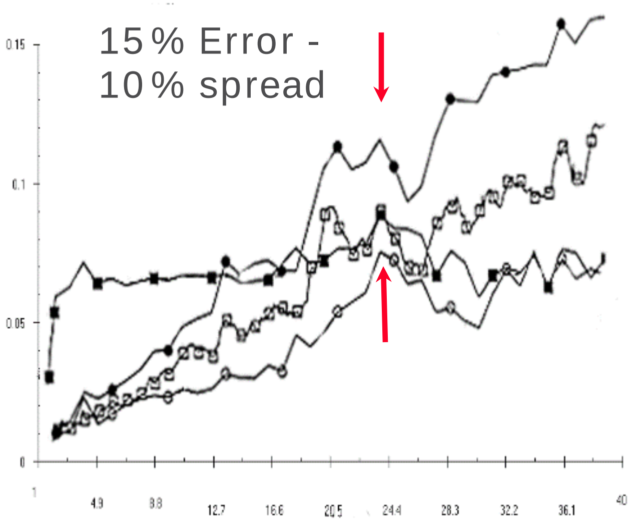


- System drift baseline
- LRRM compares with system drift limit
  - best fixed probe position calibration
- SOLT /LRM
  - growing error w/freq
  - possible CalKit error
  - possible ref plane error

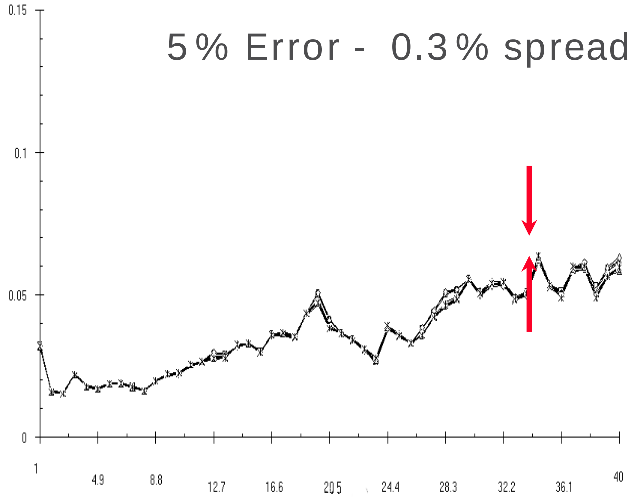
How does a manual calibration compare to an automatic calibration?

Worst Case Accuracy to 40GHz

Four Manual Calibrations



Ten Semi-Auto Calibrations



Semi-auto Prober is faster and far more repeatable!

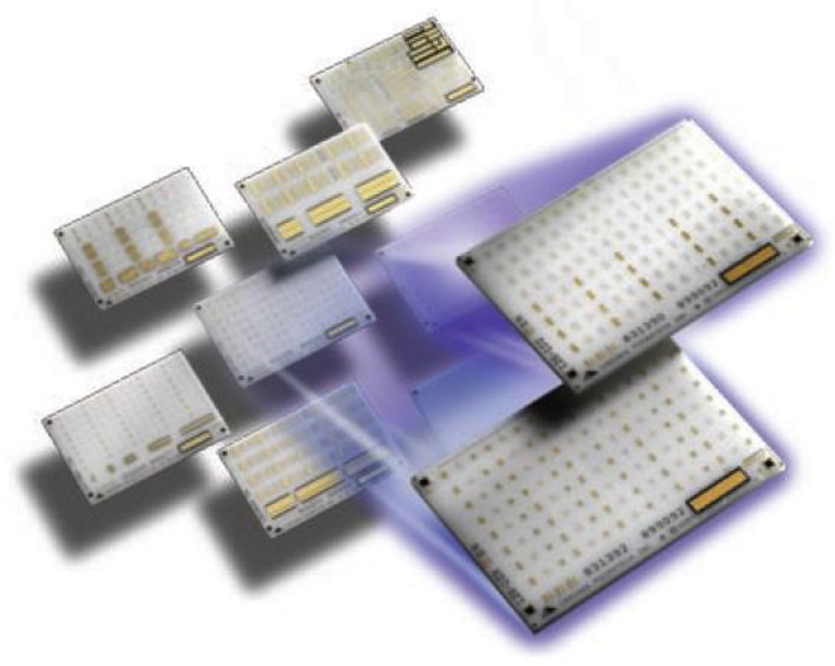
Which Calibration Technique is Best?

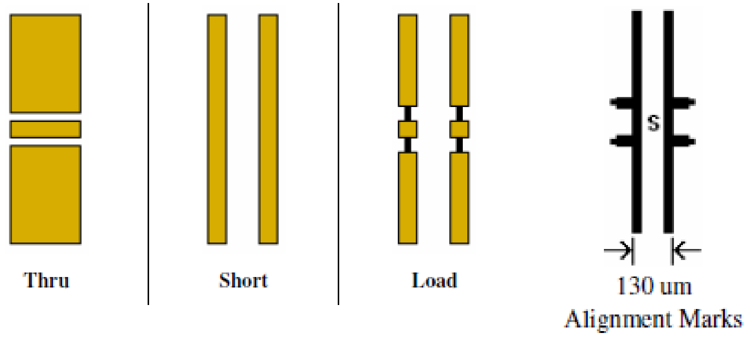
- SOLT
  - Use only when advanced calibrations are not available
  - Does allow Asymmetric probe arrangement
- SOLR
  - Probe card applications
  - All dual signal probe applications
  - Right angle probe applications
  - Note – WinCal XE now includes Hybrid LRRM
    - Combines the best of SOLR and LRRM

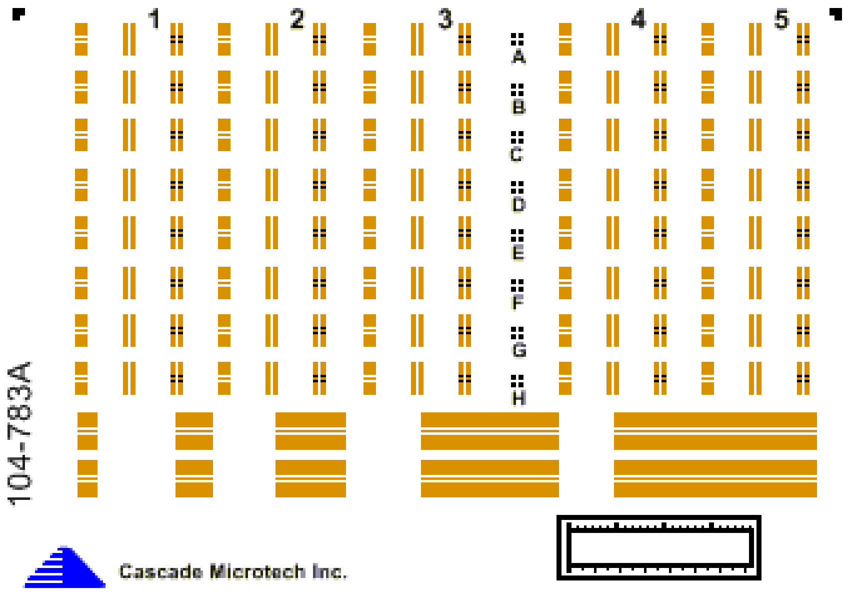
Which Calibration Technique is Best?

- LRRM (with auto load inductance)
  - Best for broadband mmW transistors
  - On-wafer standards with a single load
  - Assumptions start breaking down badly above 500 GHz but can give reliable results to 220 GHz
- TRL / MLTRL
  - Microstrip mmW & THz device characterization
  - Waveguide banded measurements
  - III-V on-wafer mmW microstrip standards
  - Less requirement for de-embedding
  - Can pose difficulties in normalising

Impedance Standard Substrate

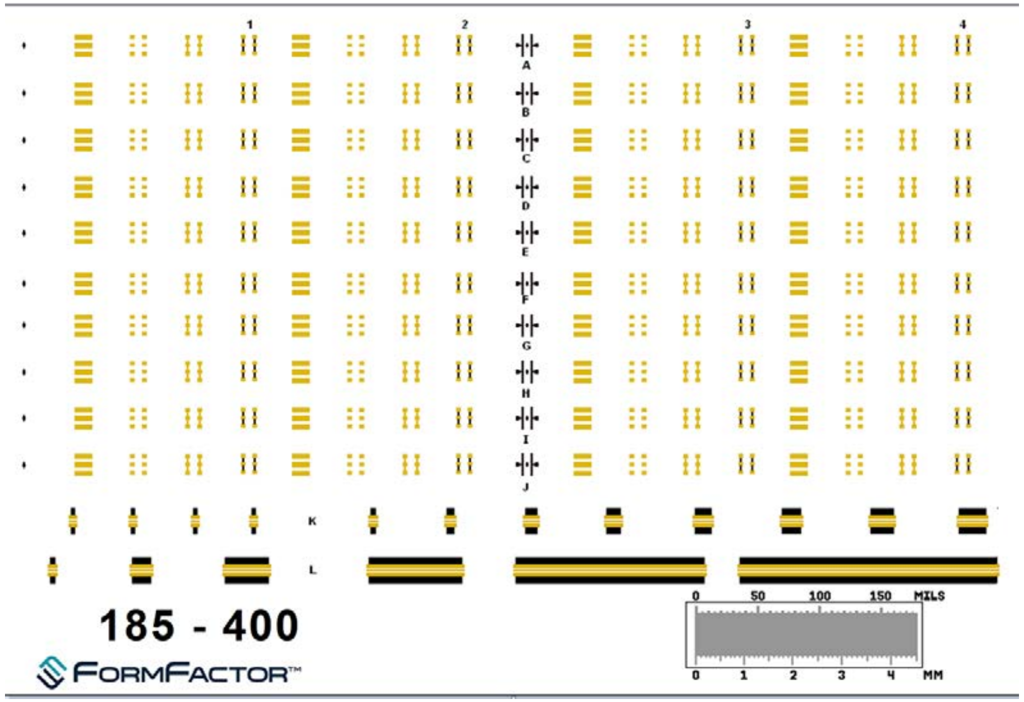


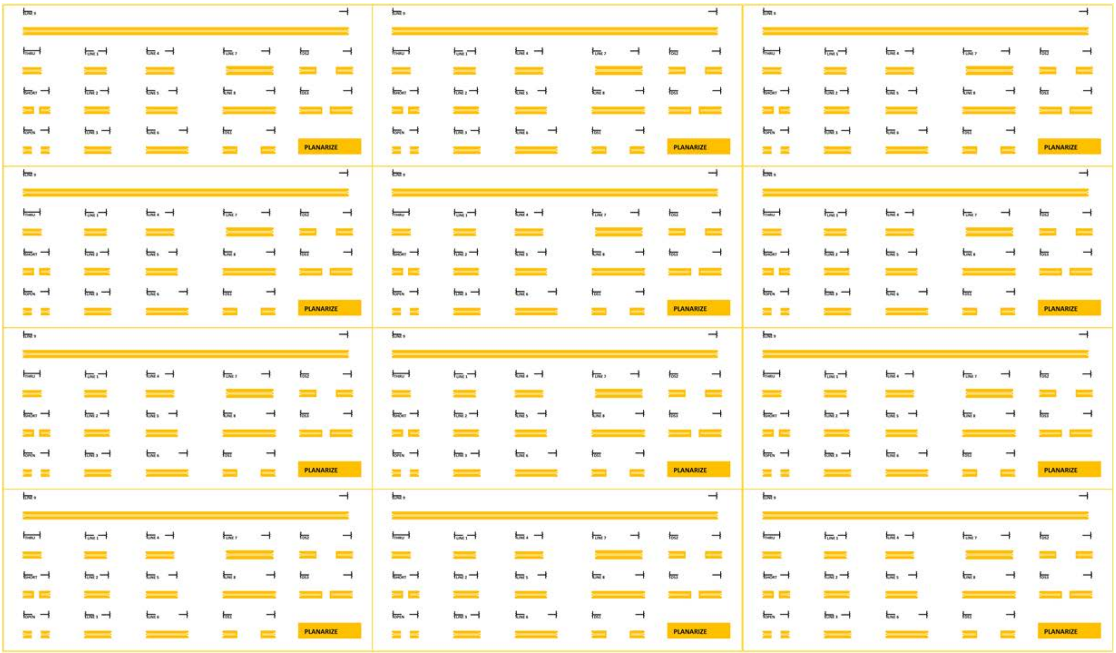




- Tip Configuration
- Probe Pitch
- Number of precisely trimmed Loads is specified

New(ish) **Iss's** you may not be aware of



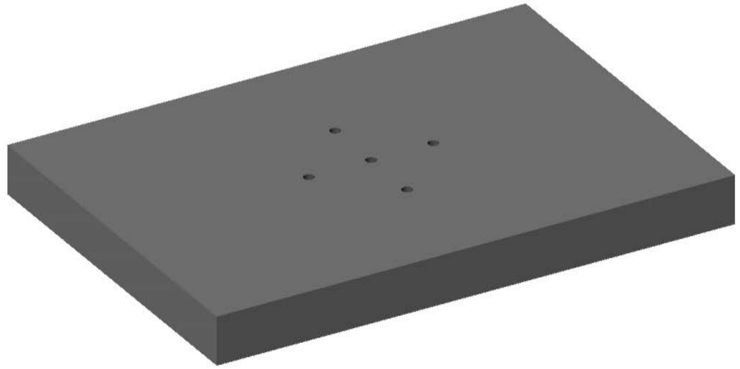


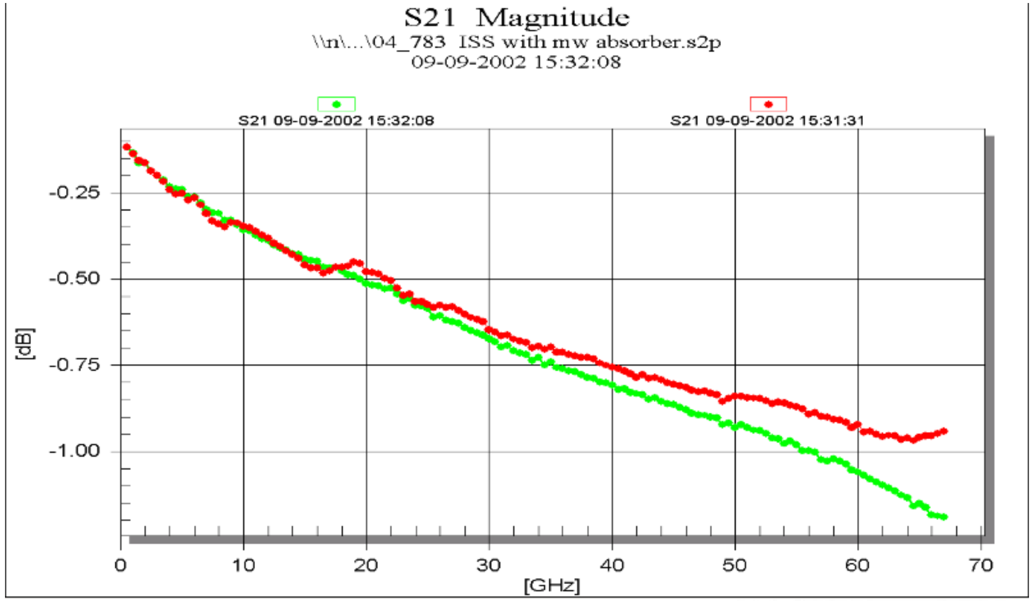
Part number	Description	Pitch (µm)
172-885	Multi-line TRL Substrate, WR1.0, WR1.5, WR2.2, WR3.4, WR4.3, WR5.1	25
172-886	Multi-line TRL Substrate, WR2.2, WR3.4, WR4.3, WR5.1	50
172-887	Multi-line TRL Substrate, WR3.4, WR4.3, WR5.1	75 and 100

- 185-400 – All locations 50 um
- 172-885 thru 887 designed primarily for T wave but will work with Infinity
- Useful offset short standards also

Absorbing ISS holder

- Measurements > 50 GHz, unwanted modes are excited – ie non CPW
- Microwave absorbing ISS holder reduces unwanted modes (PN 116-344)
  - Ideal for LRRM, LRM & SOL-R, MLTRL calibrations
- CM300 / Summit 200 have potions for this to be built into prober



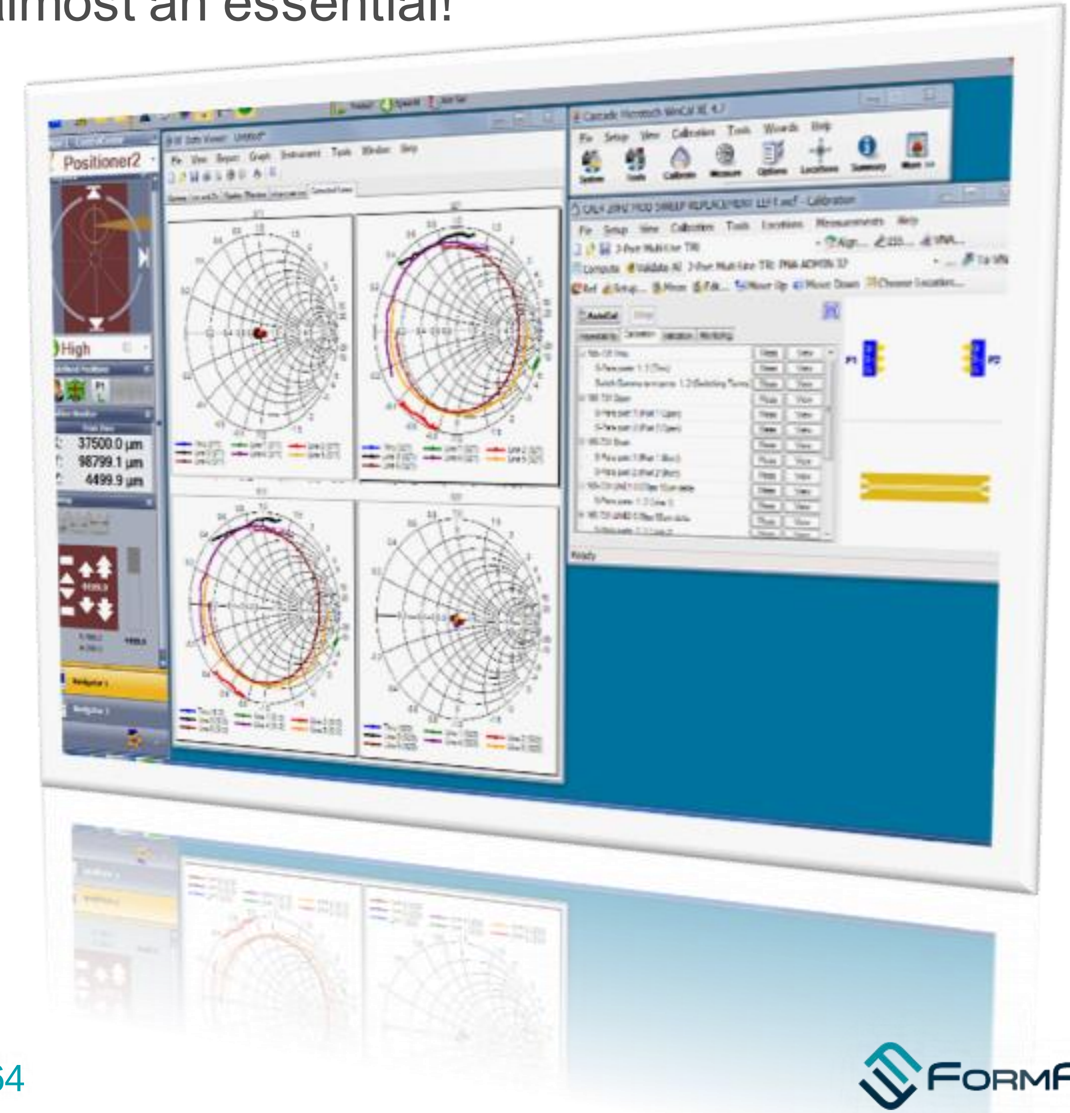


WinCal XE Calibration Software

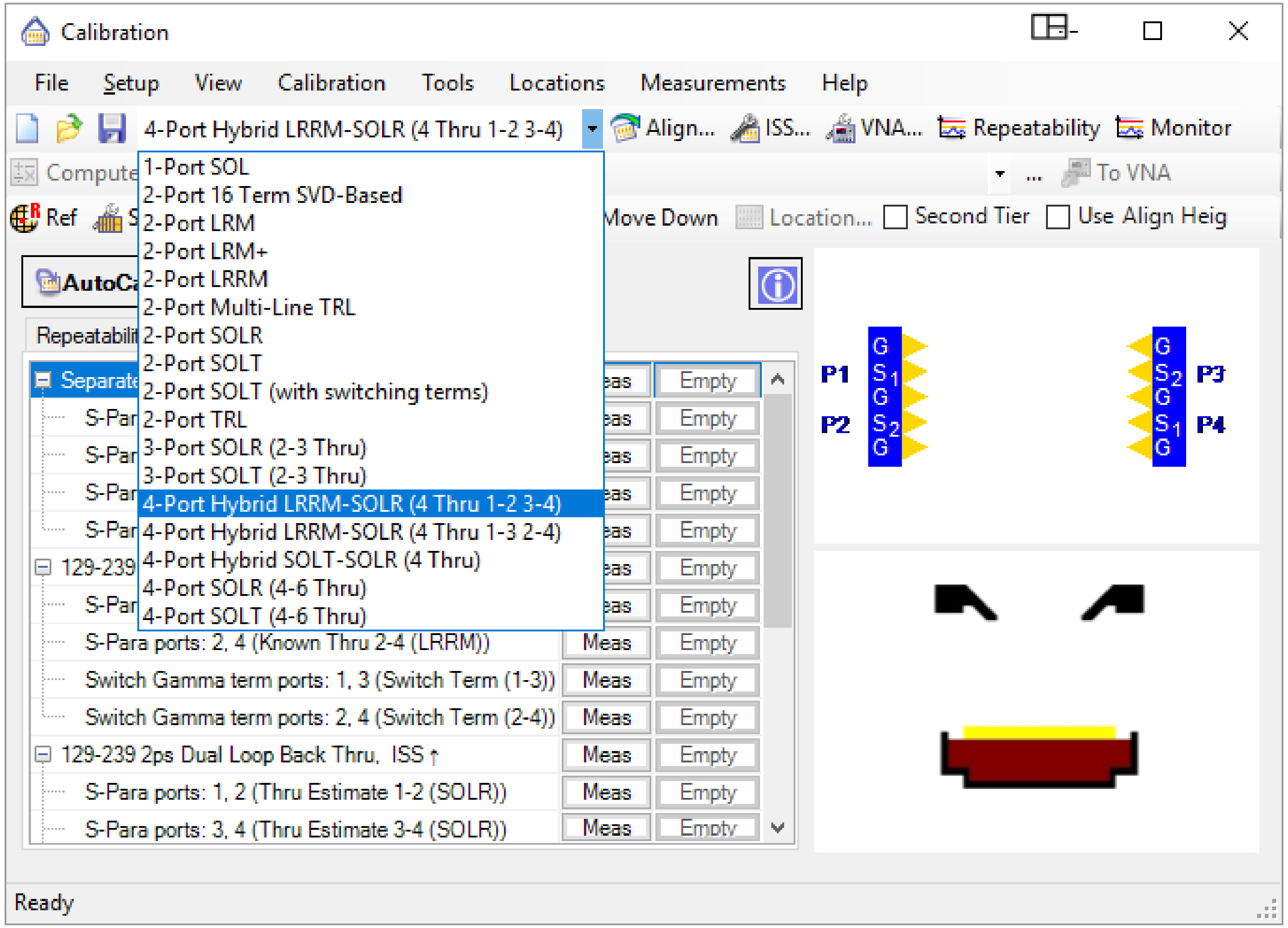
For On-Wafer Calibrations an extra Software almost an essential!

- Tools for the novice
  - Guided Wizards
  - Multimedia Tutorials
  - Intelligence in setups

- Advanced Tools
  - Multi-Port Hybrid Cals
  - Enhanced Verification
  - Advanced reports
  - Post Processing
  - Sequencing



Full family of calibration methods



- Includes more exotic methods like 16 term SVD which incorporates cross talk
- 4 Port Hybrid cals now support more flexible approaches for using GSG iss for cross calibration

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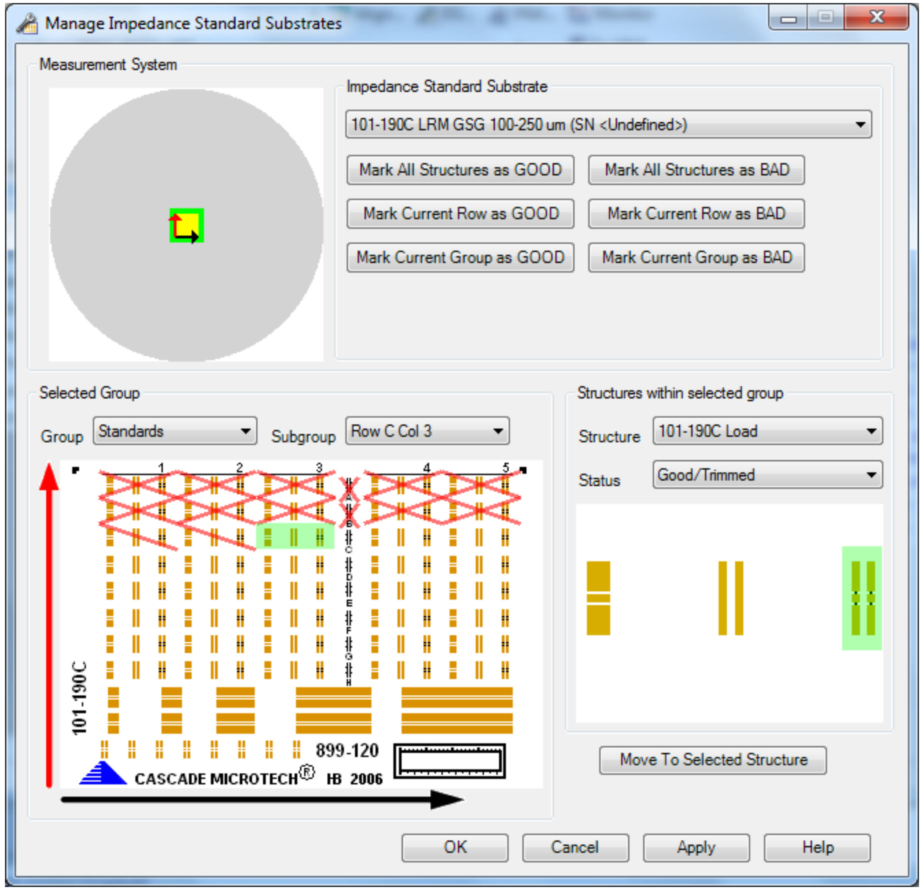
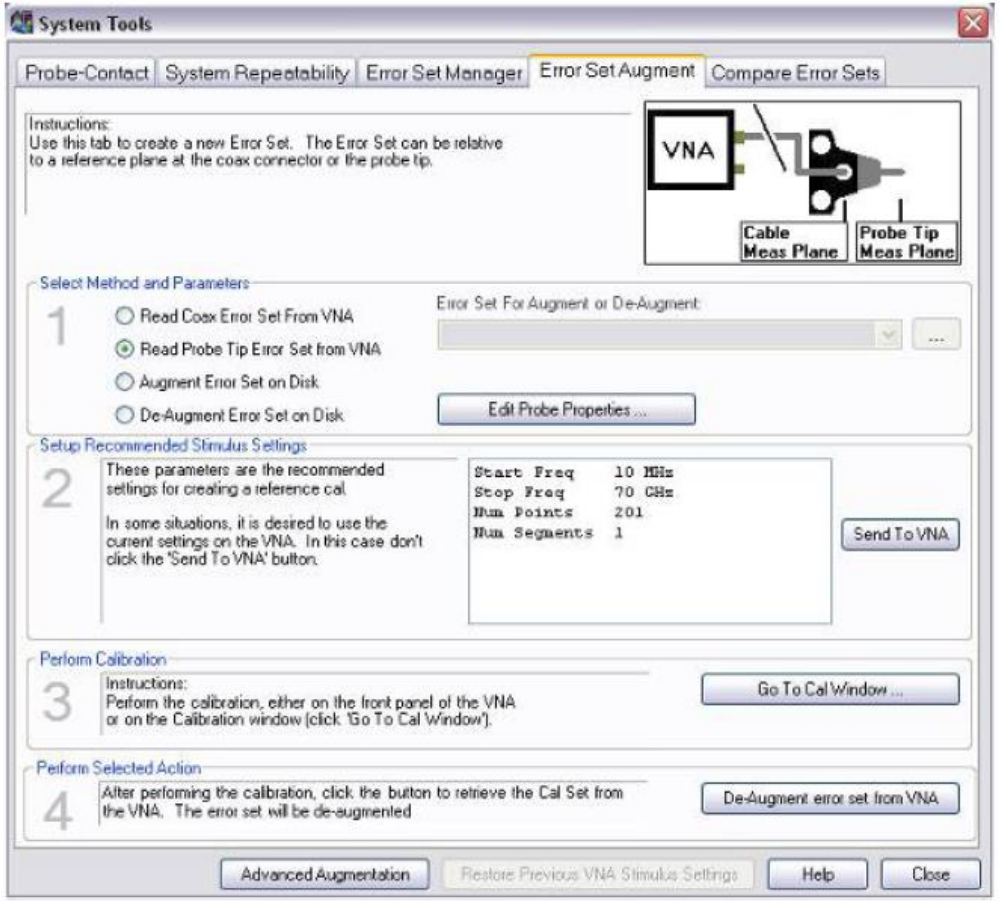
ISS Standard tracking

- WinCal automatically selects standards indicated as valid for calibration
- ISS status tracked via serial number

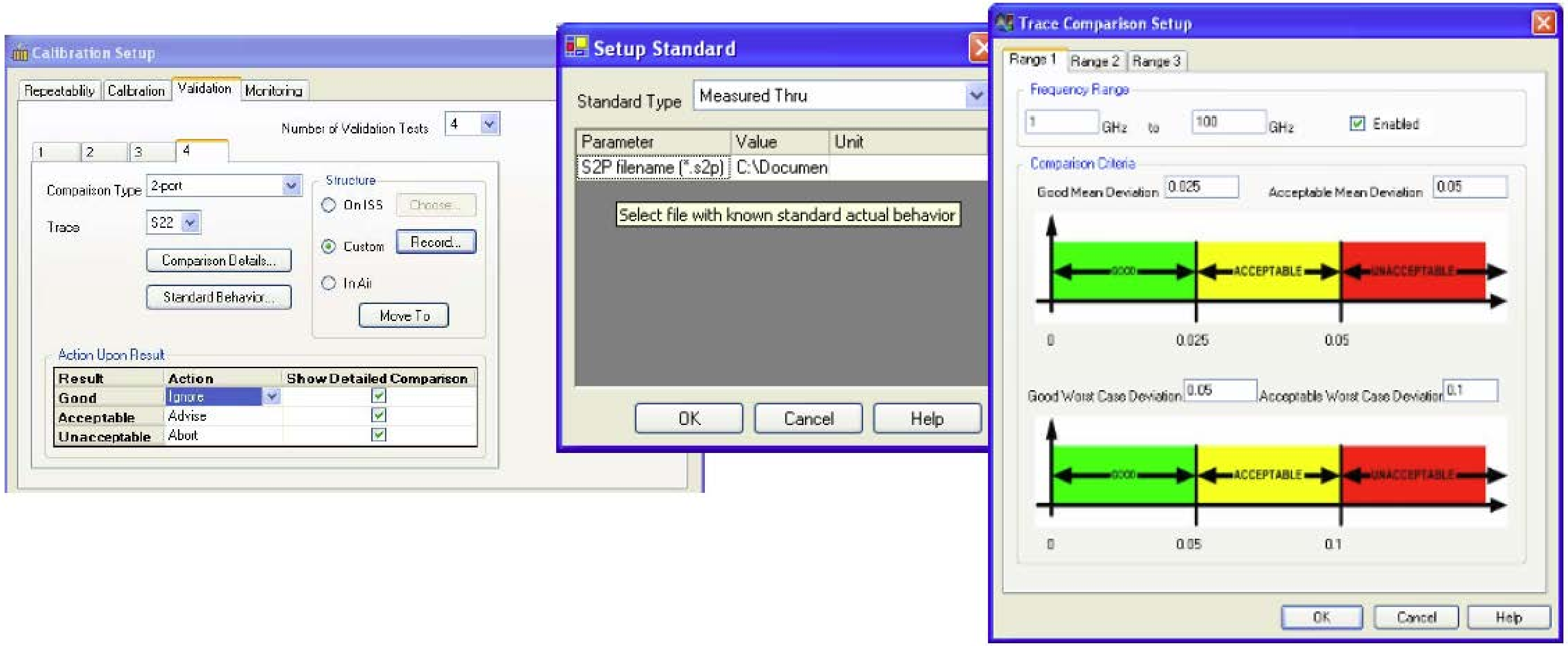


System Tools

- Compare Error Sets
- Test System Repeatability
- Check Cables, Probes, Contact Resistance & Probe Planarity
- Augment Error Sets
- Manage Error Sets



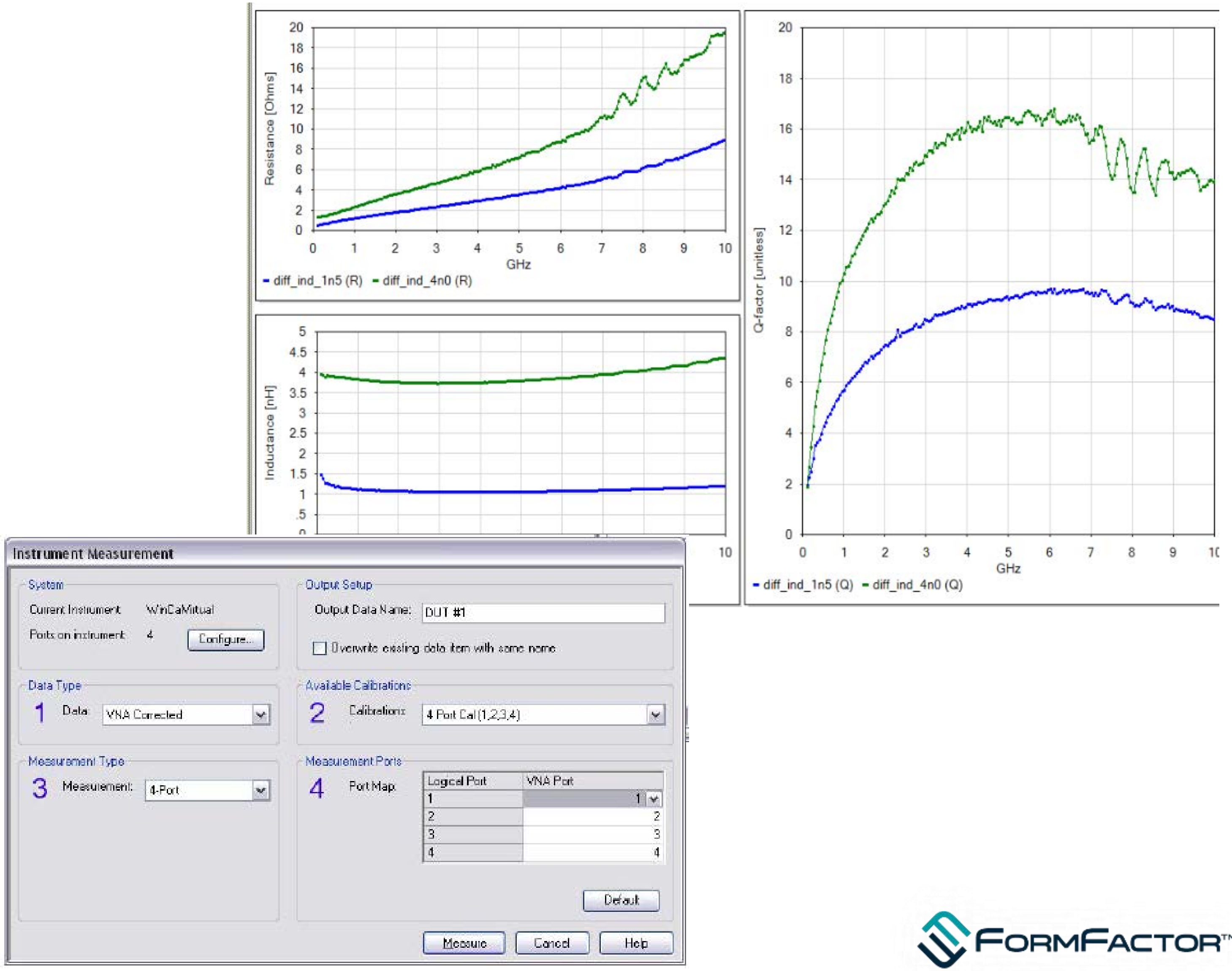
Validation and Monitoring



- Automatic validation of calibration
- Monitoring of calibration drift – can be triggered by remote comaand or automatically using Autonomous RF Measurement assistant
- Report acceptable/unacceptable behavior as desired

Measurement & Reports

- Measure RAW or corrected S-Parameters
- View
  - S-Parameters
  - Derived Data
- Can be used to measure and process data using remote control



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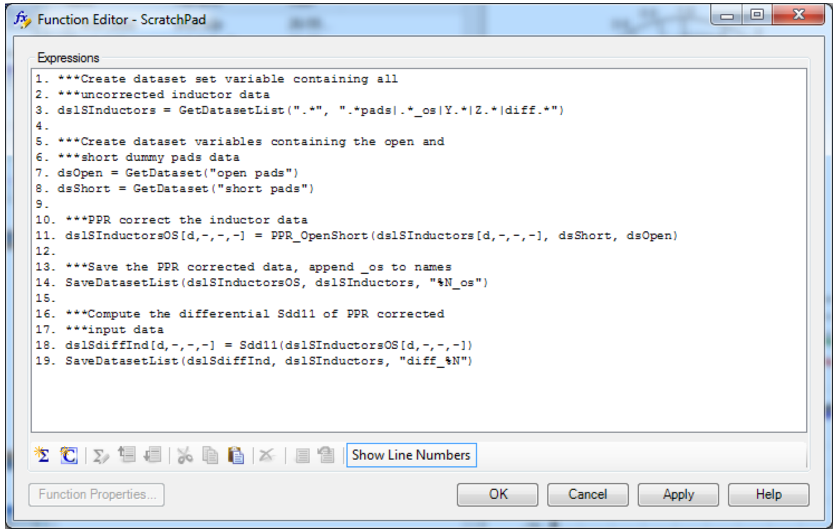
Post Processing Data

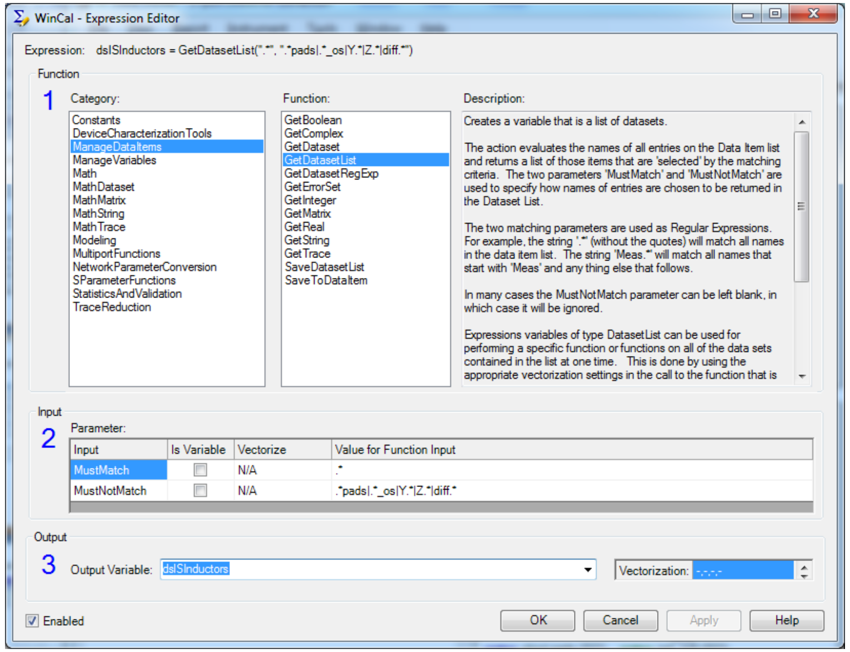
- **What is "Post Processing"?**
  - Post processing is the ability to mathematically manipulate S-Parameter data within WinCal XE by employing one or more mathematical functions.
  - WinCal XE comes with a vast library of functions for use. You can also create your own functions and add them to the library.

- Examples include:
  - Convert single-ended S-Parameters to mixed-mode S-Parameters
  - Compute Ft, Mason's Gain, Max Gain, etc.
  - Extract L, R, C and Q from circuit measurements
  - Compute the Error Vector Magnitude difference between datasets
  - Ability to use customised matrix mathematics to form specialised extraction routines

Post processing – Math scratch pad

- Math scratch pad allows matrix / data manipulation and processing with GUI generated scripting
- Very powerful
- Operates automatically during remote data acquisition – ie de-embedding on the fly





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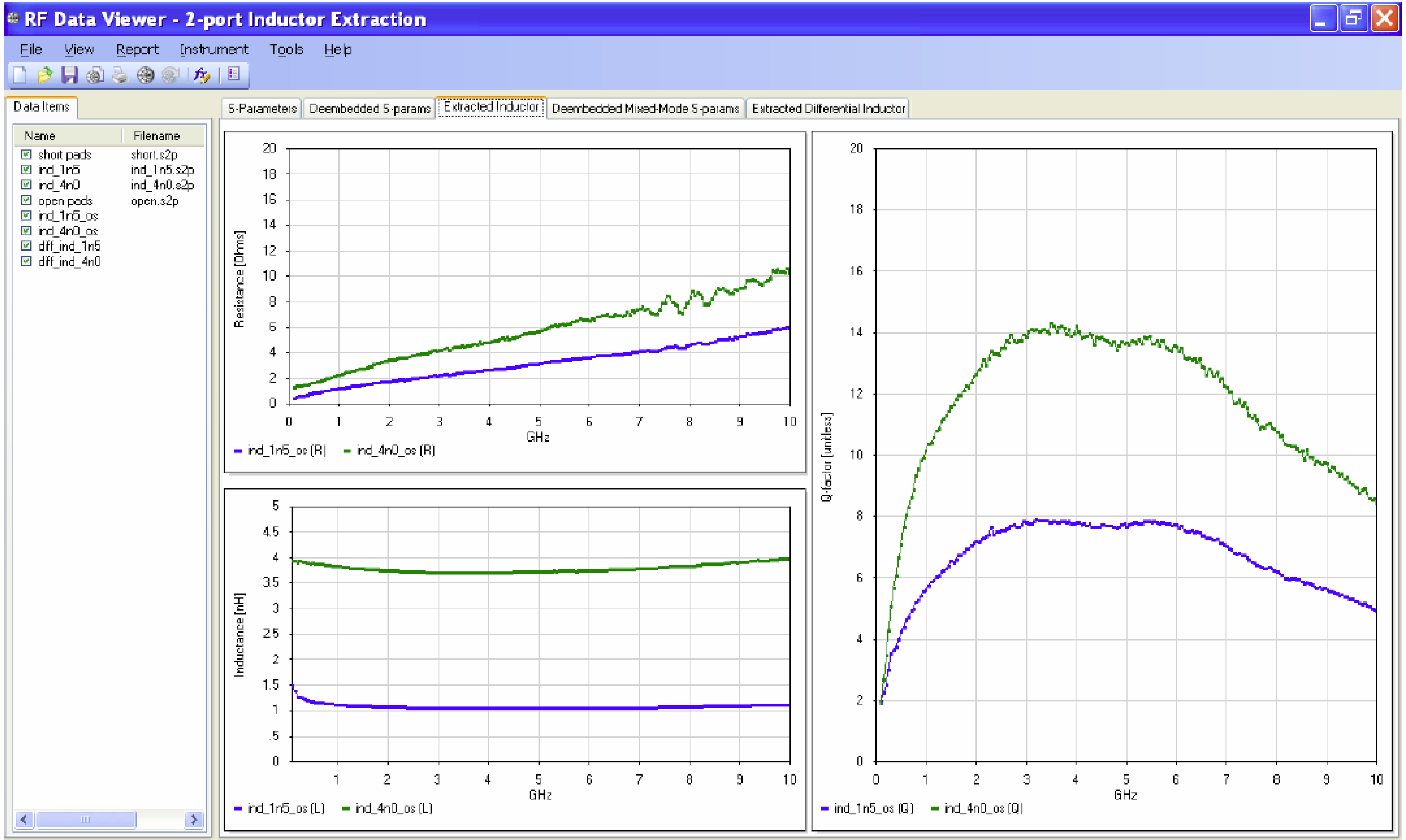
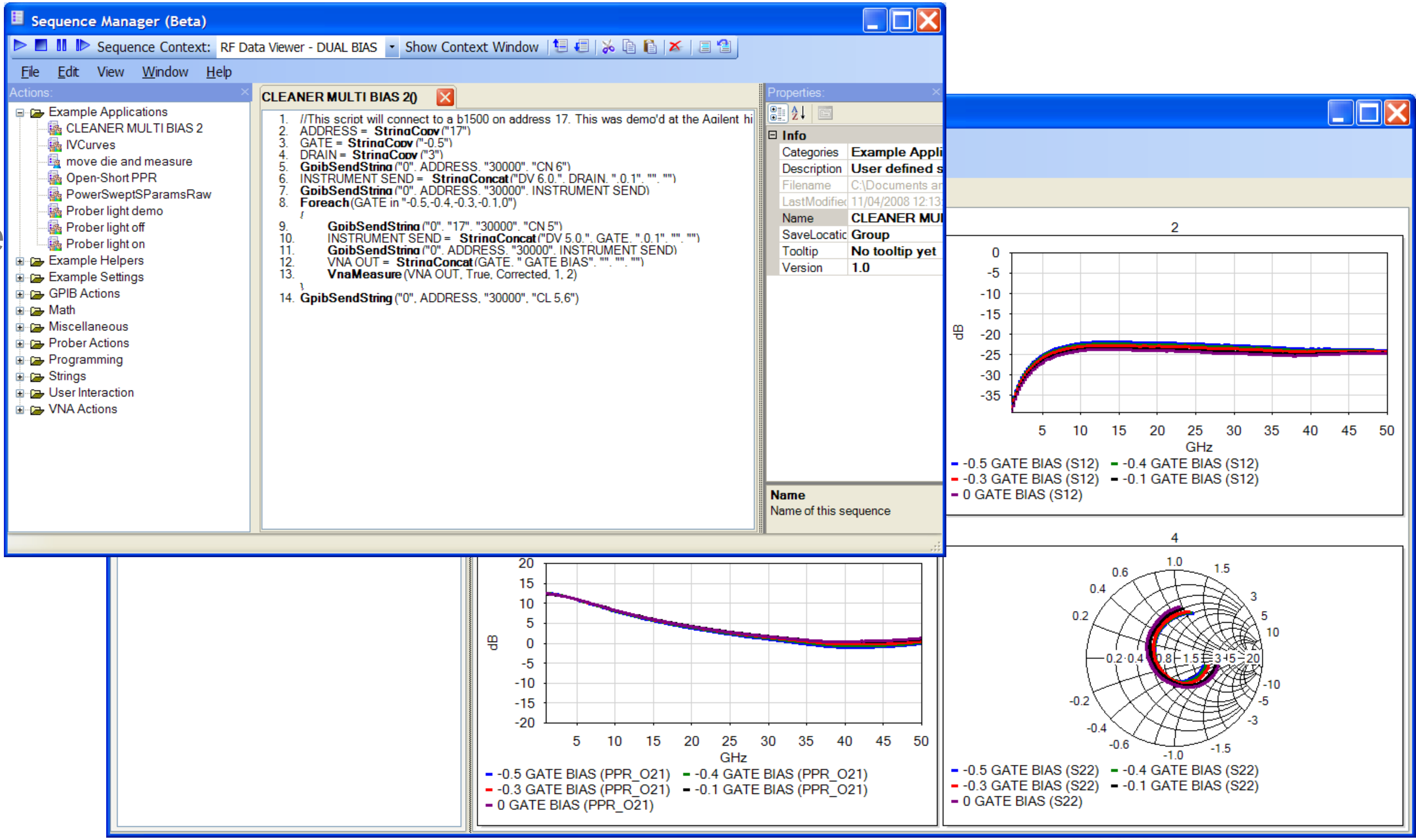
Extract Device Parameters

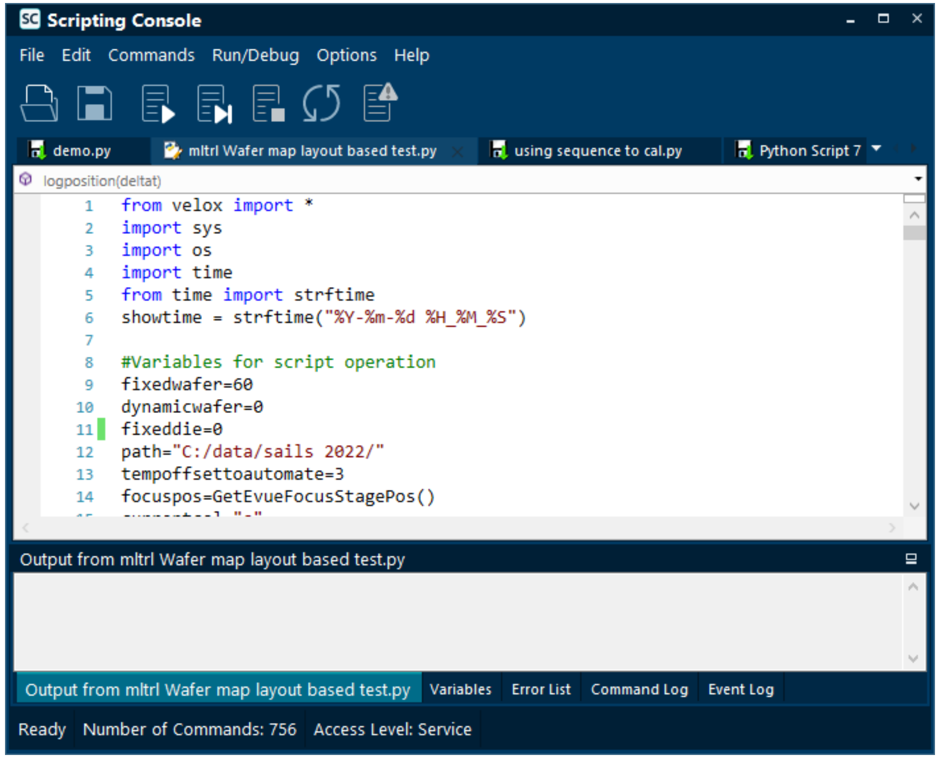


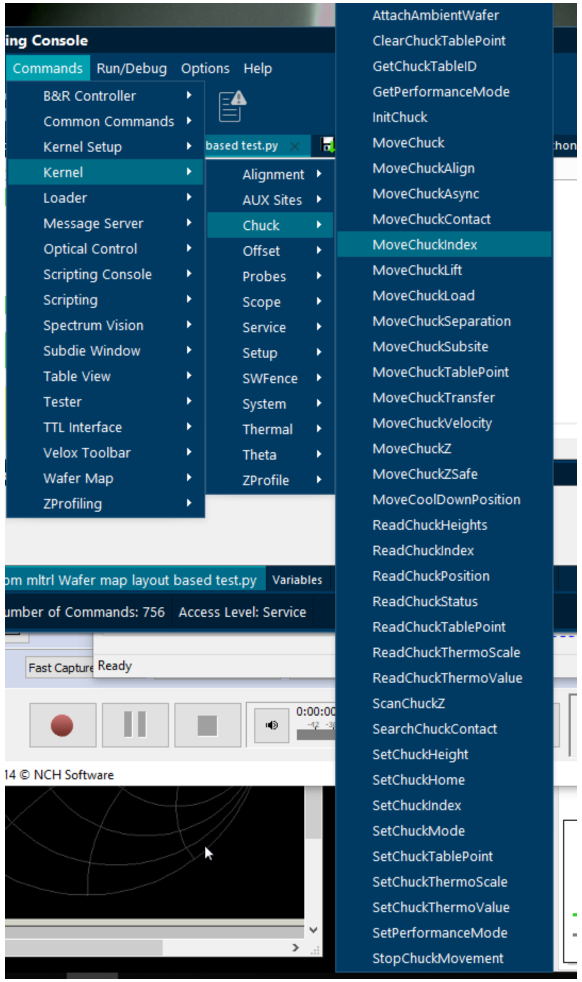
Sequences

- Sequences allow the Prober and external Instrumentation to be controlled by WinCal
- Sequences allow for more exotic post processing to be done
- Perfect for a quick and simple mini test exec
- Commands pretty similar to Basic
- Remote control of external devices is done via GPIB



Remoting





- WinCal Remoting is used to allow WinCal to be controlled by other software like Python script, .Net applications, Matlab and Labview and Vee
- Allows control of most elements of WinCal from the Velox scripting console
- Many remoting functions now accessible using GPIB via Velox using WinCal 4.9 and Velox 3.2
- Scripting console native to Velox and really convenient with command lookup

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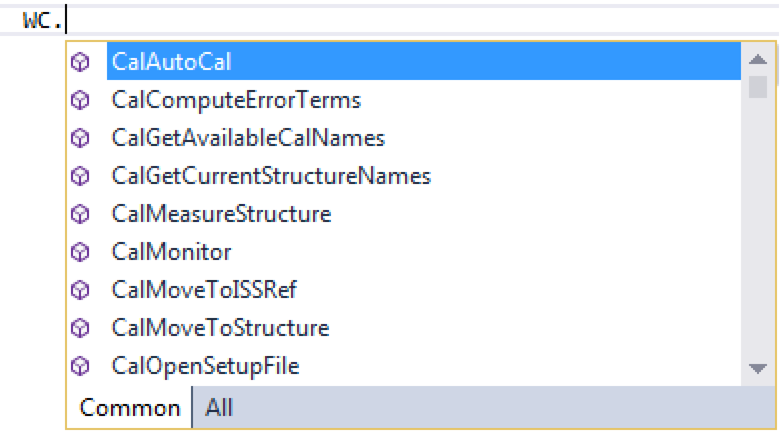
WinCal remoting and .NET

```
Private Function ConnectToWinCal() As Boolean

    WC = New CMI.WinCalRemoting.cWinCalClient

    If WC.WinCalOpenServer(txtHostName.Text, CInt(txtHostPort.Text)) Then
        Dim ServerName As String
        ServerName = WC.WinCalServerName
        lblInfo.Text = "Connected to : " & ServerName & CrLf & "via .Net Remoting" & CrLf & CrLf
        WC.EventWindowShow()
    Else
        MsgBox("Could not open wincal server.  Is WinCal Running?")
        WC.WinCalCloseConnection()
        Return False
    End If

    Return True

End Function
```

```
Dim TEST As String = ""
For i = 0 To (number_of_locations - 1)

    current_location = location_names(i)
    lblInfo.Text = lblInfo.Text & "Number of locations" & number_of_locations & CrLf
    lblInfo.Text = lblInfo.Text & " Current location " & current_location & CrLf
    Calresult = WC.LocMgrMoveToLocation(current_location)

    Calresult = WC.StaPassStringToStation("MoveChuckContact 100", TEST)
    Calresult = WC.ViewerMeasureCorrected(current_location & "_" & Cal_root_name.Text & "_Cal number_" & CStr(loopcounter))
    lblInfo.Text = lblInfo.Text & Calresult & CrLf
Next
```

- WinCal XE dll has a variety of methods available viewer by “intelli-type” once referenced
- Methods available include Autocal, Save cal file, Open and save report, move to location, measure S par data



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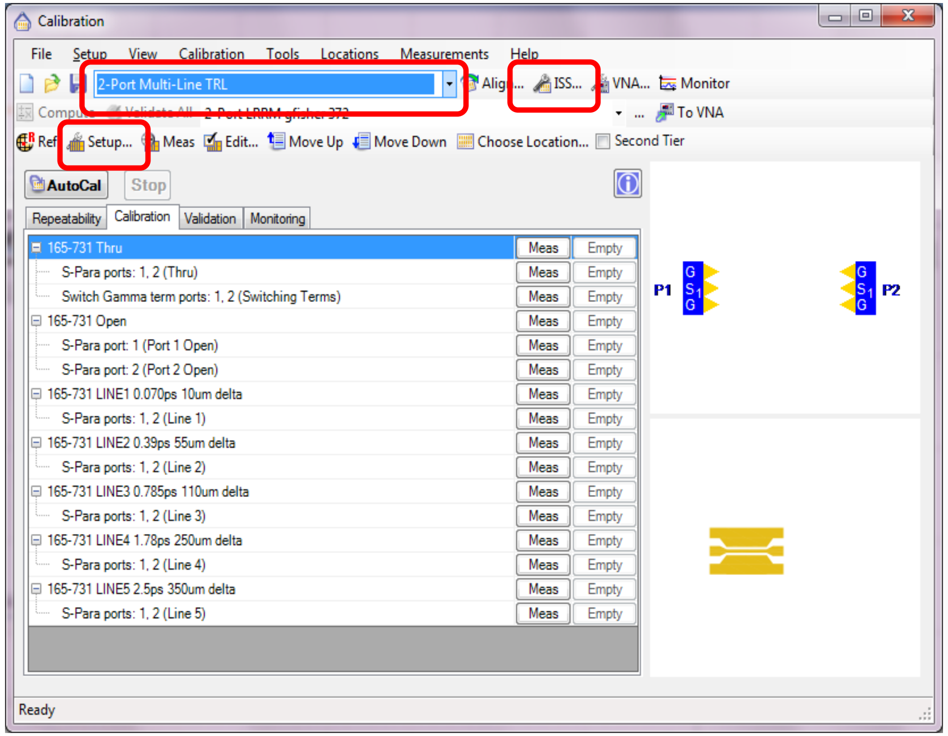
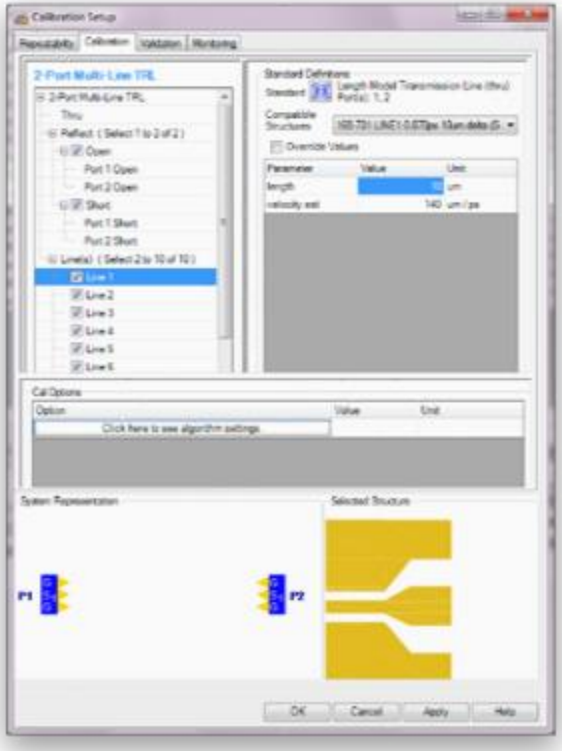
Automated MLTRL and others supported





When AutoCal is pressed WinCal XE handles all stage and positioner movements, raw standard measurement and creation and sending of error set

- Select Multiline TRL
- Press set-up to configure calibration (Lines used)
- Press ISS to configure Group used for cal
- In System setup recording reference position registers positioner location also

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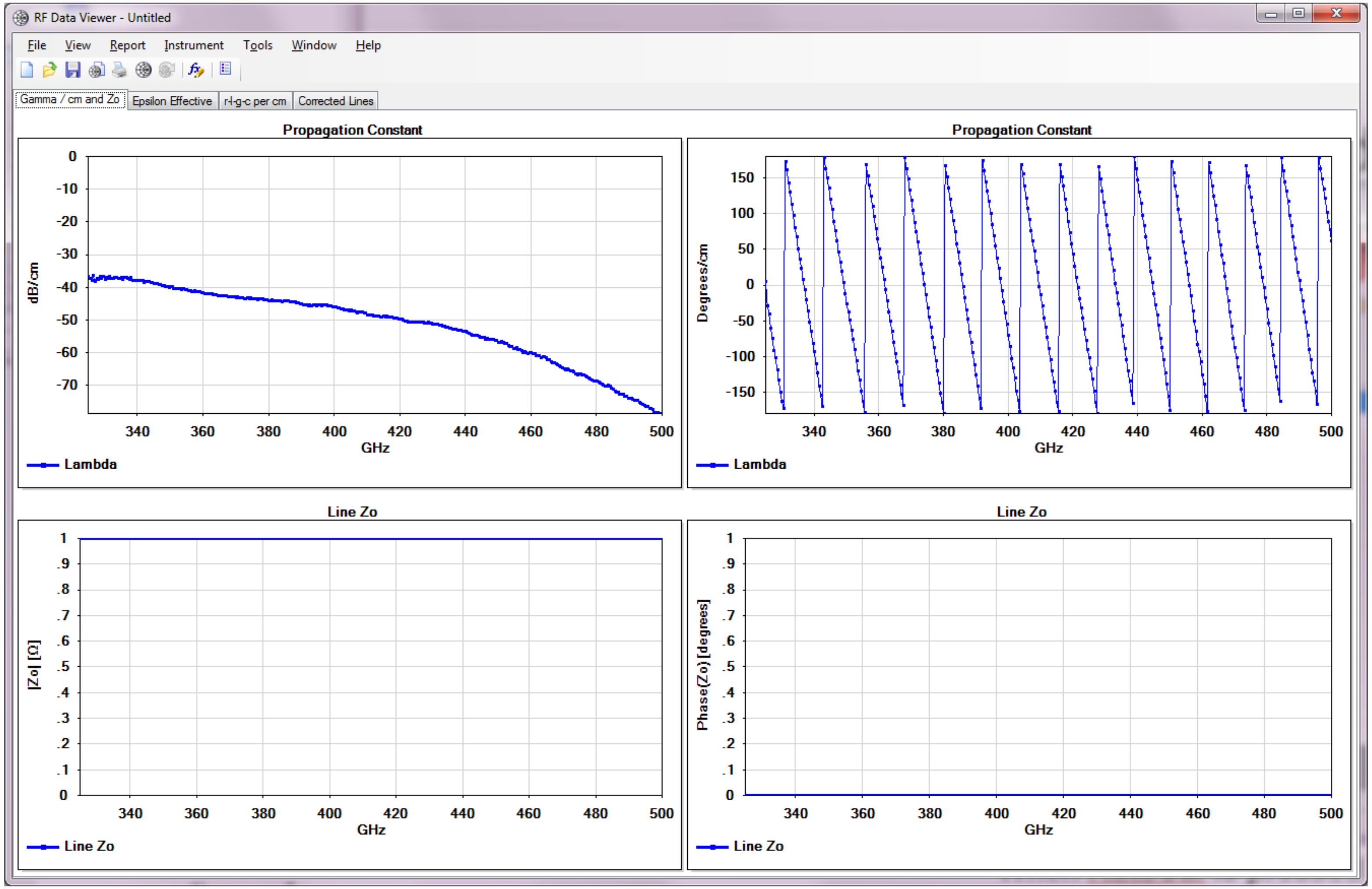
MLTRL Calibration Report provides propagation constant

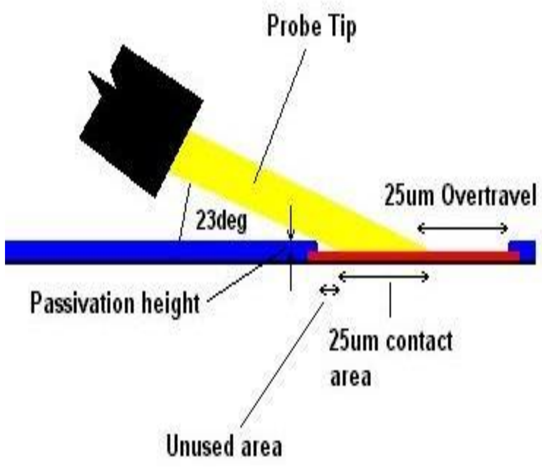


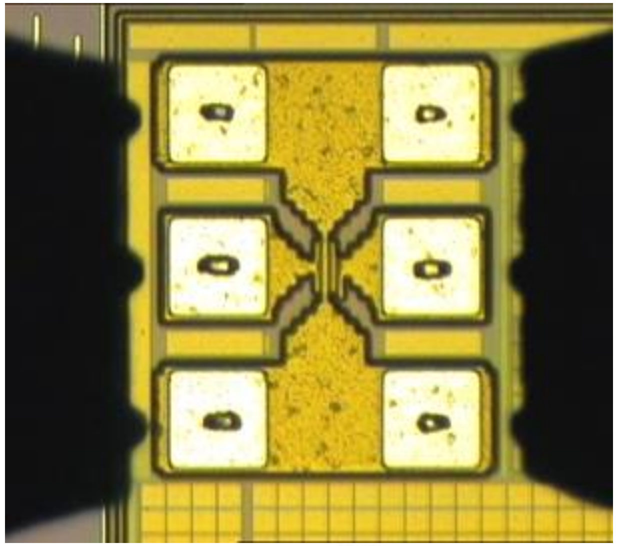
- Propagation constant characteristics give a reasonable metric of cal performance
- This can be used by Wincal to move the reference plane to the probe tips

Device design considerations

Pad Sizes

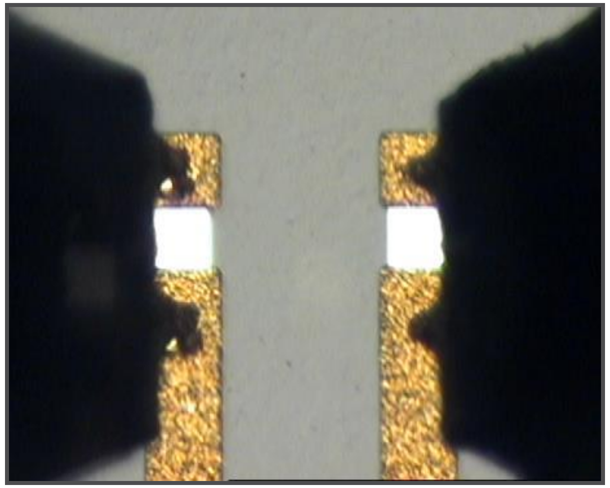
- Recommended minimum pad is 80 µm x 80 µm for ACP Probes
- Infinity Probe Allows 50 µm x 50 µm probing
- Passivation height must be considered
- Pad height variation must not exceed 25 µm for ACP or 0.5 µm for Infinity

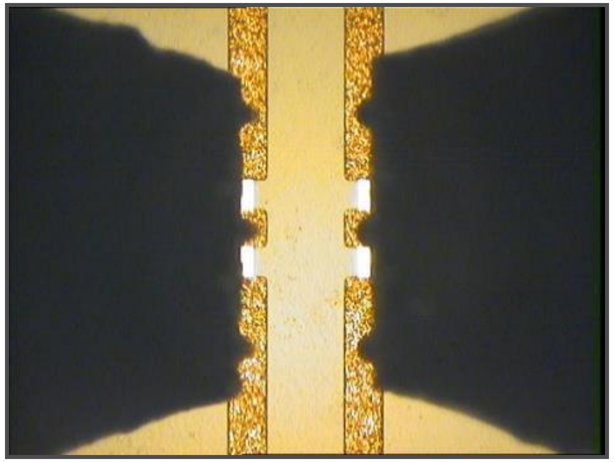




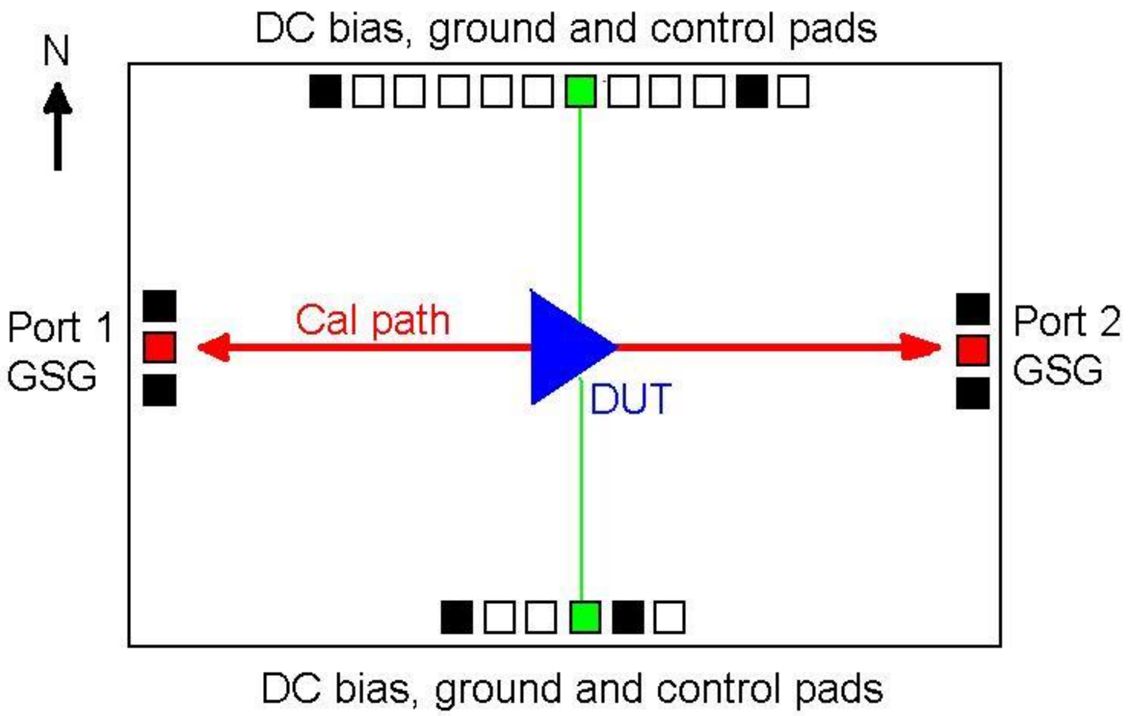
Probe Configuration

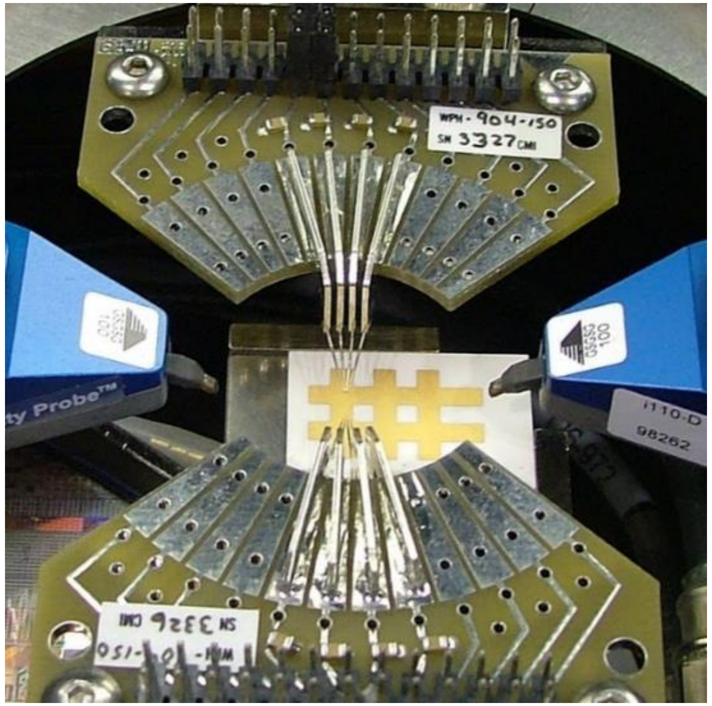
- Whenever possible use GSG
  - Use GSG above 10GHz
- Probe pitch affects S-parameters
  - Use smallest practical pitch
    - 1/50th λ of highest frequency for GS
    - 1/20th λ of highest frequency for GSG



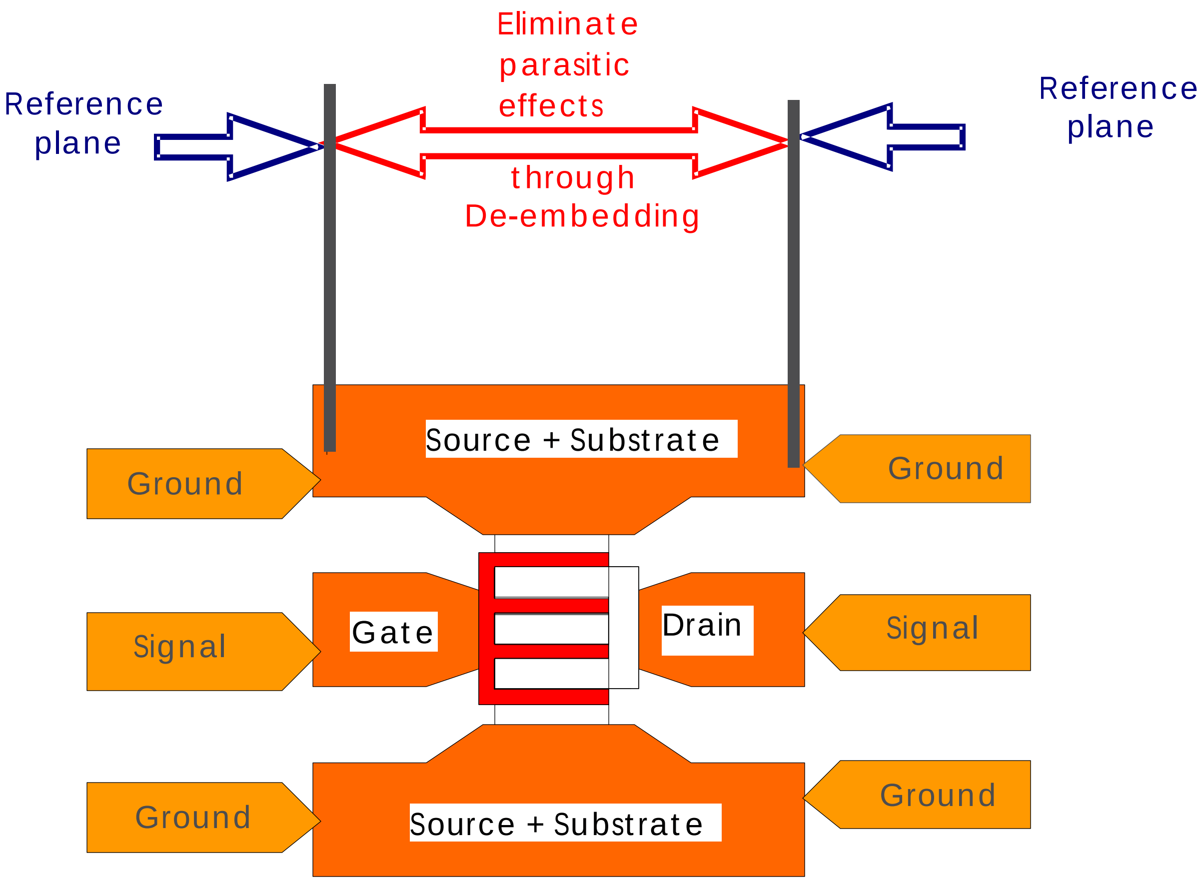


Device Pad Layout





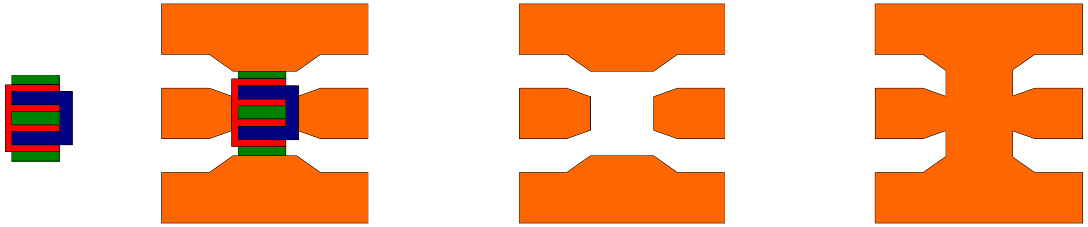
Measurement and De-embedding



- After calibration, the measurement reference plane is at the probe tip
- What is measured is the response of the device and the parasitics associated with the pads

De-embedding dummy devices

De-embedding from OPEN and SHORT



The parasitics of the OPEN consists only of parallel elements to the DUT

- More importance for high impedance devices

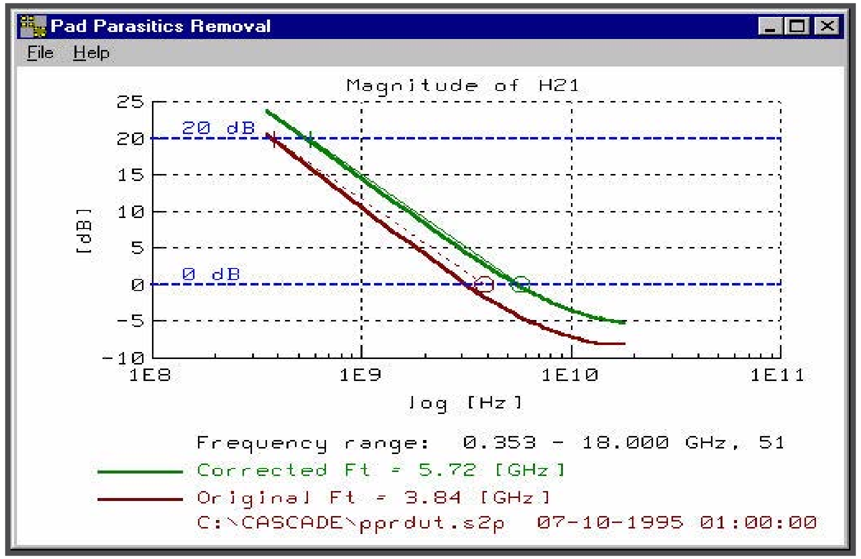
The parasitics of the SHORT consists only of series elements to the DUT

- More importance for high impedance devices

Use of Z and Y correction also helps eliminate residual cal errors

De-embedding Techniques

- Open and Short 'dummy' devices need to be measured
- S-parameters are transformed to Y, Z-parameters
- The dummy devices can be subtracted from the actual device
- The resulting Y, Z-parameters can be transformed and displayed
- These functions are also built into WinCal XE



System performance metrics and tips for repeatability

Solution Benchmarking & Guarantees

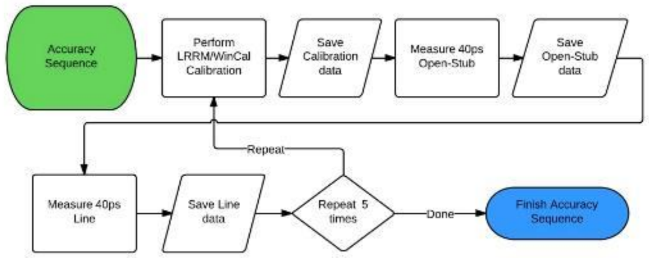
Only the Keysight and FormFactor Alliance can provide a complete solution which includes System guarantees

- ❖ Guaranteed Configuration – No missing parts
- ❖ Guaranteed Integration – Installed, verified and working
- ❖ Guaranteed Support – One contact, one call
- ❖ Guaranteed Performance (optional) – Known, documented performance

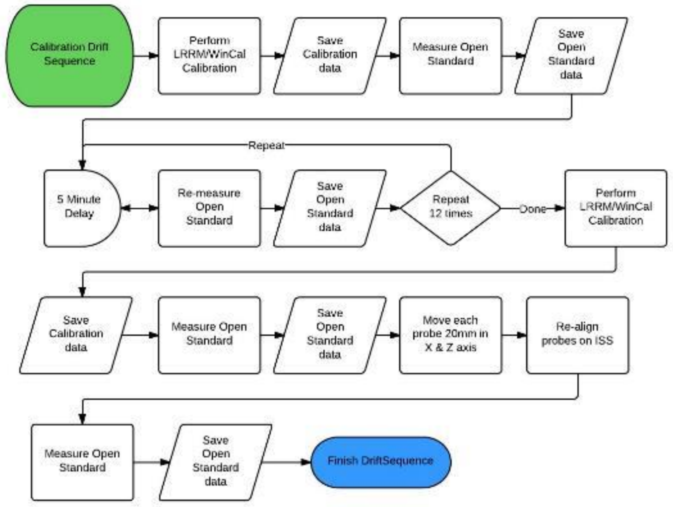
Guarantees Require Factory Measured Performance (FMP) measurements

FormFactor™

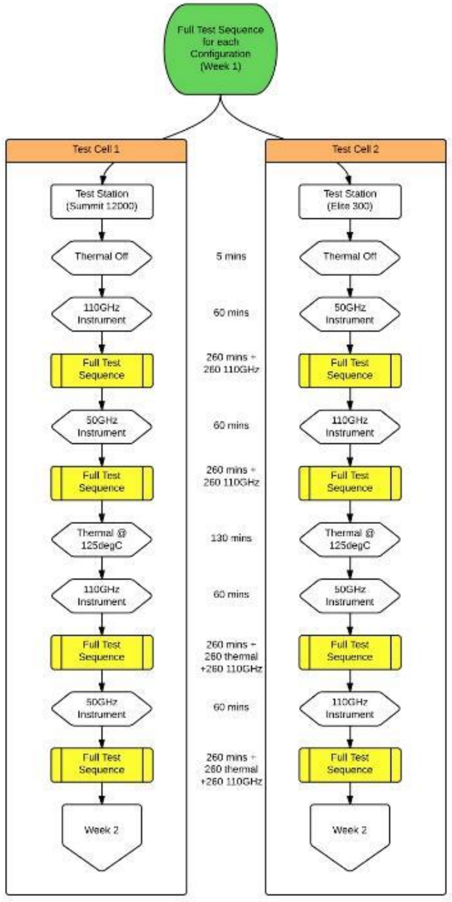
Comprehensive Test Suite



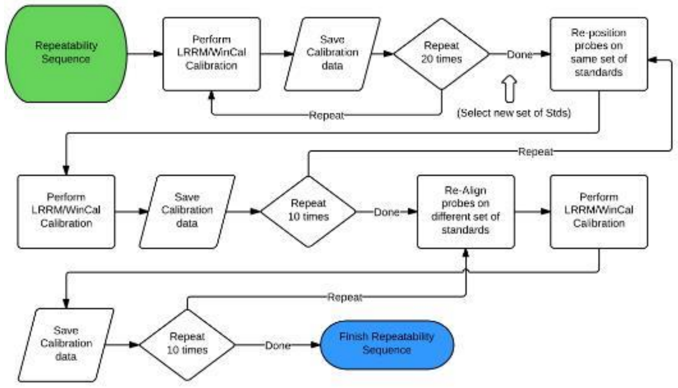
Sequence Time Estimate = 30 minutes



Sequence Time Estimate = 70 minutes



Sequence Time Estimate = 49hours 35min



Sequence Time Estimate = 70 minutes

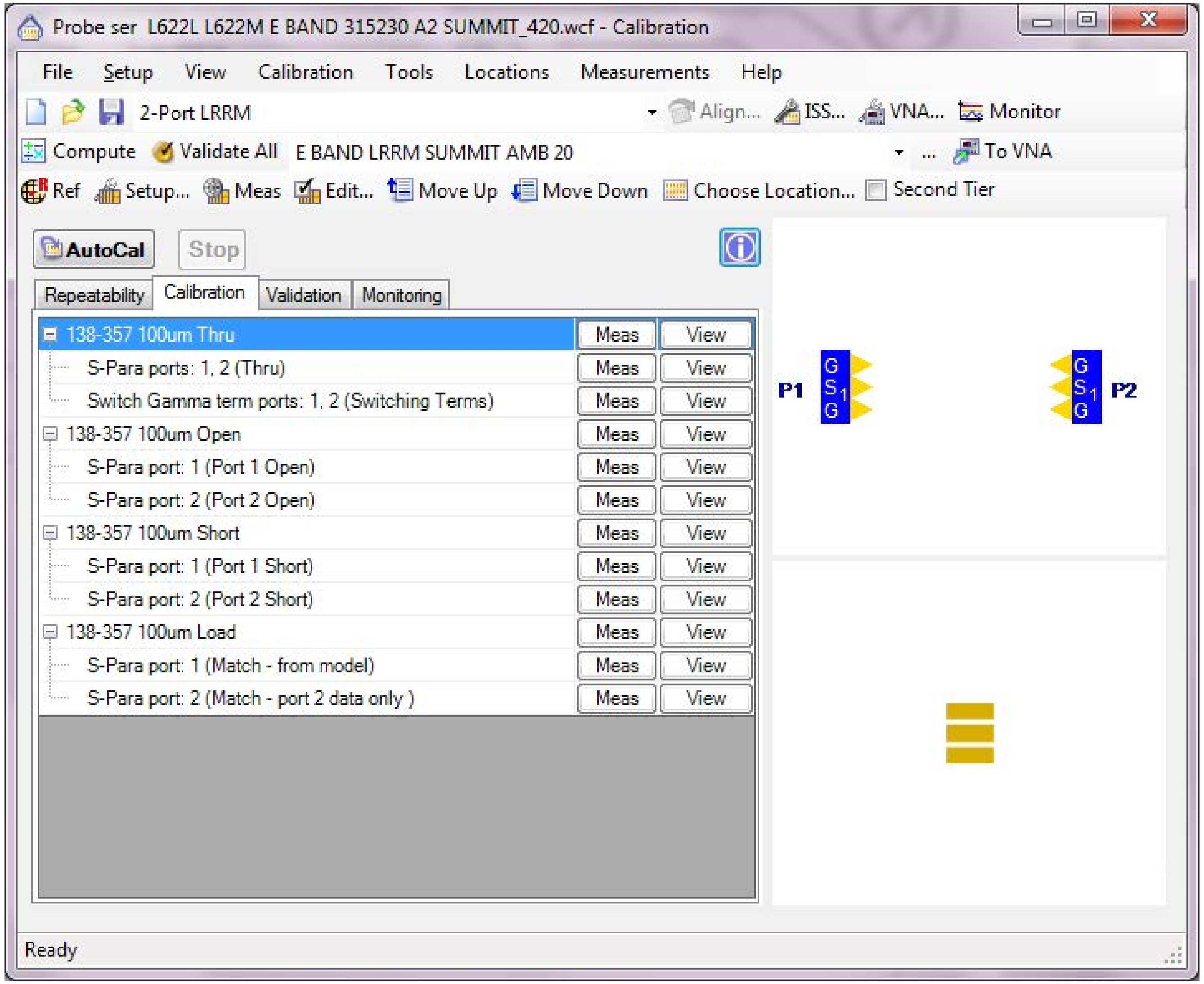
FORMFACTOR™

Guarenteed Set of Performance Attributes – WR12

		Up to 90 GHz		
Verification test	**Measure**	**Ideal**	**Limit**	**Typical**
Measure 5 x 40 ps Line. Delta from first measurement	S21	0%	4.5%	2.7%
Measure 5 x 40 ps stub. Delta from first measurement	S11/S22	0%	8%	5%
20 Cals, measure open response	S11	0dB	+0.3dB	+/- 0.23dB
20 Cals, delta between first and all other Open measurements	S11/S22	0%	0.8%	0.4%
Cal worse cal Sij delta over 20 cals with respect to first cal	Sij	0.00%	7%	5%
Drift open response 1 hour after calibration, 10 min intervals, measure open	S11/S22	0dB	+0.3dB	+/- 0.22dB
Drift open delta after 1 hour, 10 min intervals, measure open	S11/S22	0.00%	1.00%	0.55%

Customer WMS Solution Validated against these Attributes

Repeatability - Calibration file .wcf



- WinCal setup file contains all raw data and settings related to calibration
- Error set can be created and if desired changed
- If desired if cal used same standards to can opt to use different cal method afterwards ie SOLT / LRRM /SOLR

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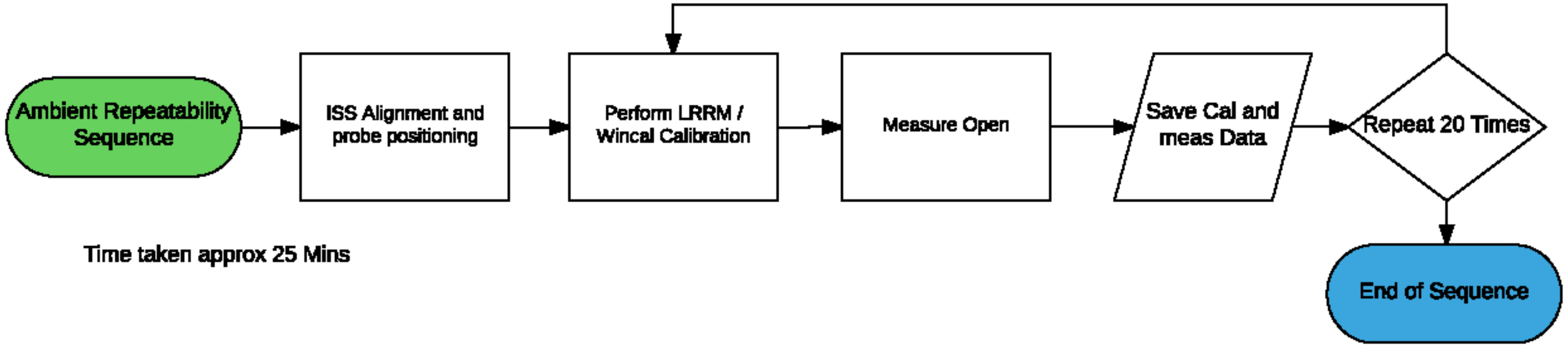
Measurement repeatability, Ambient – Open in air

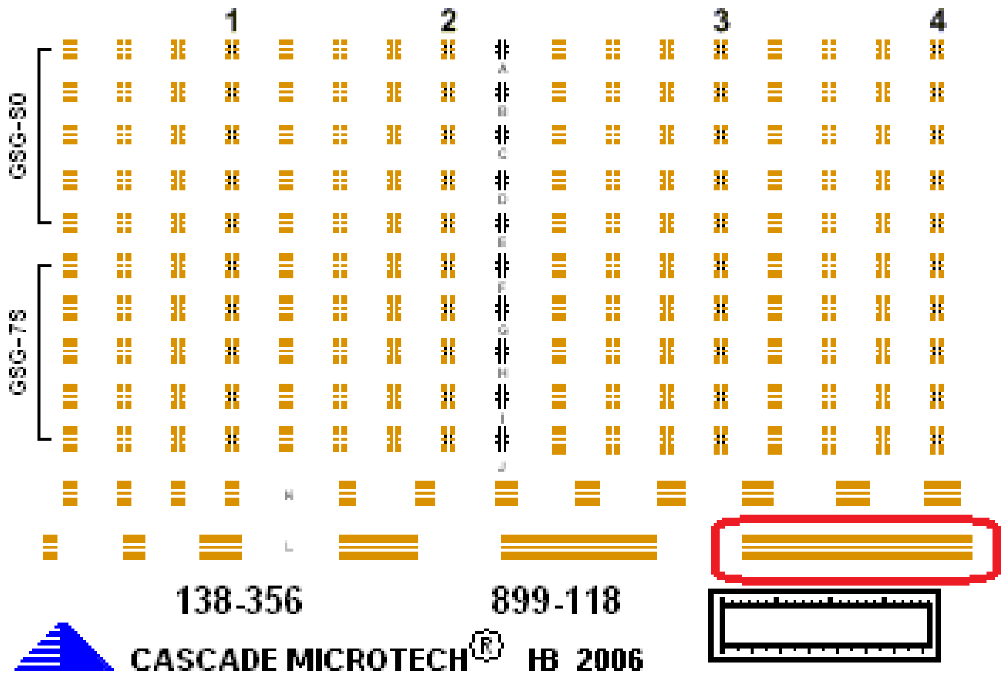


- For this test we repeatedly calibrate using LRRM with auto load inductance and measure Open response.
- Probe position is left alone during cal cycles
- From this we can also determine the worst case error term variation using WinCal error set comparison
- Open in air used as the standard is largely independent of probe position

Practical Example – Using WinCal XE as Repeatability Comparison Tool

Accuracy measurements

- We make measurements of Line / Stub standards on ISS using successive calibrations
- Assuming the standard is not damaged by measurements the measurements should all be the same independent of error term variation due to systemic changes. Metric is how similar they are



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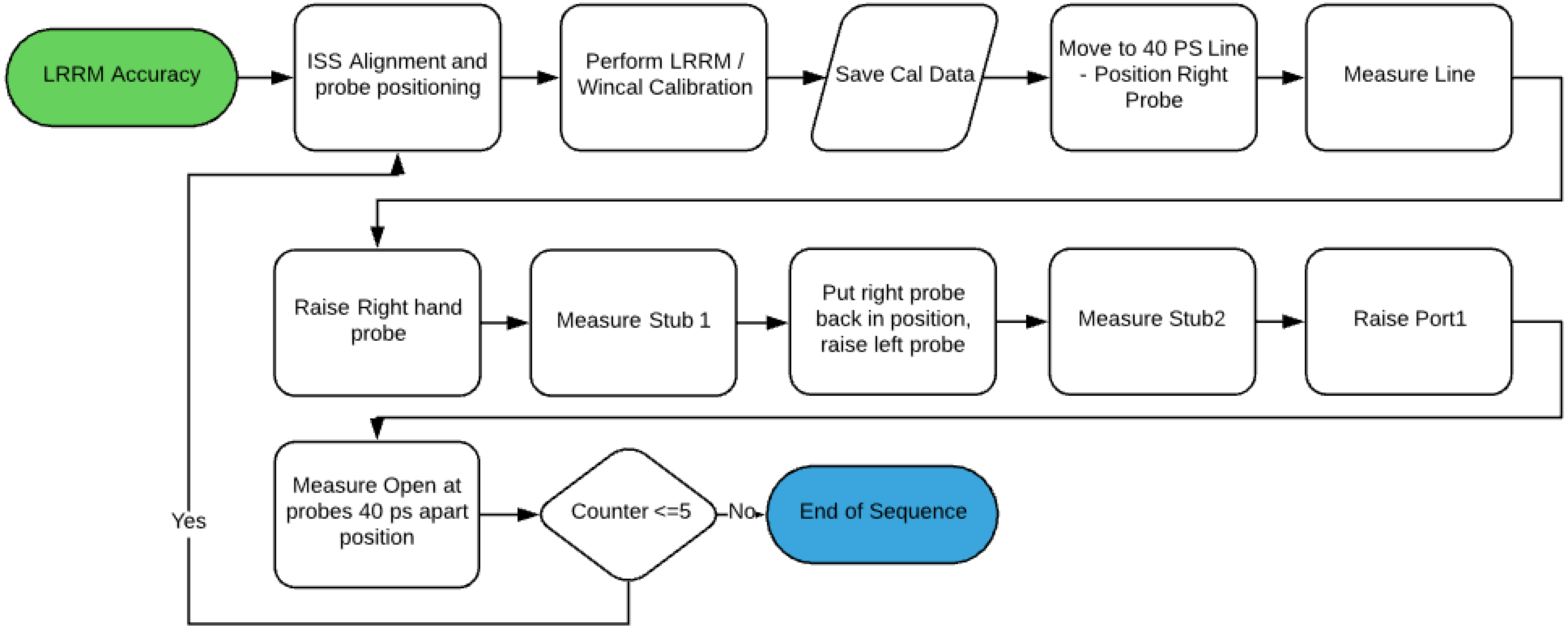
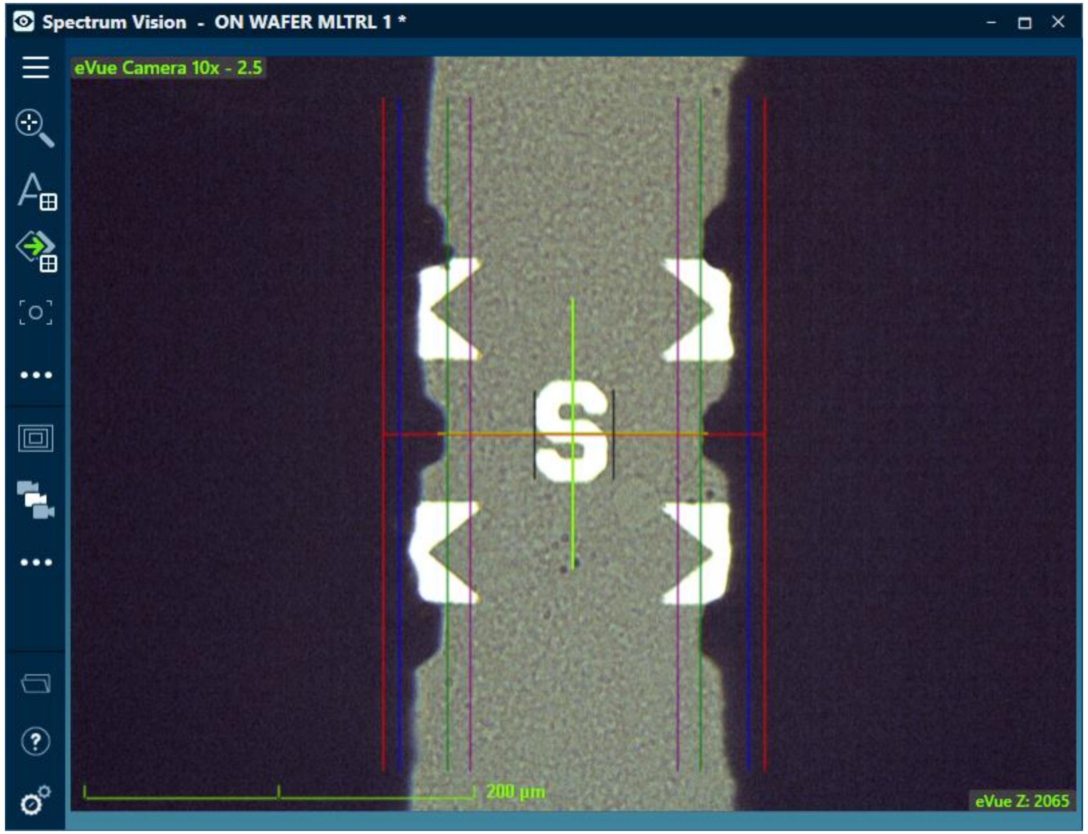
Ambient Accuracy measurements



- Sequence measures Open when probes are moved, Line and both stubs
- % Difference approach used for comparison metric

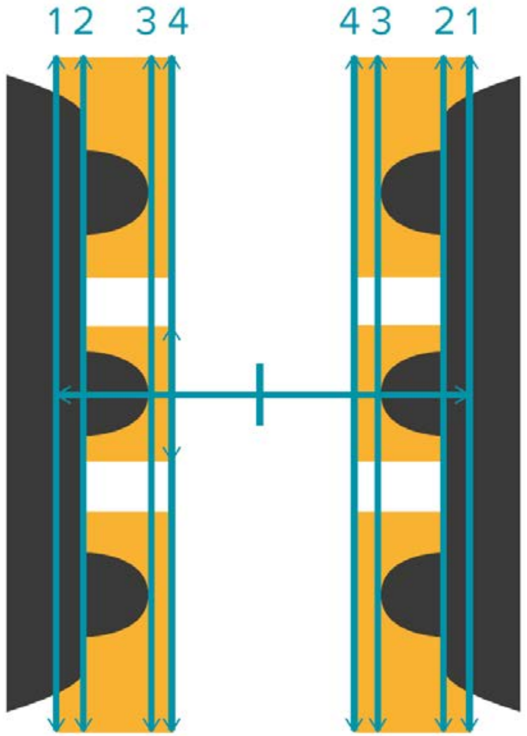
Augmented align



- Augmented align overlays markers for perfect probe placement specific to the iss in use
- Software can query wincal for current iss or it can be picked

FORMFACTOR™

Augmented align



AugmentedAlign Tool:

The outermost lines (1) align to the outer edges of all standards.

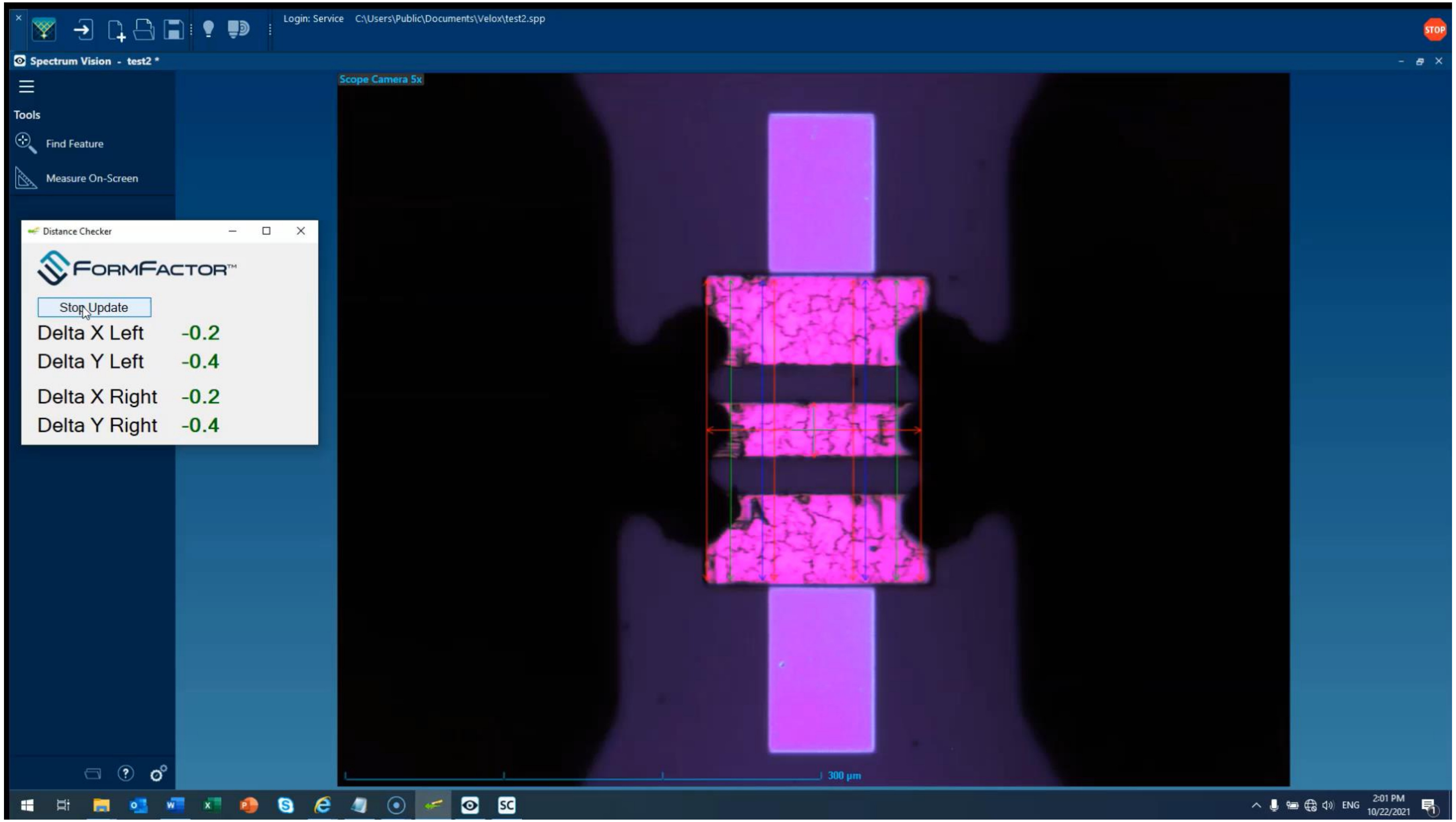
Next line in (2) is the initial contact point of the probe, and line (3) shows its final location. The lines allow the user to scrub their probes into contact by a known amount.

The innermost lines (4) align to the inner edge of reflect standards.

Vertical arrows align to width of lines for vertical alignment.

- This tool makes placement of probes on line ends super accurate
- Especially useful for speed and accuracy on manual stations but useful for all

Augmented align - video



- Find feature can be used to assist probe placement
- Here we have an application to monitor changes in the probe to nichrome offset

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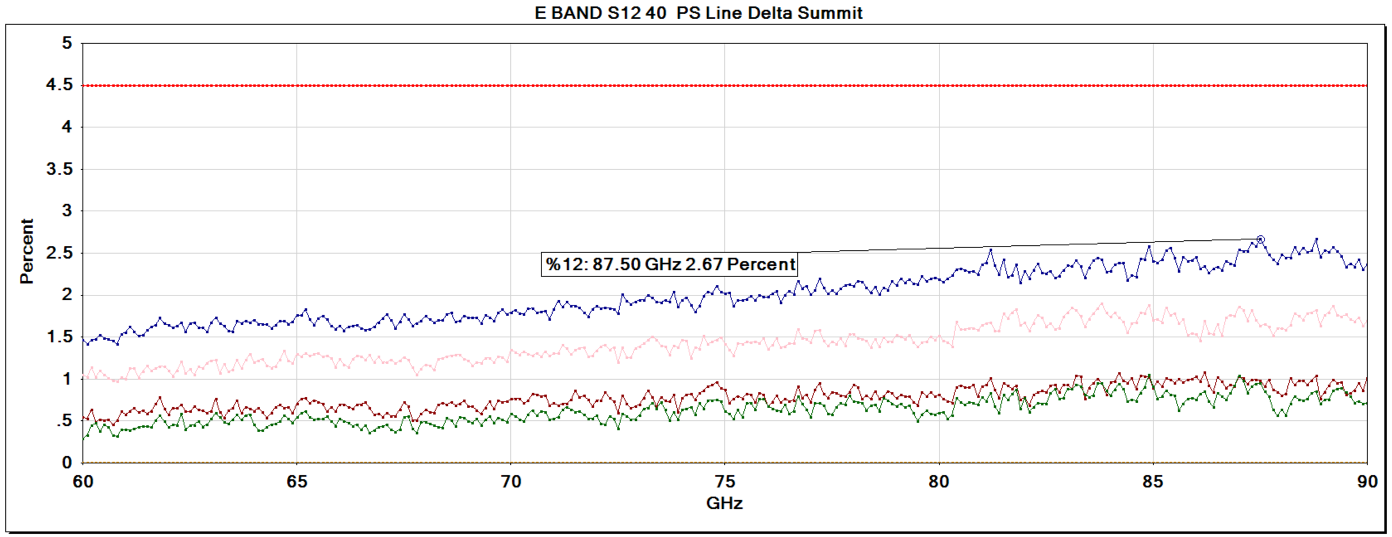
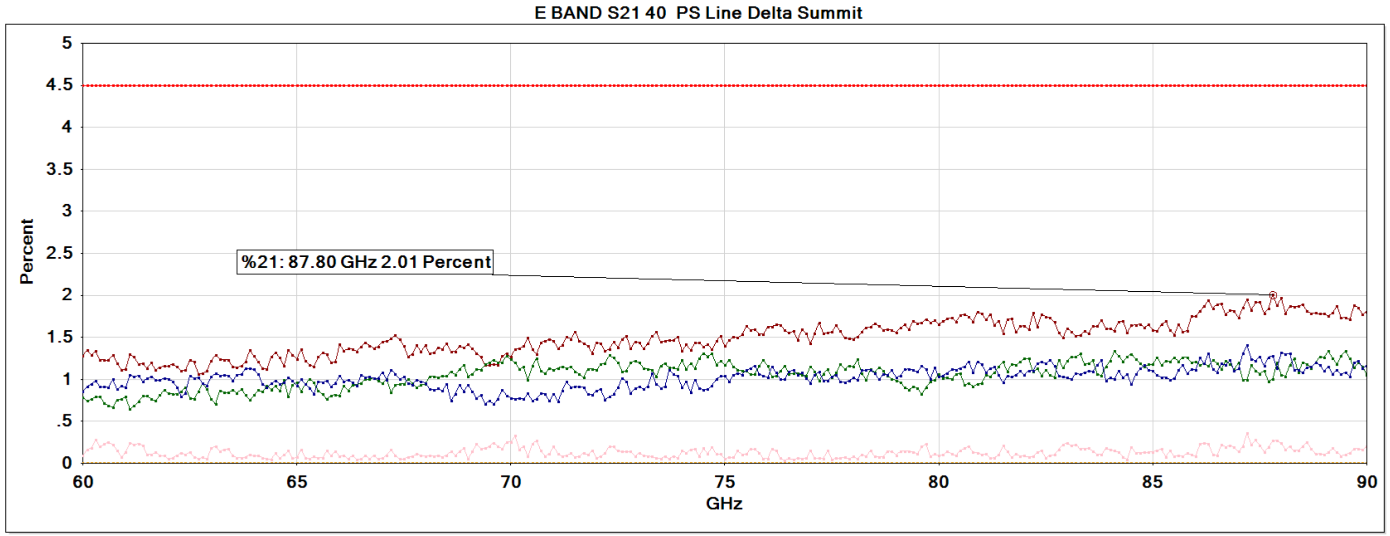
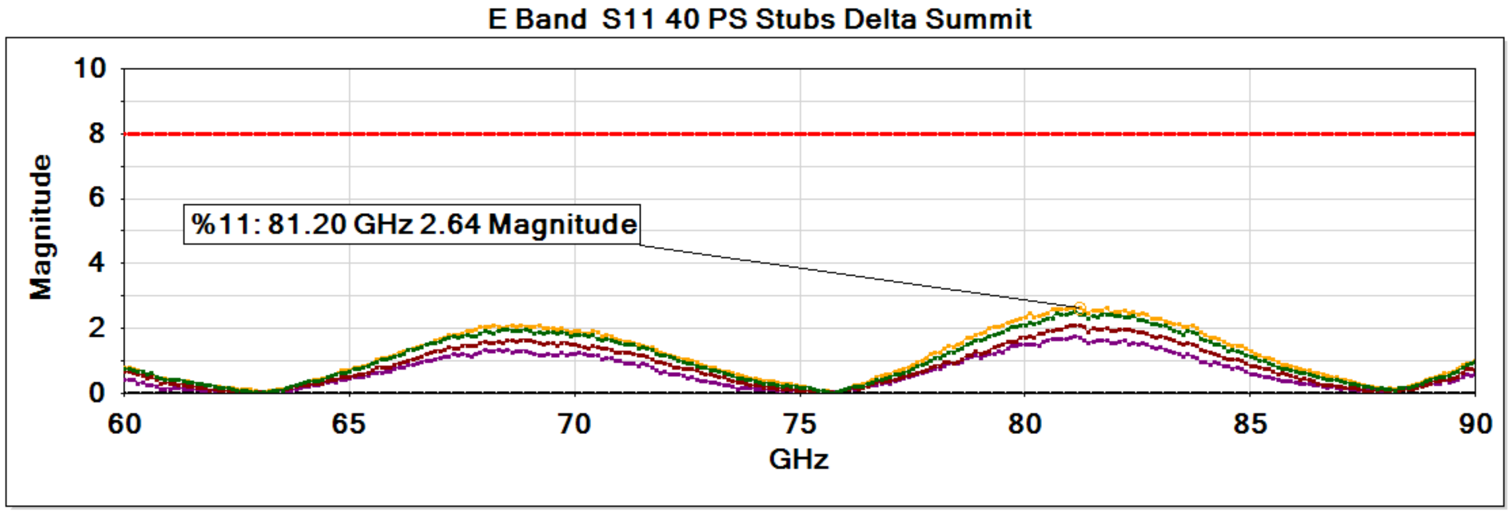
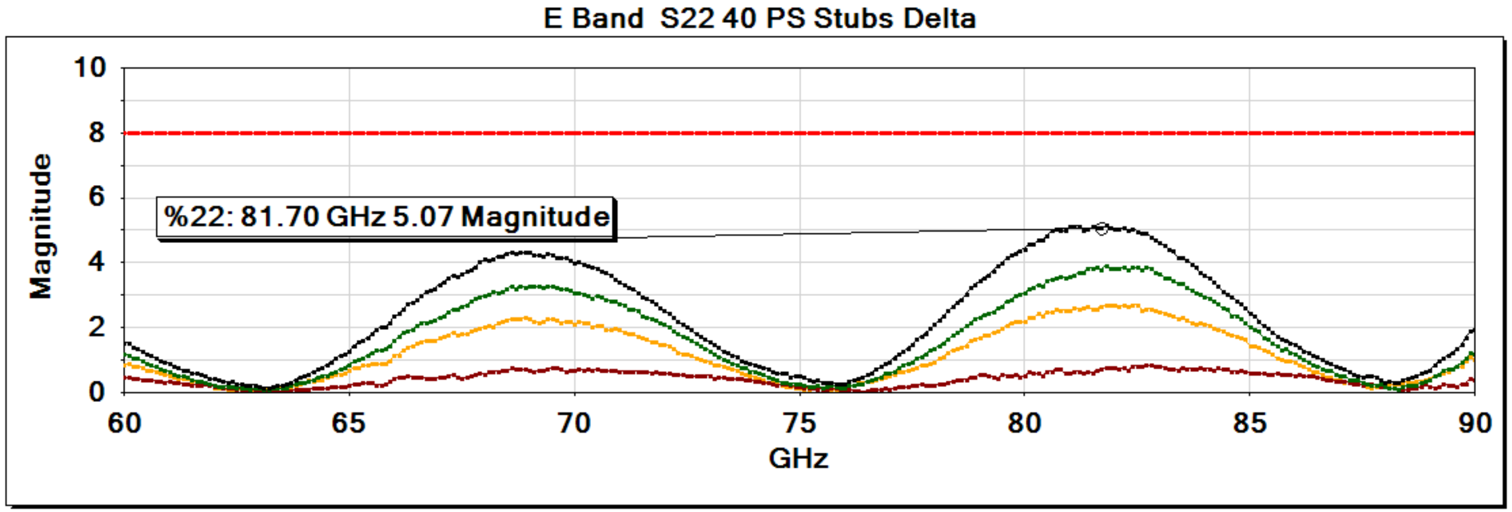
Accuracy Transmission line % Delta





Accuracy – Stub delta

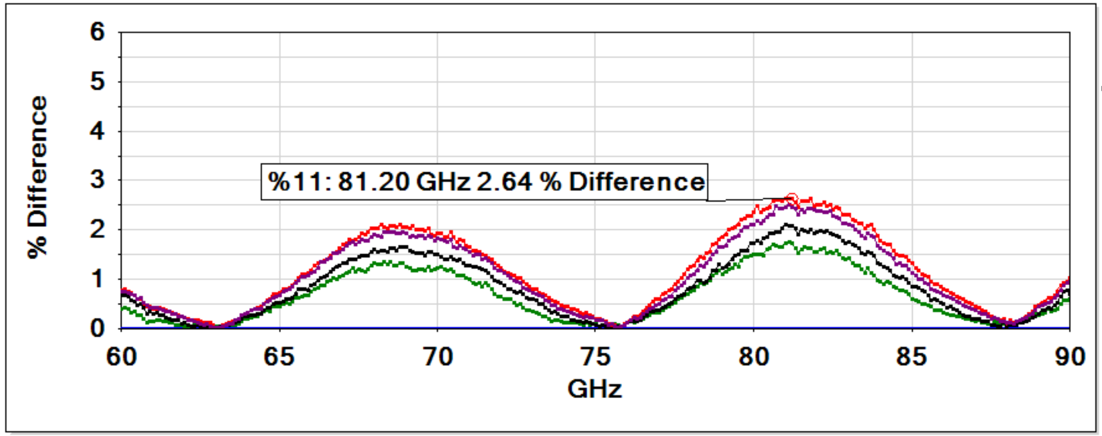




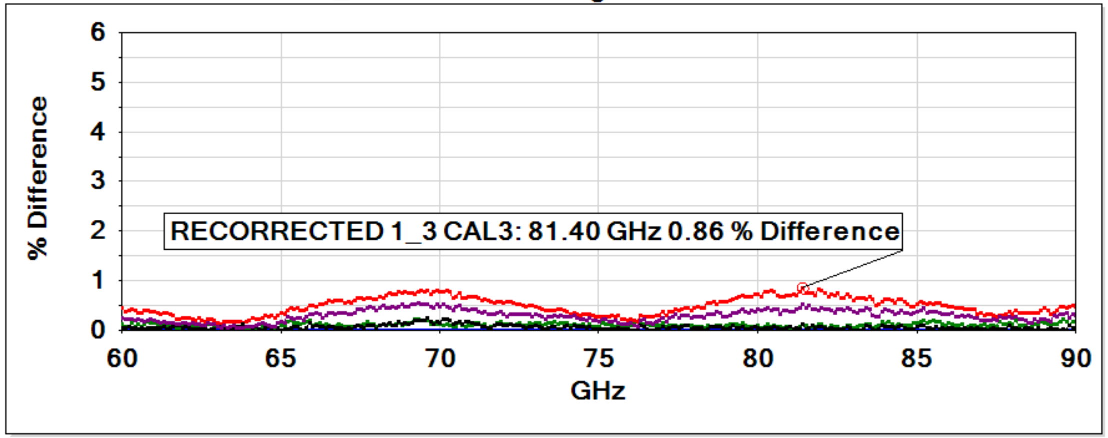
- Stub deltas are typically double of transmission as standard is twice as long
- Port 2 delta is generally larger than port 1 and probe is moved mechanically

Is stub delta due to cal variation or placement / Contact

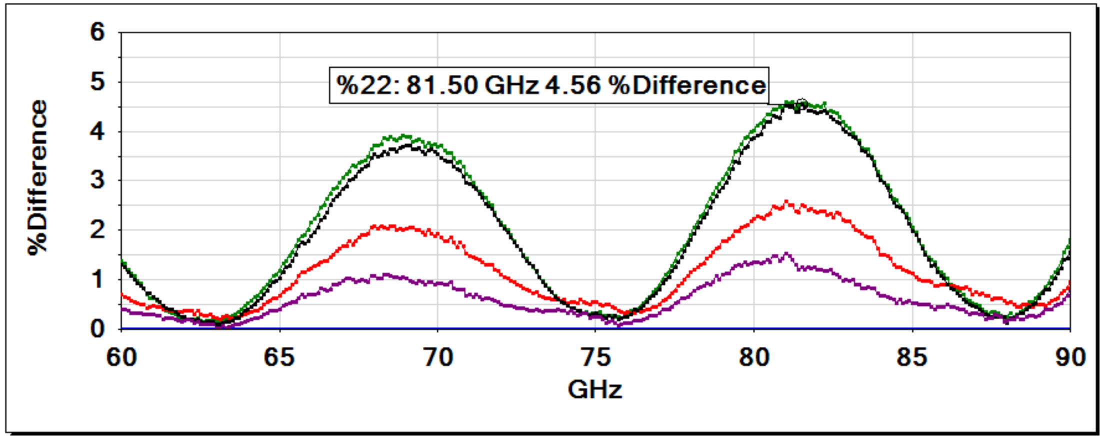
ACCURACY DATA STUB PORT1



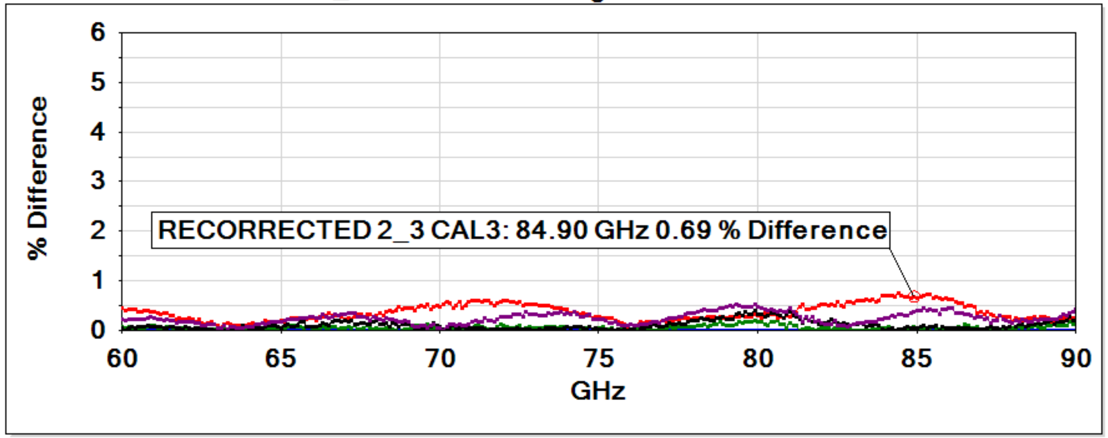
Stub 1_3 Recorrected using Calibrations 1 thru 5



ACCURACY DATA STUB PORT2

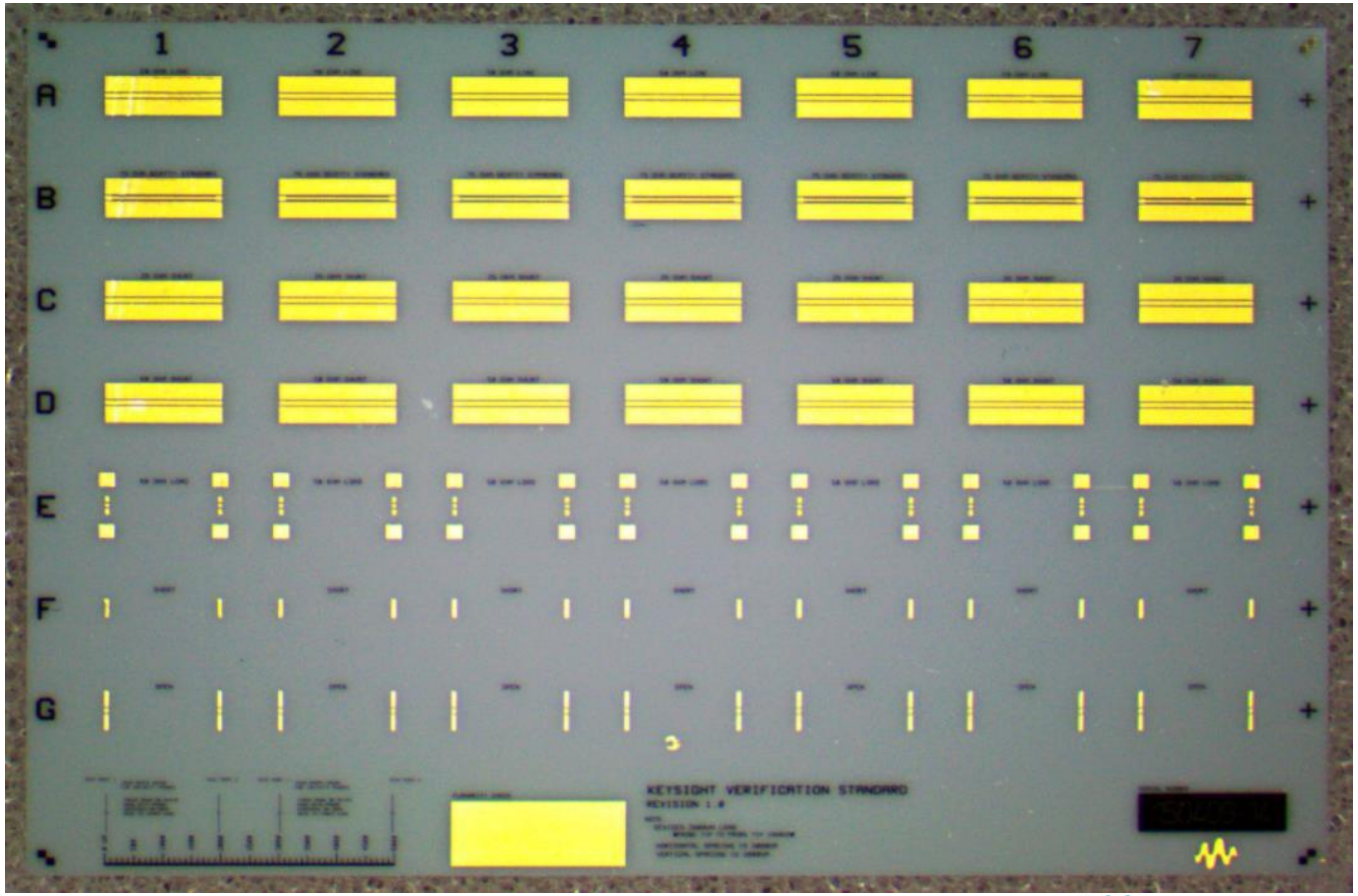


Stub 2_3 Recorrected using Calibrations 1 thru 5



Independent Measurement Standards from Keysight

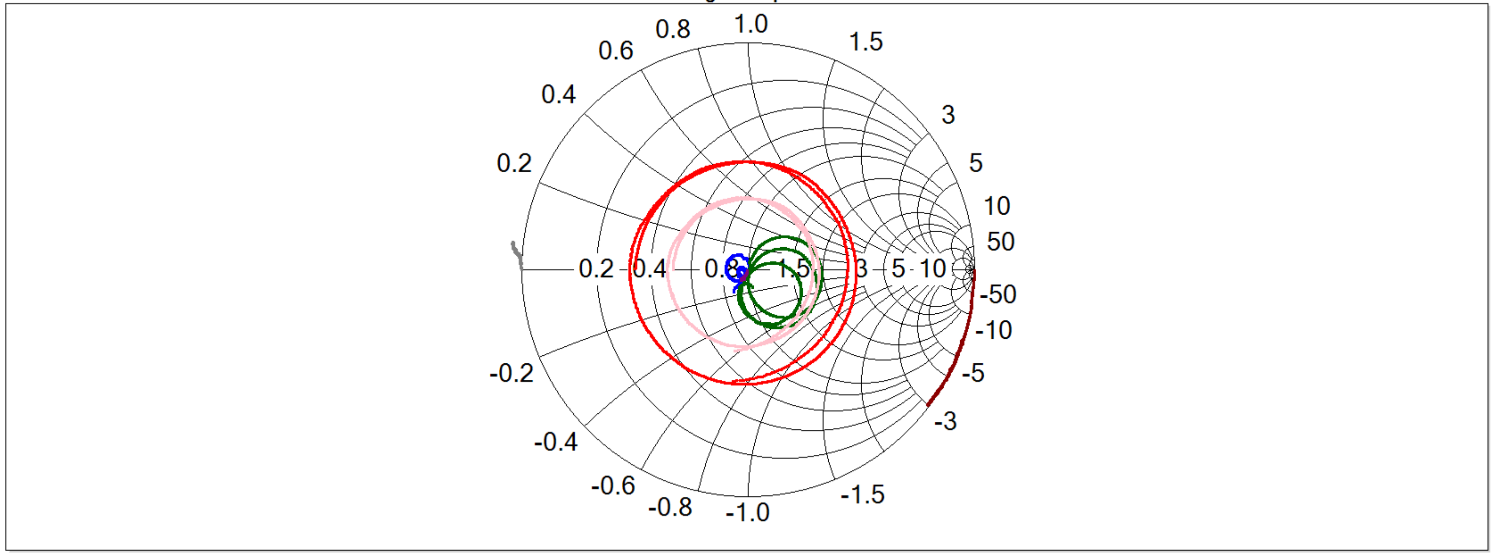
- Keysight technologies worked in conjunction with FormFactor to develop and test a standard for cross comparison of field measurements directly with factory measurements



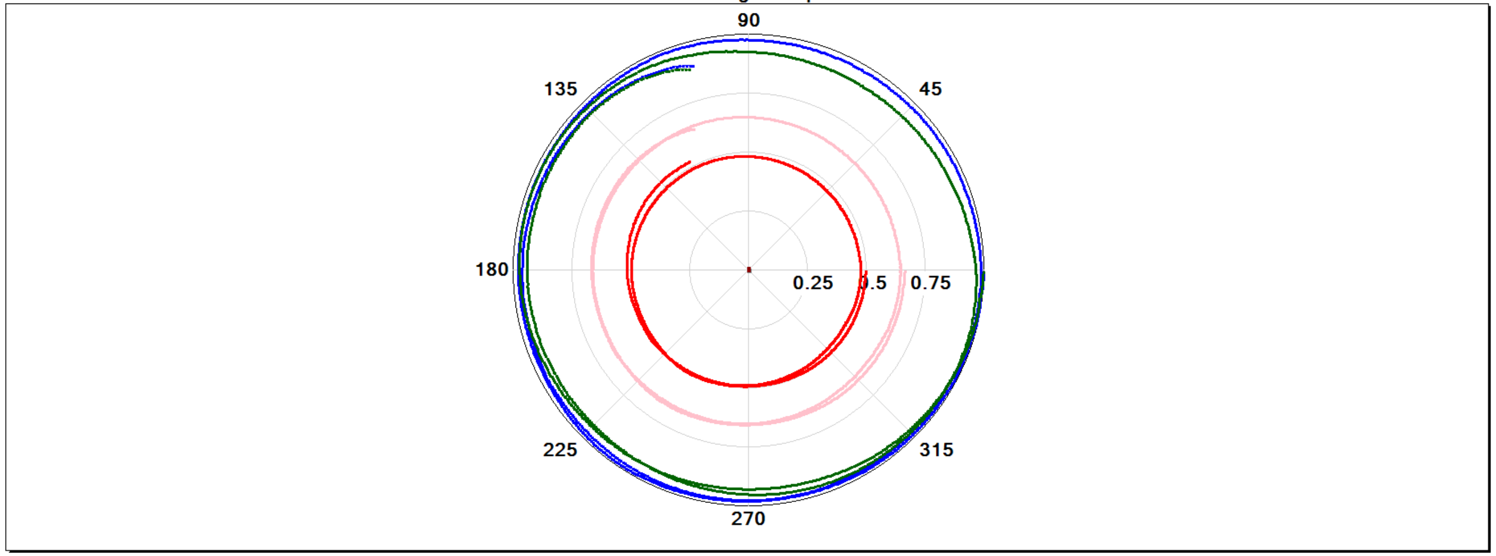
FormFactor™

Broad impedance coverage

Reflect Coverage Independent Standard



Transmission Coverage Independent standard

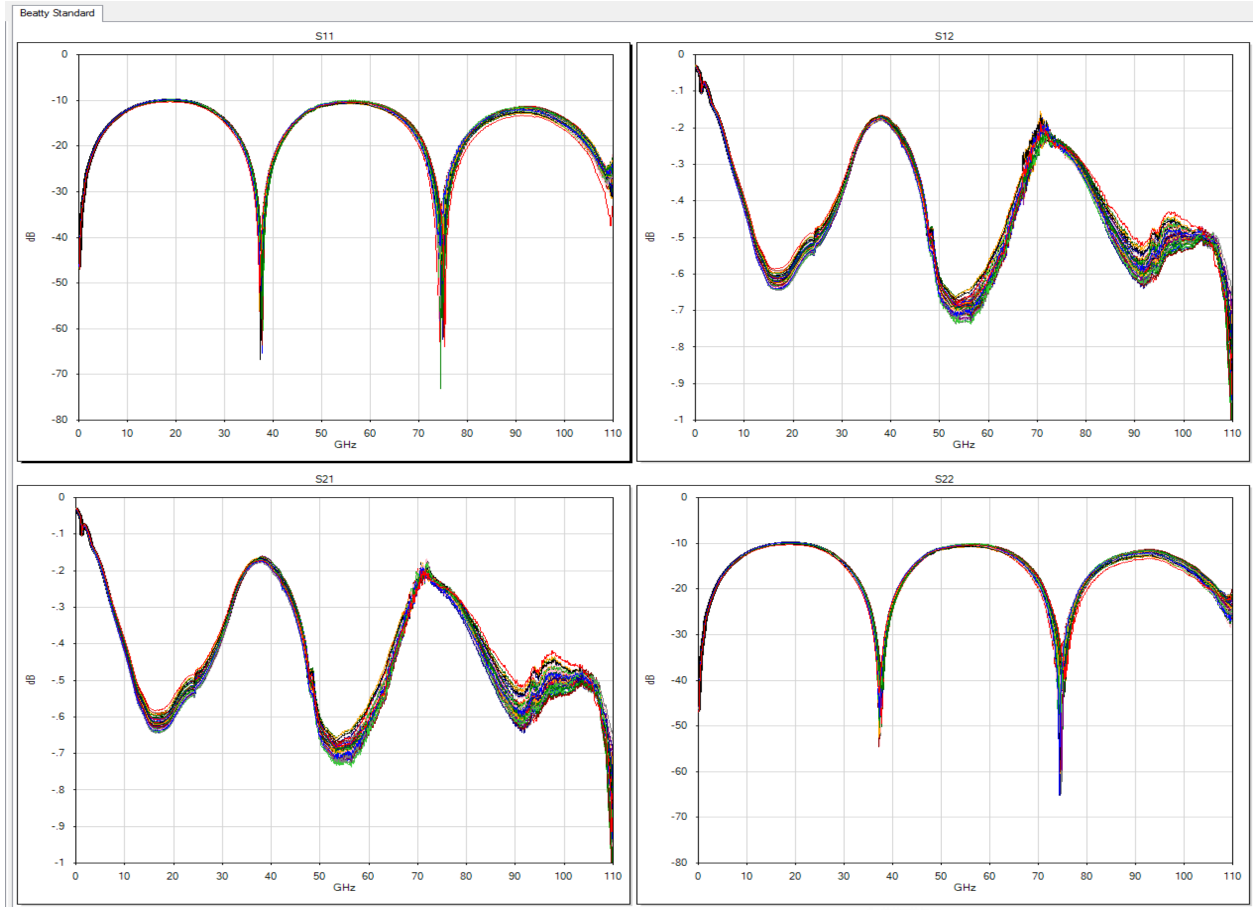


- Idea of the verification substrate is to present a broad but repeatable range of impedances to the probe
- On wafer equivalent to coax verification kit

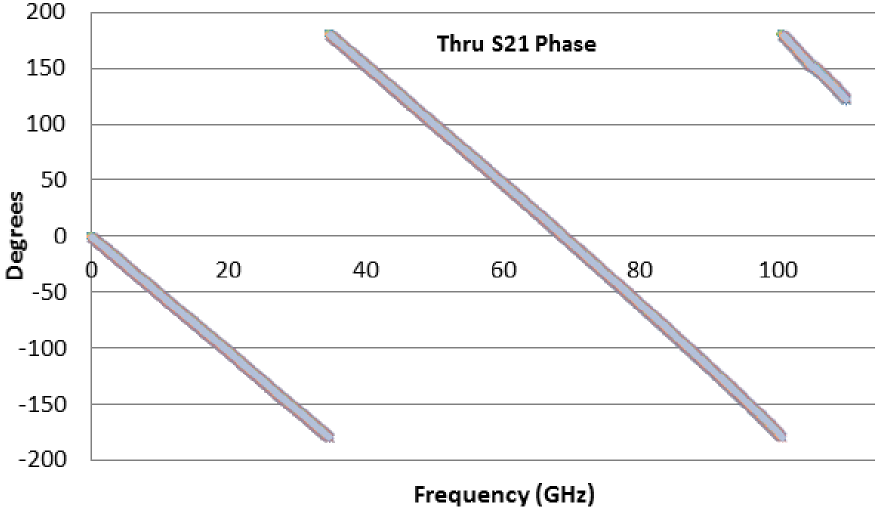
FormFactor™

Mismatch Line (Beatty Line)

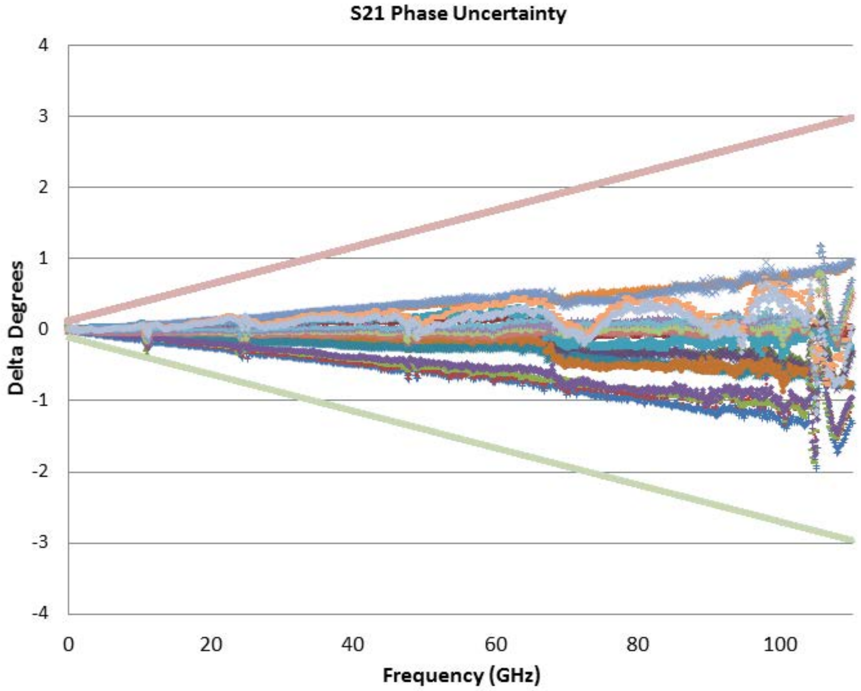
- Manufacturing, Calibration, and Measurement Repeatability
  - ➢ 14 Substrates
  - ➢ 7 Devices/Substrate
  - ➢ Multiple LRRM Calibrations



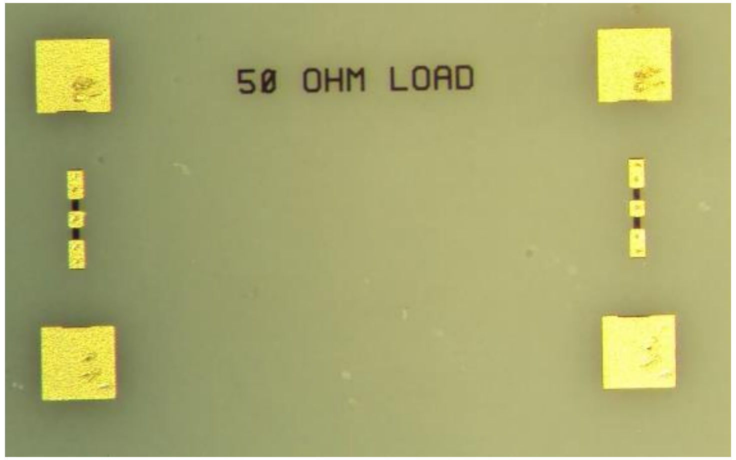
50 Ohm Transmission Line

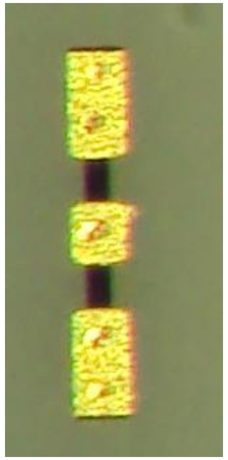


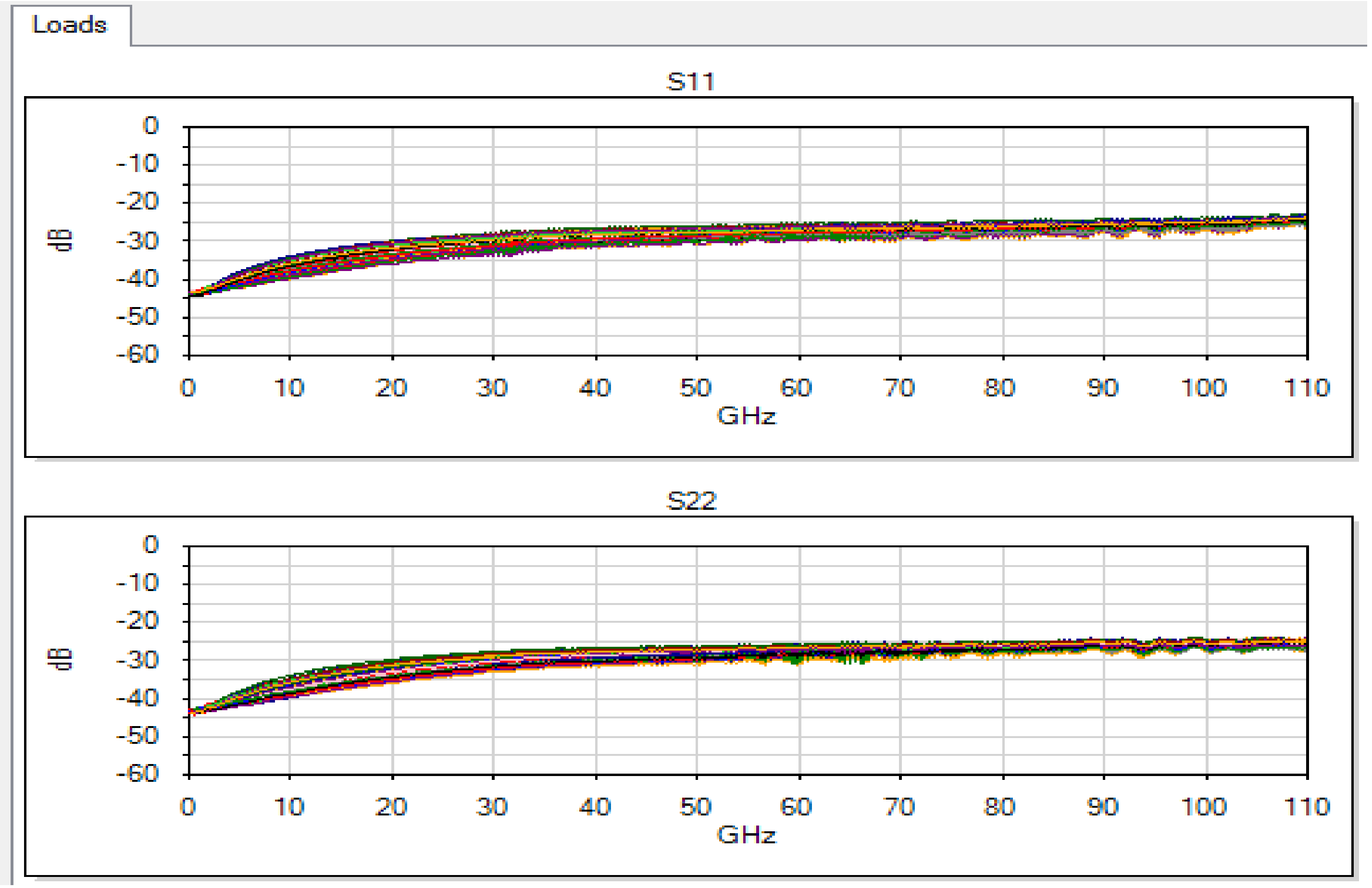
S21 Phase Unwrapped and Normalized with Uncertainty shown



50 Ohm Loads



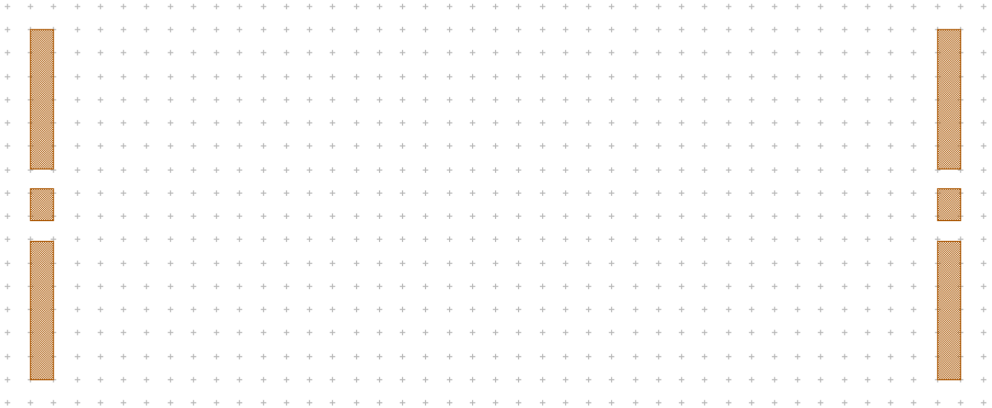




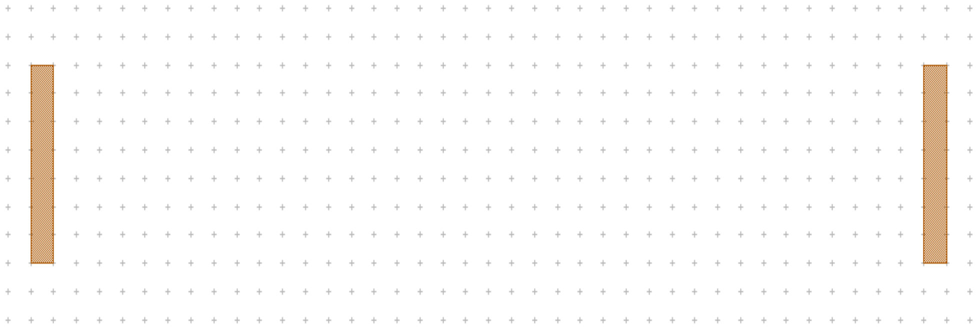
– Better than 23 dB Return Loss to 110GHz!!
– Joule trimmed like ISS

Independent standards

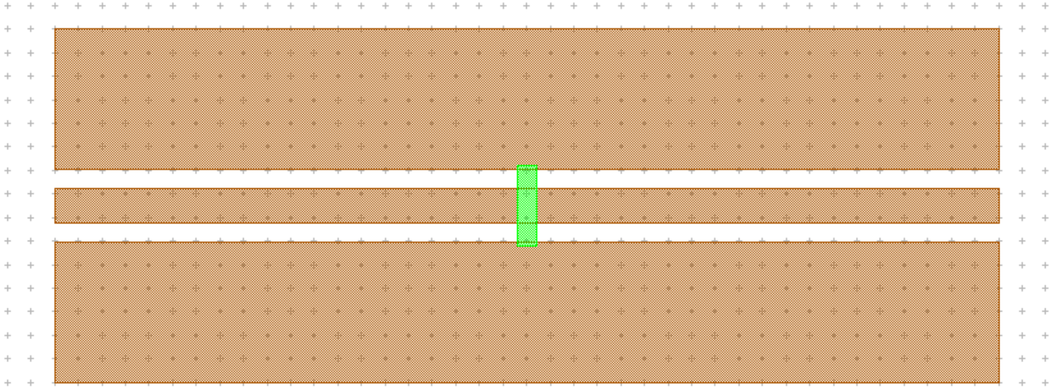
On Substrate Opens



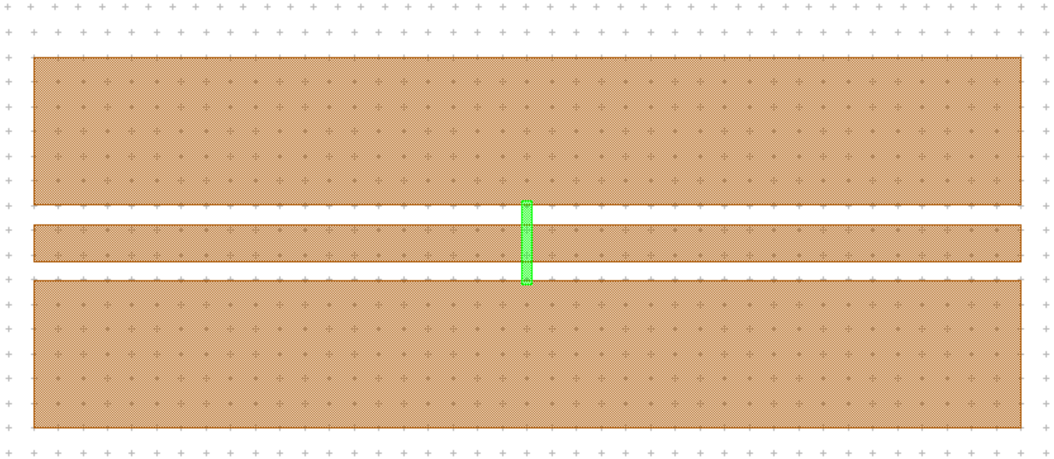
Shorts



25 Ω Shunt resistor



50 Ω shunt resistor



Independent standards metrics

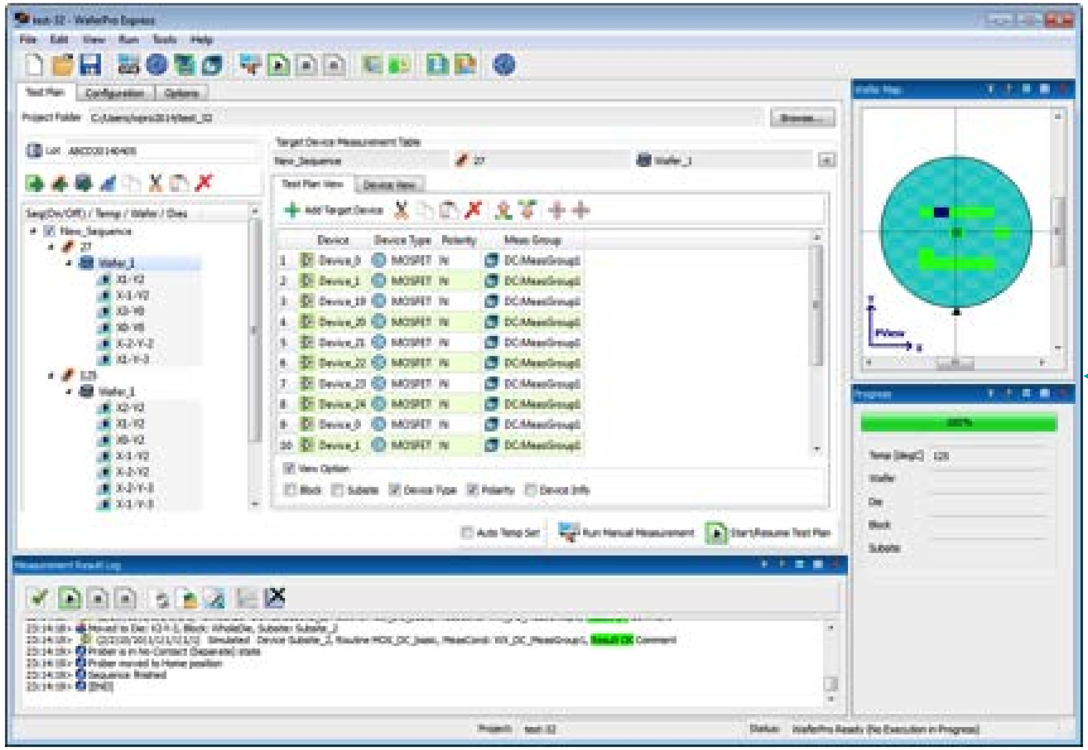
Device	Measurement	Limit	<=20 GHz	<=40 GHz	<=50 GHz	<=67GHz	<=90 GHz	<=100GHz	<=110GHz
ShuntR25	Reflection Uncertainty Magnitude	Upper and lower		0.35 dB		0.5 dB		0.7 dB	1.5 dB
ShuntR25	Transmission Uncertainty Magnitude	Upper and lower		0.35 dB		0.35 dB		0.7 dB	1.5 dB
ShuntR50	Reflection Uncertainty Magnitude	Upper and lower		0.35 dB		0.5 dB		0.7 dB	1.5 dB
50ΩLine	Transmission Uncertainty Magnitude	Lower only		0.12 dB	0.16 dB	0.2 dB		0.25 dB	0.5 dB
50ΩLine	Transmission Uncertainty Phase	Upper and lower		Linearly increases from 0.1° at 100 MHz TO 3° AT 110 GHz					
Open	Reflection Uncertainty Magnitude	Upper and lower		0.1 dB		0.23 dB	0.26 dB	0.53 dB	0.6 dB
Short	Reflection Uncertainty Magnitude	Upper and lower	0.05 dB		0.08 dB	0.15 dB	0.2 dB		0.4 dB
Load	Reflection Absolute Magnitude	Upper only	-28 dB	-25 dB	-25 dB	-24 dB	-23 dB	-22 dB	-21 dB

- Short, Open, Line, Shunt 25 an Shunt 50 pass metrics are all based on uncertainty values of the individual standards
- Load is based on absolute return loss
- Beatty is based on absolute average limit currently

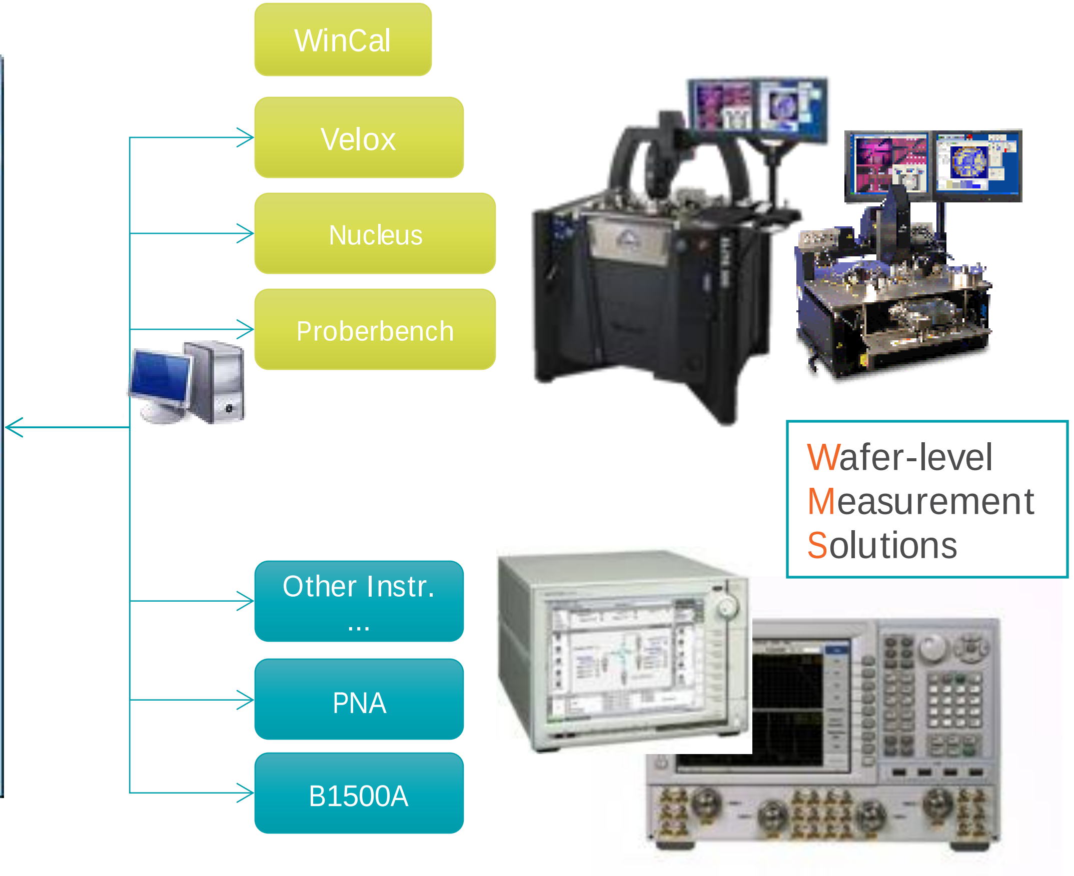
WaferPro Express™ (WaferPro-XP)

A modern, cost effective, easy to use, yet powerful and efficient software platform to control automated on-wafer measurements of devices and circuit components.

Developed and sold by Keysight Technologies

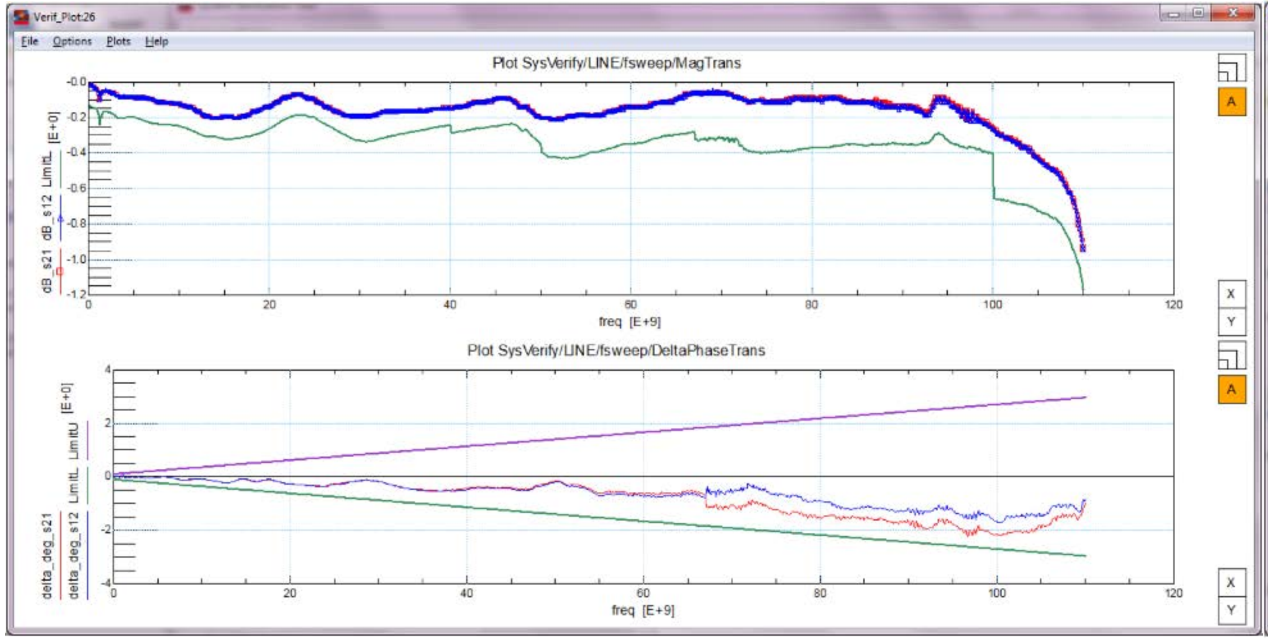


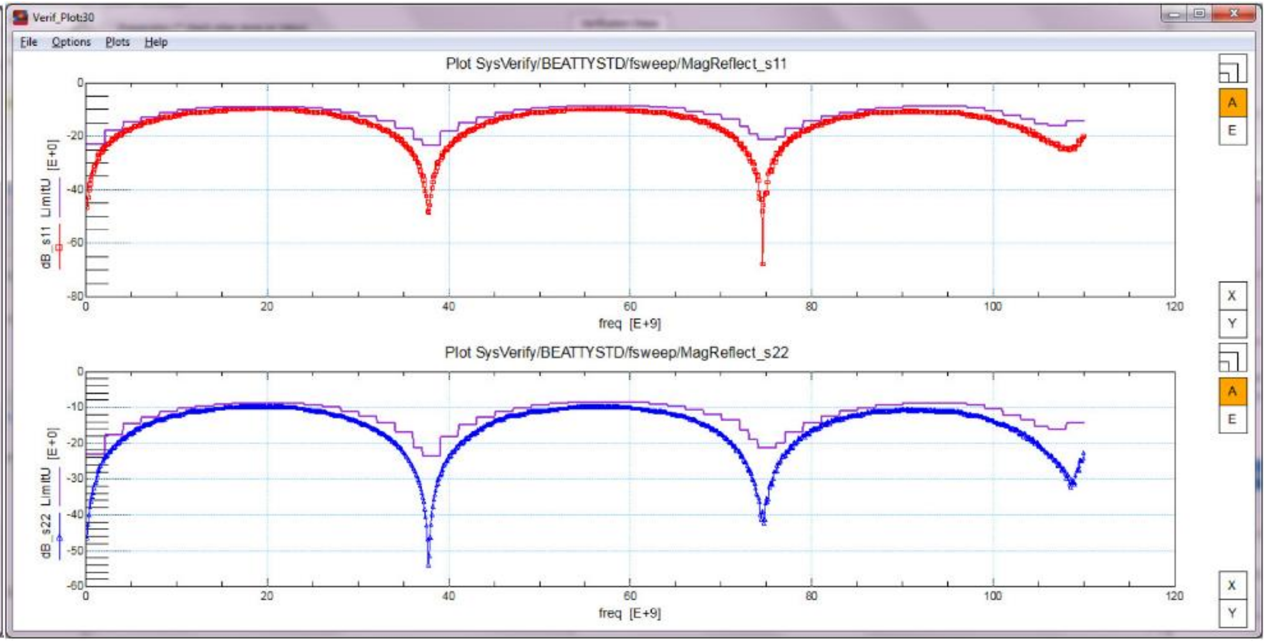
WaferPro-XP unified software environment



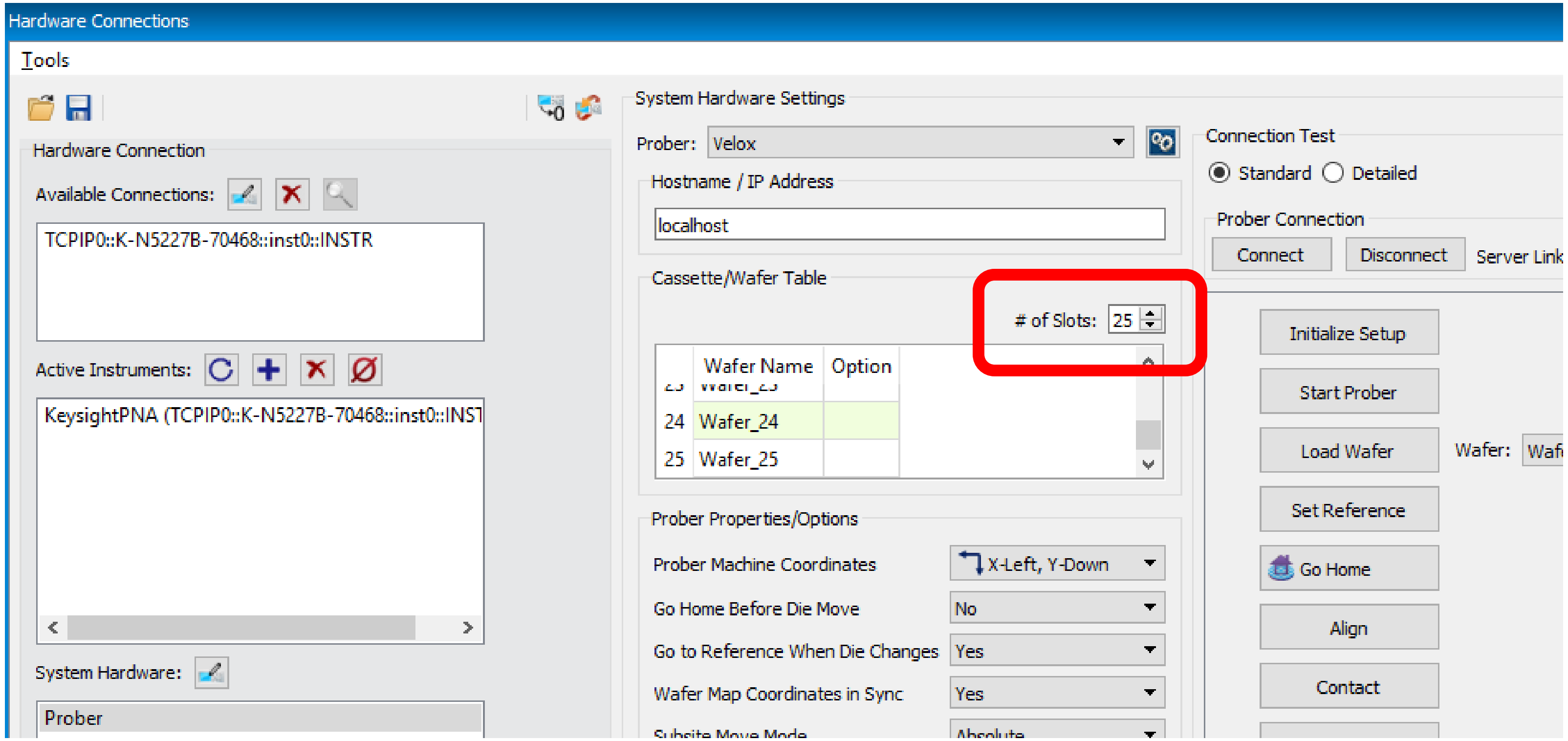
Field testing – WaferPro Express

- All measurements of the independent standards are handled using Keysight WaferPro Express which automates the data acquisition and measurement
- Comparison is for against serialised standard data for the individual substrate



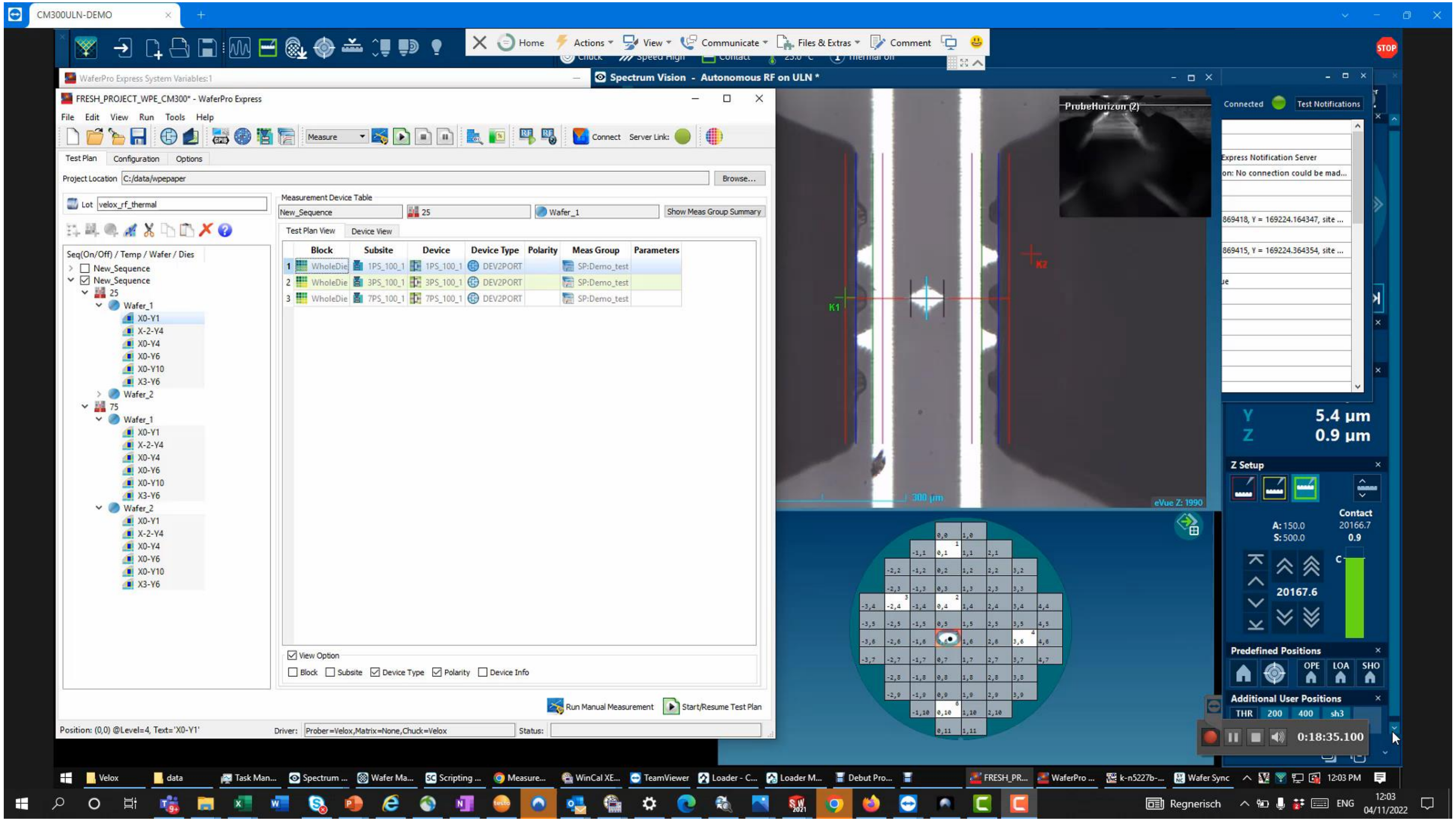


Waferpro express with wafer loaders



- Wafer pro express can work with our fully automated probers and Autonomous RF also
- Formfactor robots typically have 25 slots in the cassette
- That needs configured as default is 3 in WPE

Quick overview of WaferPro express with Autonomous auto prober testing



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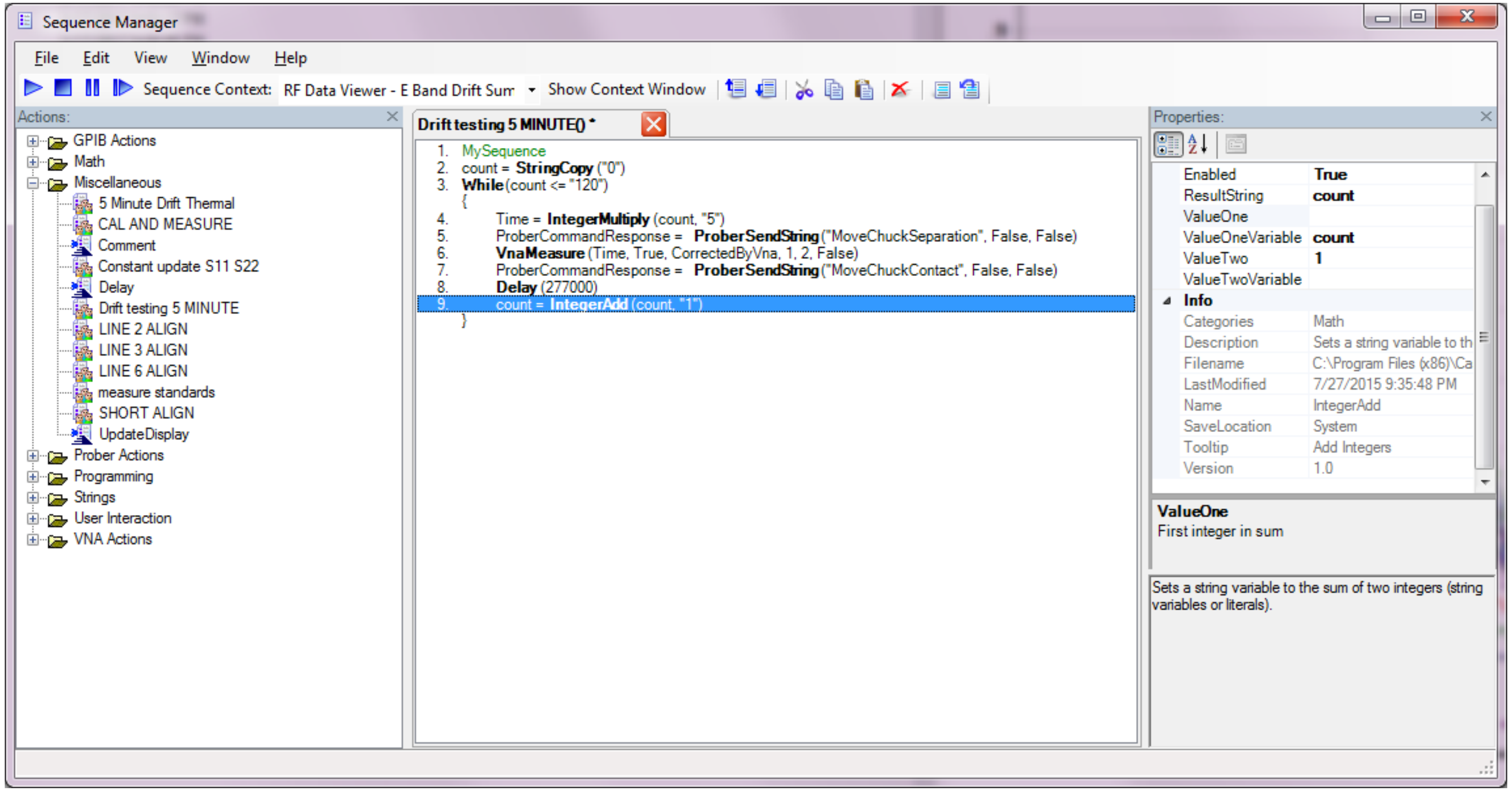
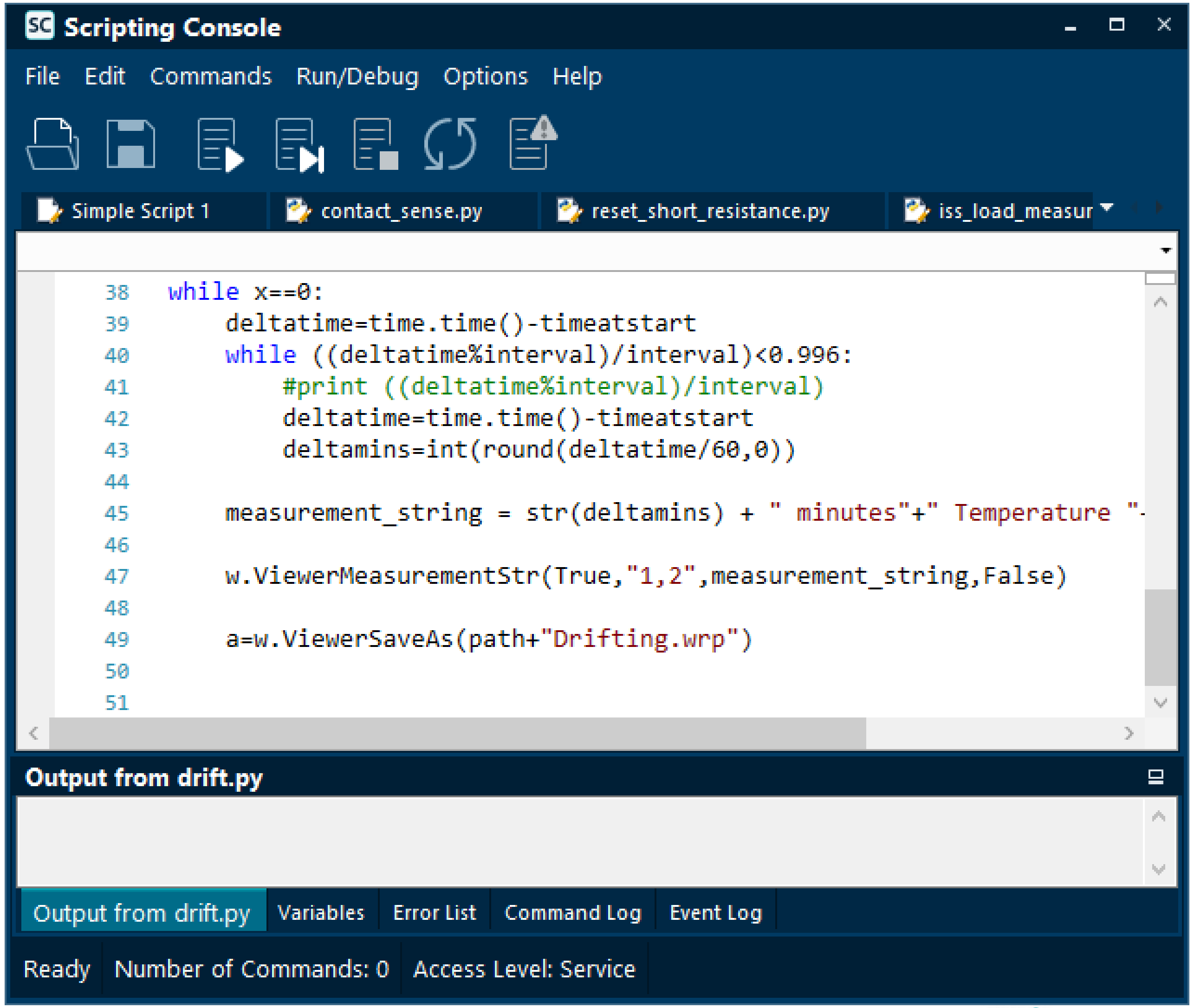
Drift Data capture using sequences



- Drift was measured using a sequence
- This was done just for simplicity reasons
- Sequences are a great simple way of carrying out measurements and does not rely on external code
- Drawback is timing isn't accuracy (python preferred for this)

Drift Data capture using Python



- Very useful as gives exact time multiples – no need to guess delays
- This approach can show the evm of the current trace only if desired

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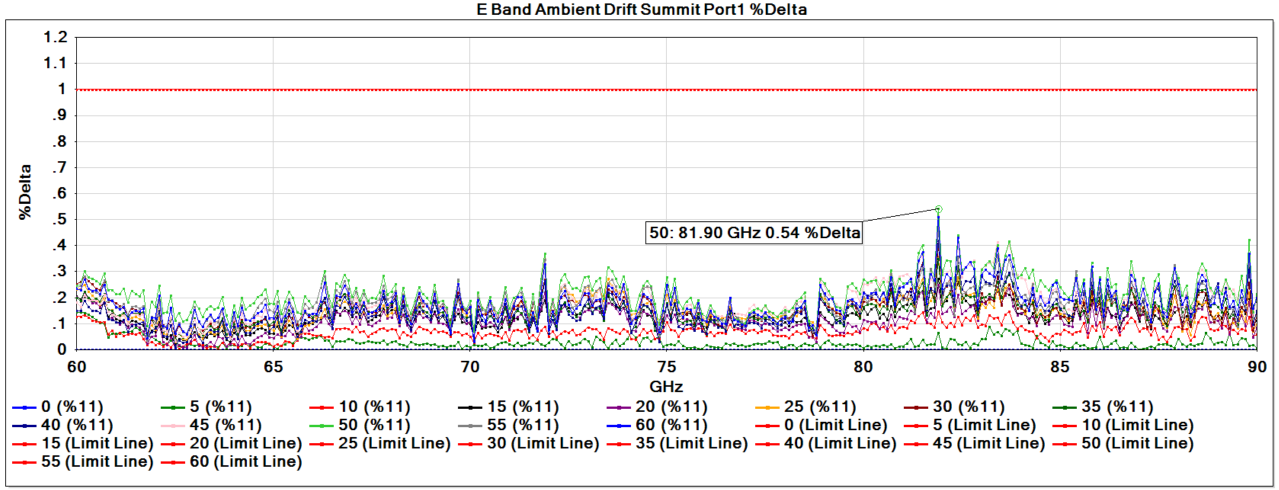
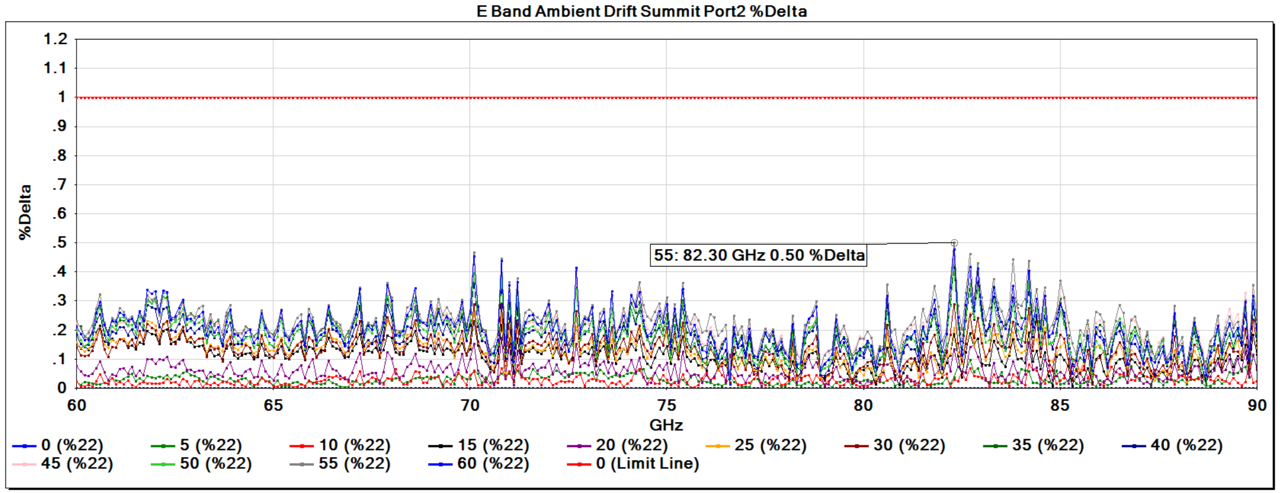
Ambient drift testing



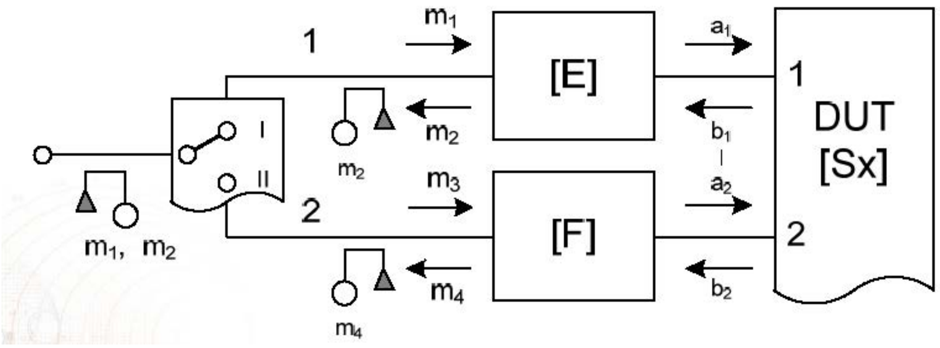


- Ambient drift is simple
- We calibrate and then measure open in air repeatedly
- Metric looks at both the open in air magnitude and the % Difference
- Open in air avoids issues with contact variability and probe expansion
- Limit set with larger tolerance as temperature variation of the lab was smaller than the limit we typically set of +/- 1°C

High Frequency measurements

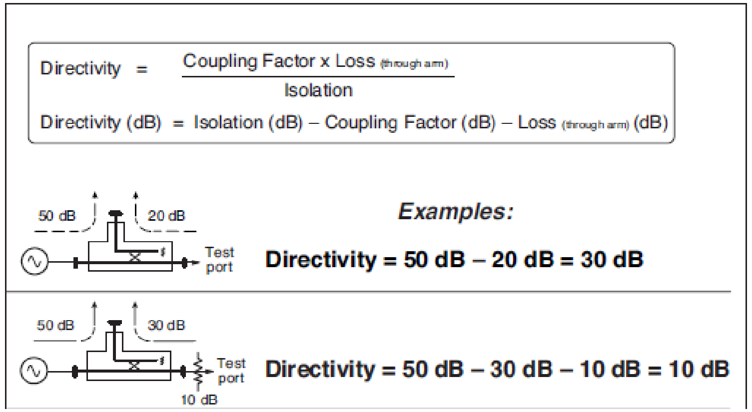
Why is system stability important?

- Vector network analysers have systemic errors
- Calibration routines characterise these errors to produce accurate corrected data
- If systemic error changes, corrected data is no longer valid
- Reduced directivity and increase path length increase sensitivity to small environmental changes
- Reduction of loss and path length improves directivity and changes due material expansion
- Reduced sensitivity to environmental changes also reduce time wasted in recalibration
- Curbs tendency to except data that is “reasonably” good
- Calibration standards will last much longer as less cal cycles needed



Why shorten path to the –probe tip?

- Raw directivity of system is degraded by up to 2 x Insertion loss between test port and probe tip
- For T geometry T wave probe at 330 GHz insertion loss is approx. 2.9 dB and guide insertion loss approx. 5.8 dB (approximately double probe dB loss)
- Reflected signal from ISS Short will be attenuated by 11.6 dB compared to a directly connected probe assuming 8″ path length
- Degraded directivity = Increased drift
- Increased loss also degrades dynamic range which can affect measurements with high return loss / insertion loss like long lossy transmission lines



Ref Keysight note 5965-7708E

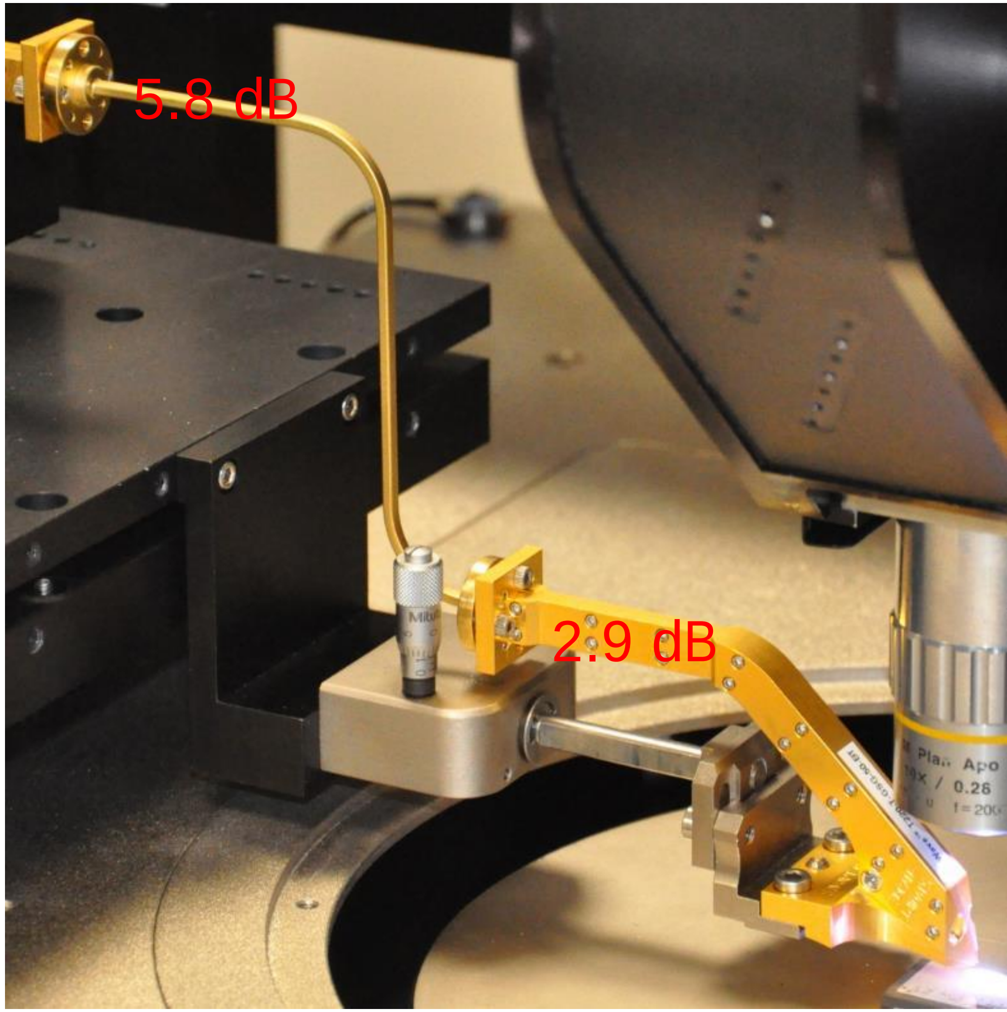
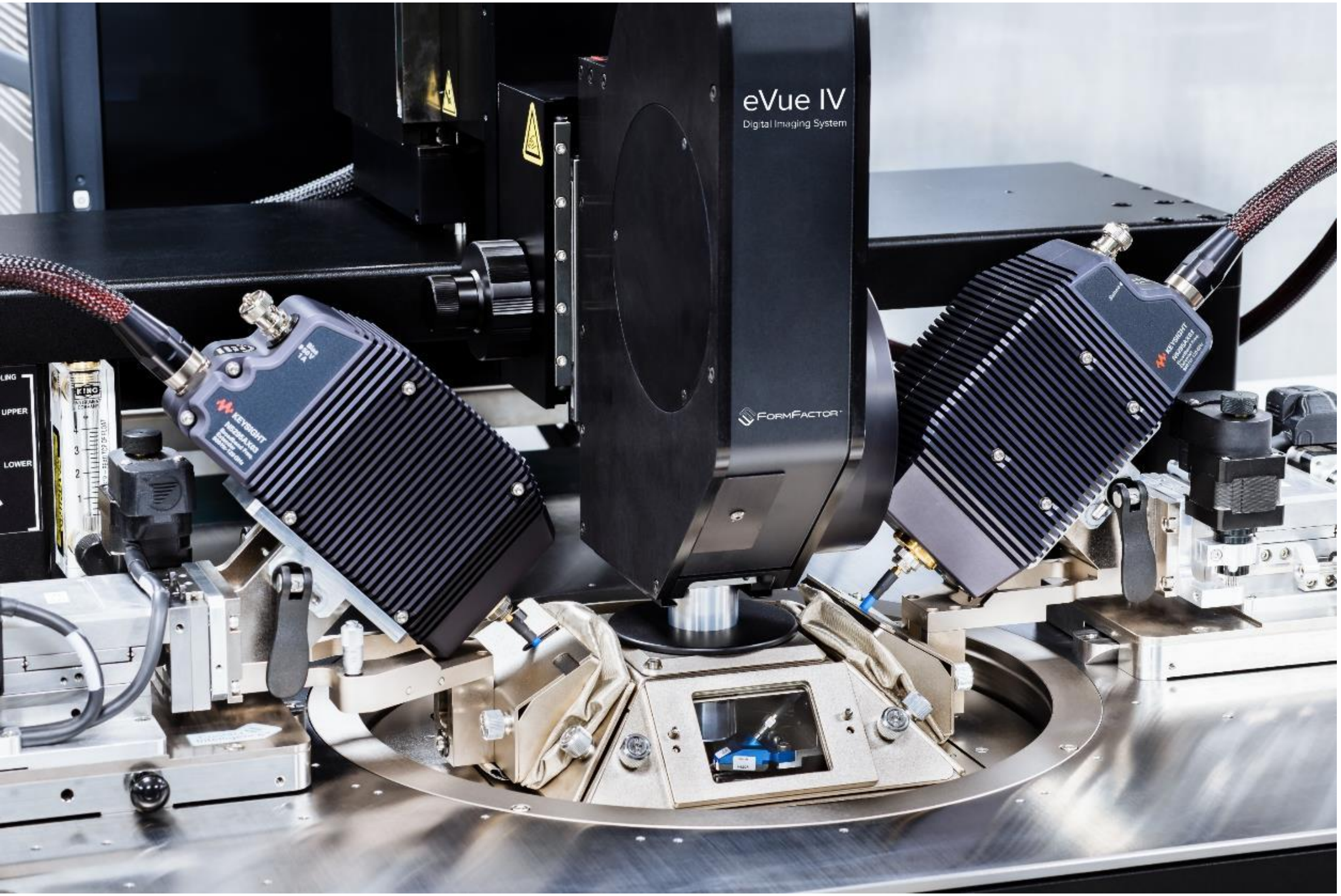


Image shown is with T-Wave "T" geometry probe with large area positioner

110 GHz Previous approach

- Fully auto capability also with chamber for dark . Dry measurements
- Large area positioners
- Cable length 24cm (approx 3.4 dB Insertion loss)
- N5251 System

Coaxial 200 mm solution 130 GHz over temperature

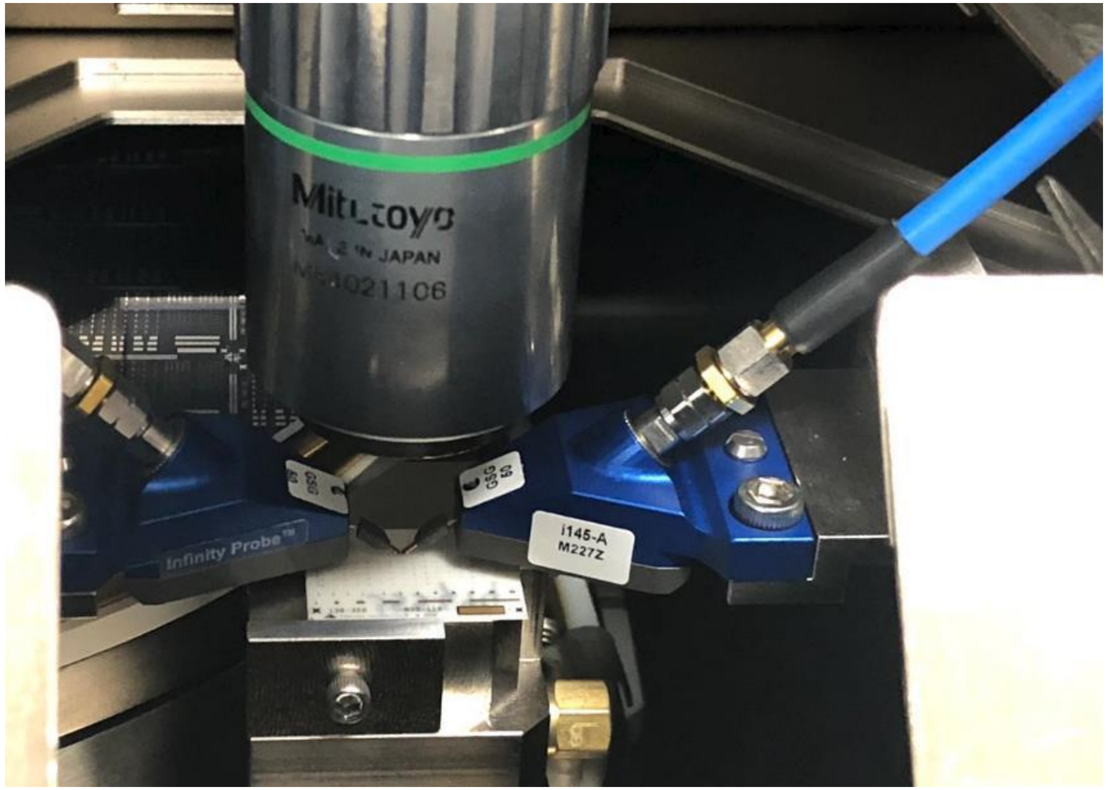


- Fully supports N5291A solution and Autonomous probing
- Minimal path length but capable of thermal autonomous probing
- Same solution used on all probers for full flexibility

RF-TopHat ‘ProbeWindow’

- Excellent visibility during setups
- Window glass has conductive coating to prevent charge build up and also keeps chamber dry
- Cover quickly installed to provide full light / emi shielding (has full emi gaskets)

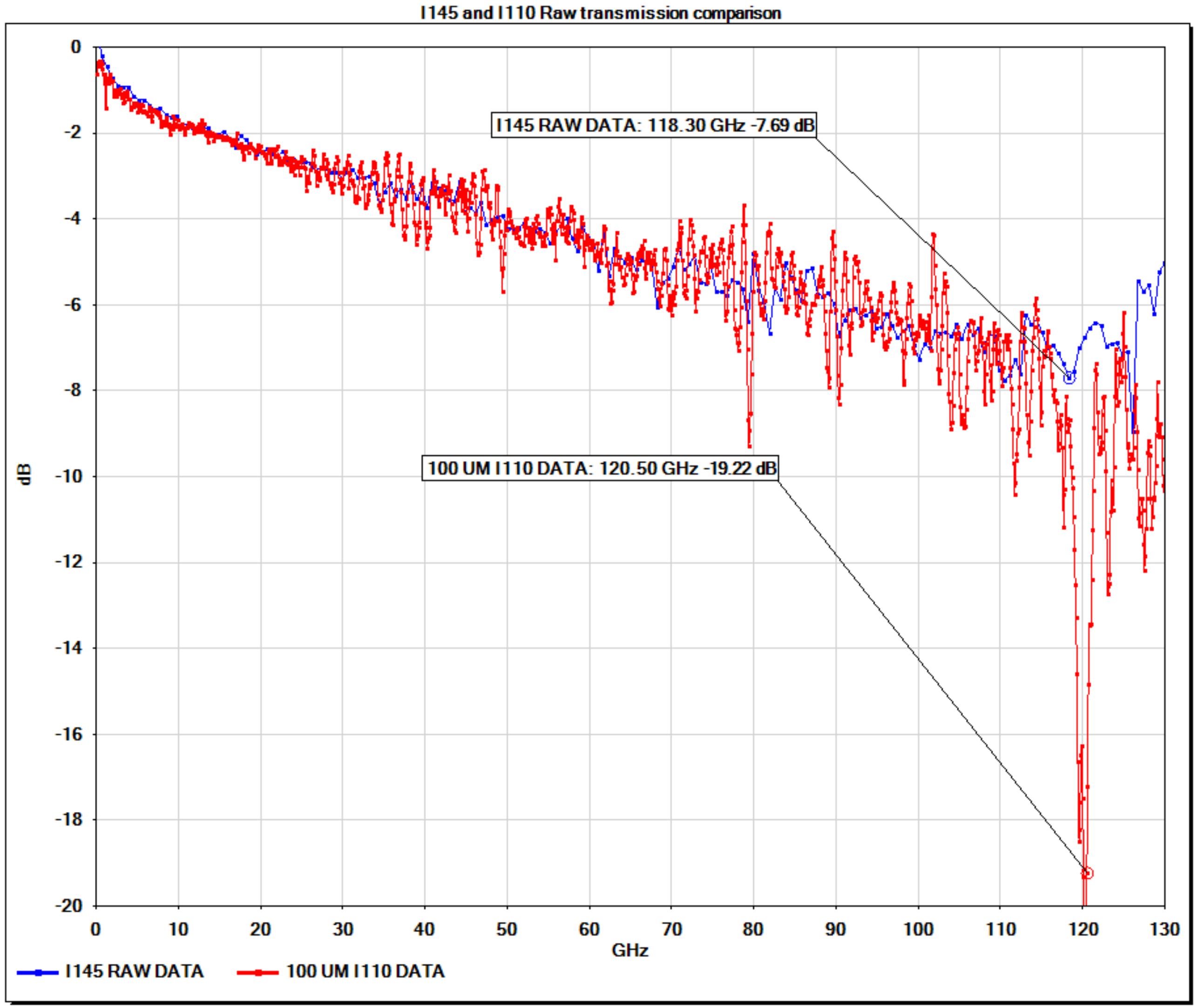
Measurement to 130 GHz using I145 Probe



- Uses same 10 or 13 cm cables
- Needs 1mm F to 0.8mm M adaptor
- In this instance we used a 50 um pitch probe and 138-356 ISS but this is not the reason for improvement
- Cable adaptor cable also available 775-00032

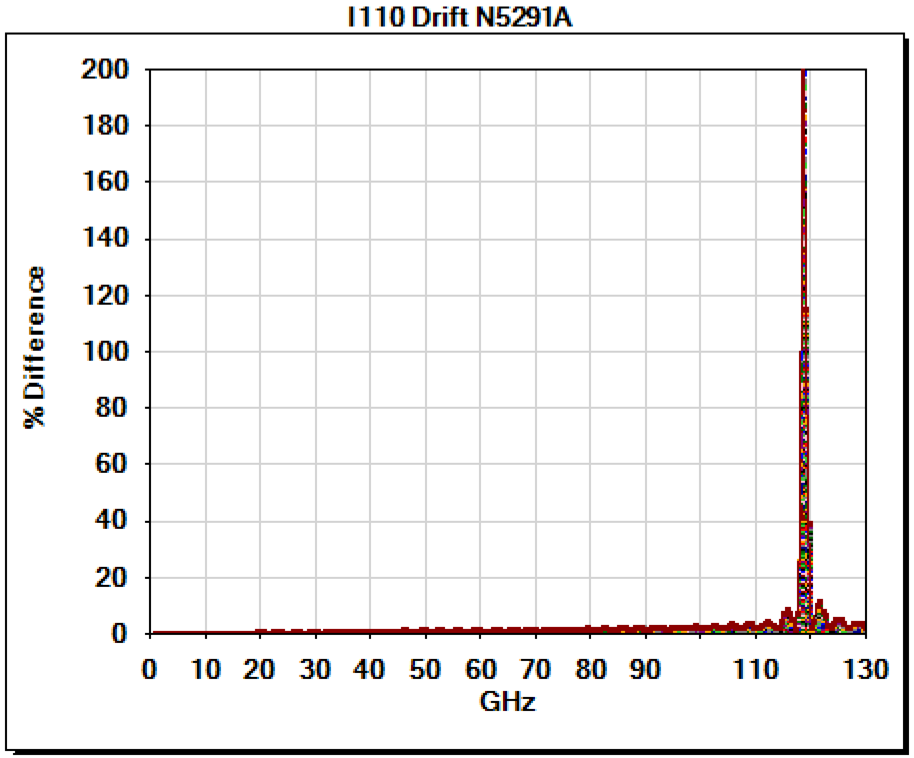
FormFactor™

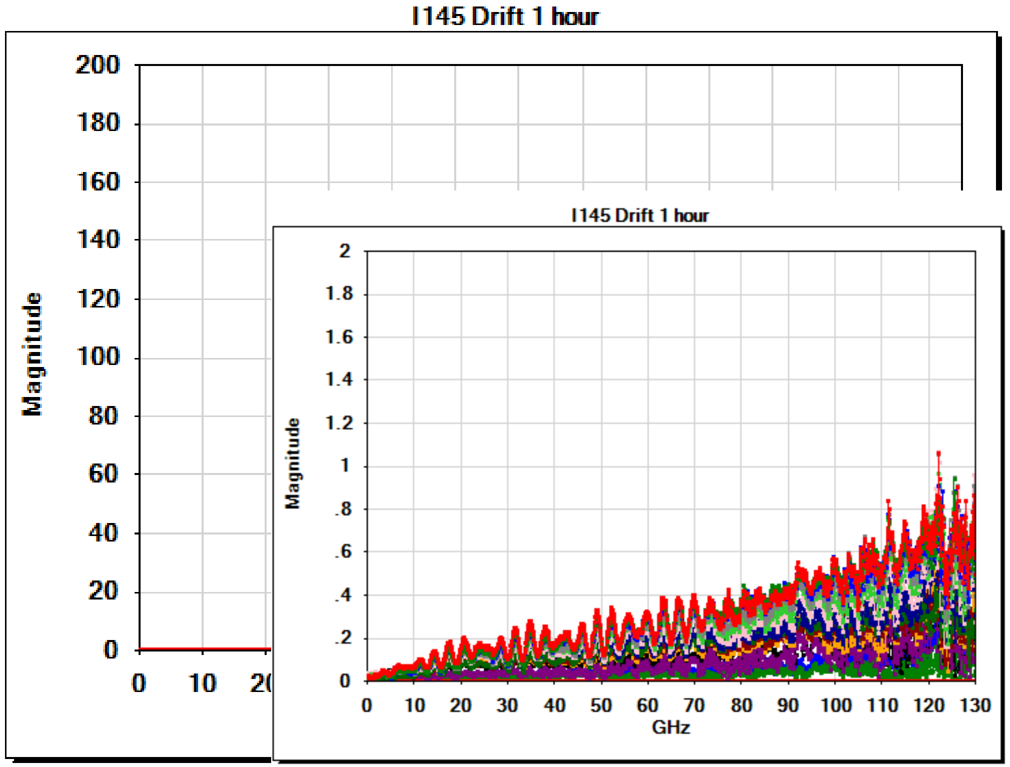
Comparison of Raw performance 2 probes + 2 cables on Thru



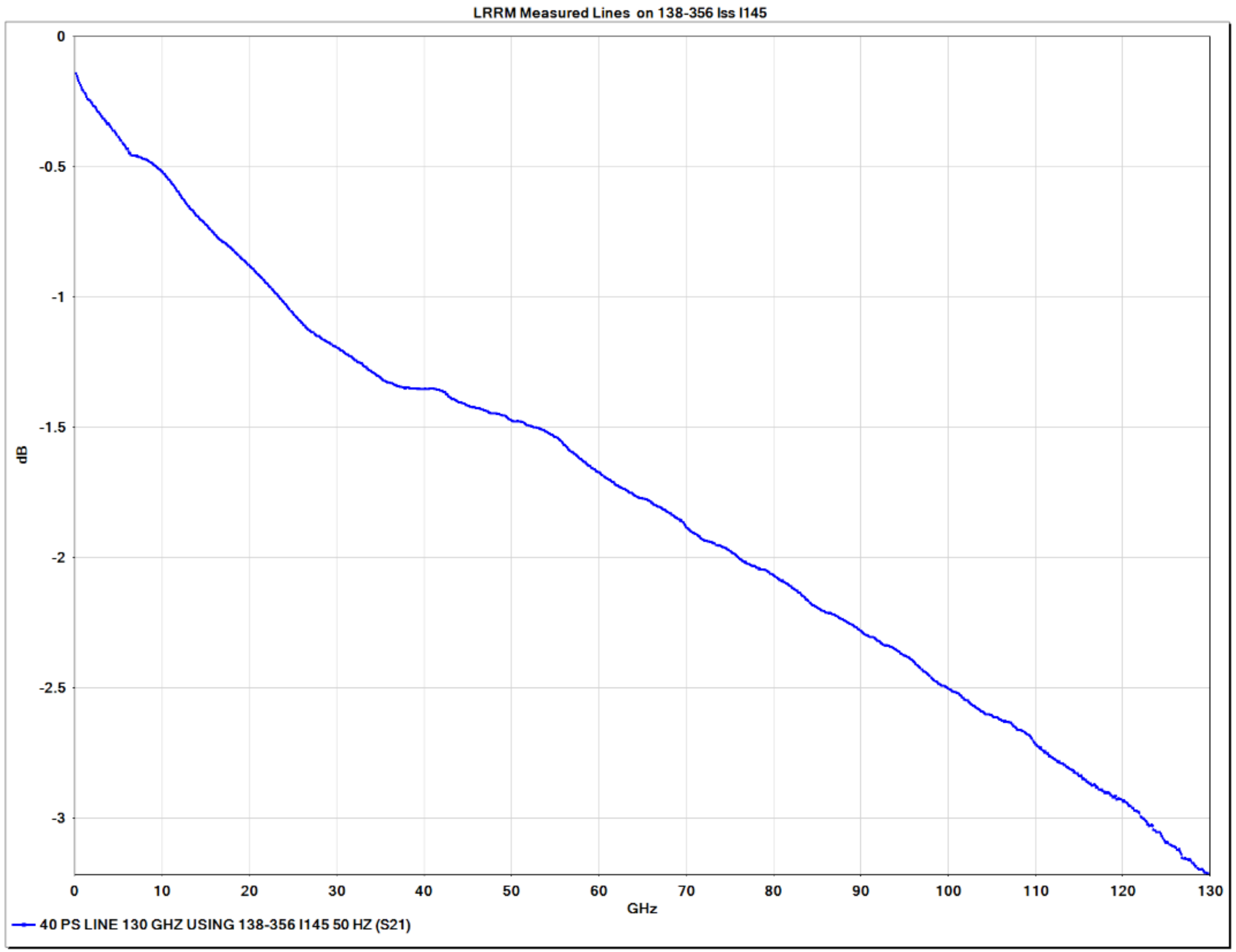
- At 120 GHz there is approximately 12db worse raw insertion loss for the I110 probe
- This is a function of the probe connector and solved using I145
- Other vendors have the same issue or worse

Massive improvement in drift I145





Line measurement to 130 GHz



Optimized 120GHz+ On-Wafer Solution Summit 12000

- Available on Summit 12000, Summit 200, Elite, CM300 and EPS Platforms
- New RF-TopHat
- 2 or 4-Port Solutions
- North & South DC Positioners
- Raised shelf provides ergonomic access to VNA and allows for short test head cables

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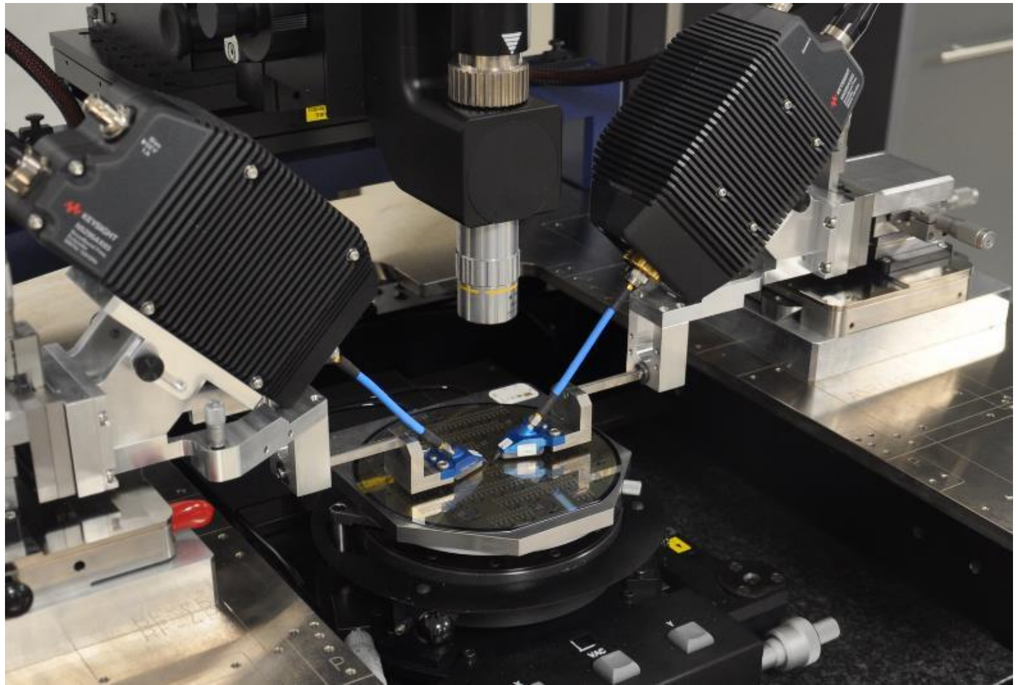
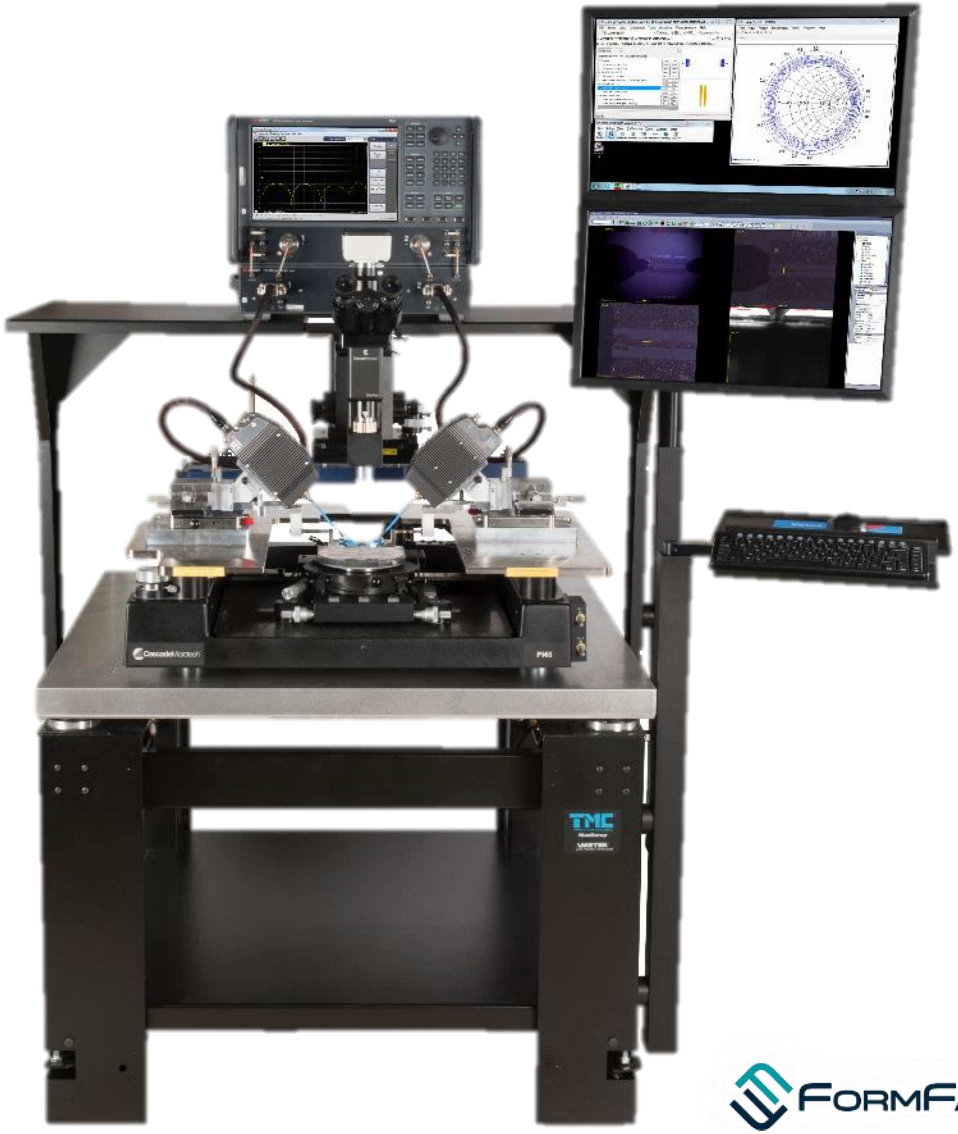
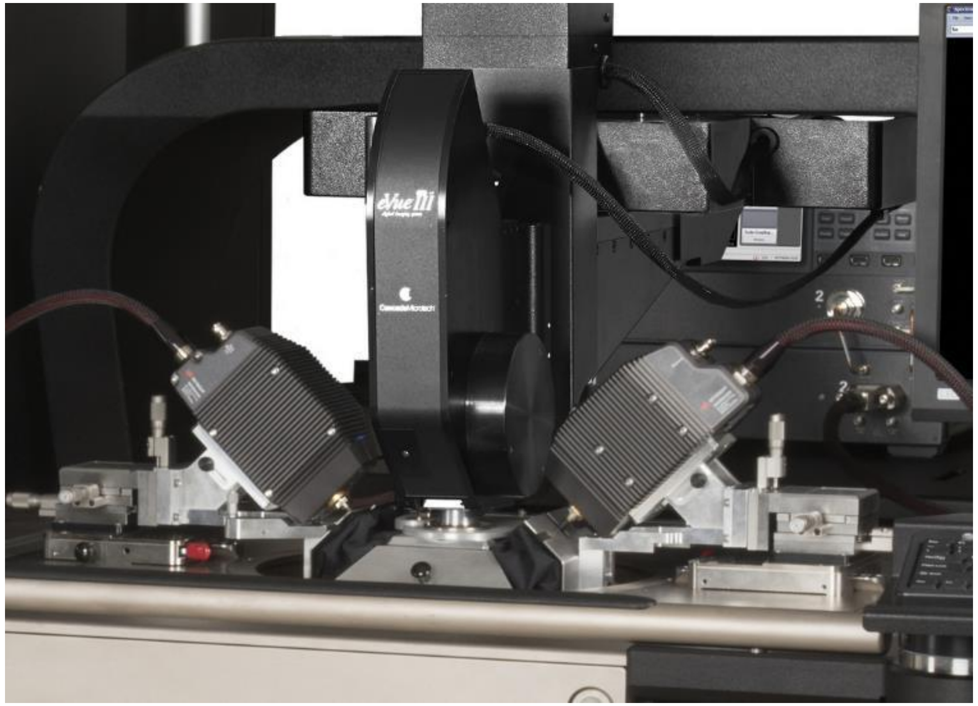
EPS 150mm & 200mm Solution

- Use EPS-150 or EPS200 with mm-wave platen
- Thermal option (hot only)
- Compatible with SlimView microscope
- 2 or 4-Port RF (E/W)
- N/S/E/W Positioner options





CM300 Integration



- Maintains Short 10cm Cable Length for 2 port setup
- Rear Instrument Shelf 176-613
- Loader Compatible
- Cable lengths same as for equivalent 12k solution
- No issues supporting loader

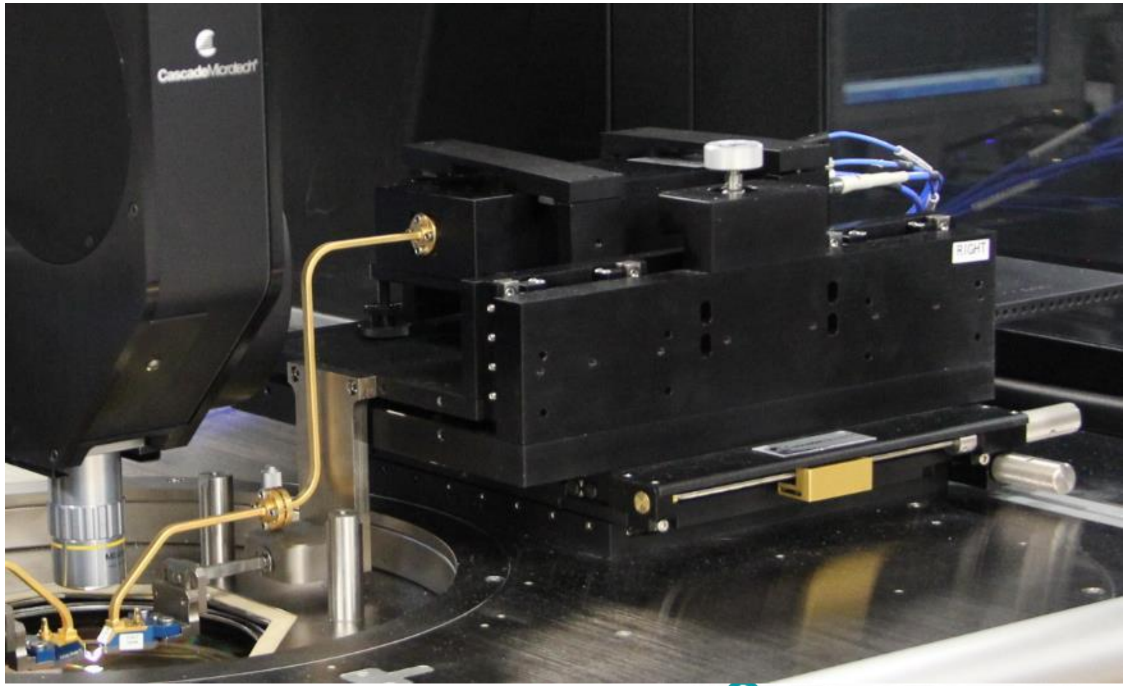
Contribution of Waveguide to insertion loss (Tall setup)

	WR15	WR12	WR10	WR8	WR6	WR 5	WR3.4
Band	V	E	W	F	D	G	H
Frequency	50-75	60-90	75-110	90-140	110-170	140-220	220-330
Loss per cm (dB)	0.0230	0.0340	0.0610	0.0920	0.1280	0.1850	0.2270
S Bend Loss calc (dB)	0.34	0.50	0.89	1.34	1.86	2.7	4.3
Probe insertion loss Infinity (dB)	2.1	2.6	2.6	3.1	4.7	5.2	6.5
Probe insertion loss T-Wave (dB)						2.3	4.3
Total insertion los (dB)	2.44	3.10	3.49	4.44	6.57	7.9/5.0	10.8/8.6

- Probes used WR5 and above are T-Wave
- VDI Waveguide loss table values extrapolated based on measured loss for WR5
- Losses to WR12 are fairly small percentage of overall
- At WR5 with reduced probe losses waveguide loss becomes more considerable

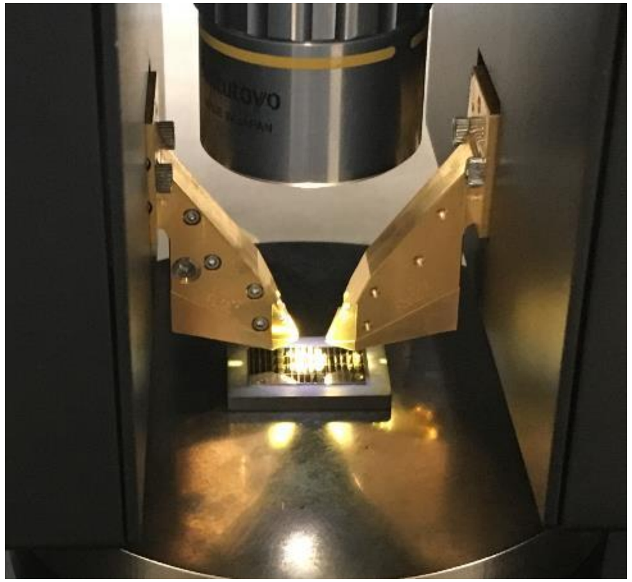
Conventional banded approach

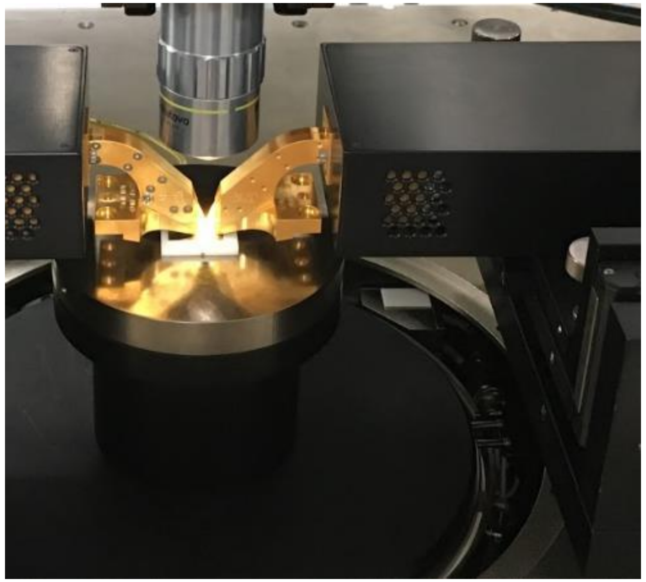
- Tested solution uses S bends and T geometry probes
- Although not tested the raised chuck solution will work with modification if desired



Semi-automatic – Raised chuck solution for best performance

- Highest Frequency supported by our probes (1.1 THz in this case)
- Allows probes to connect directly to extender which gives best possible performance
- Raising probes limits usable chuck diameter and no access to thermal chuck
- Same approach can be used by all bands and extender types
- Motorised positioner allow automatic MLTRL





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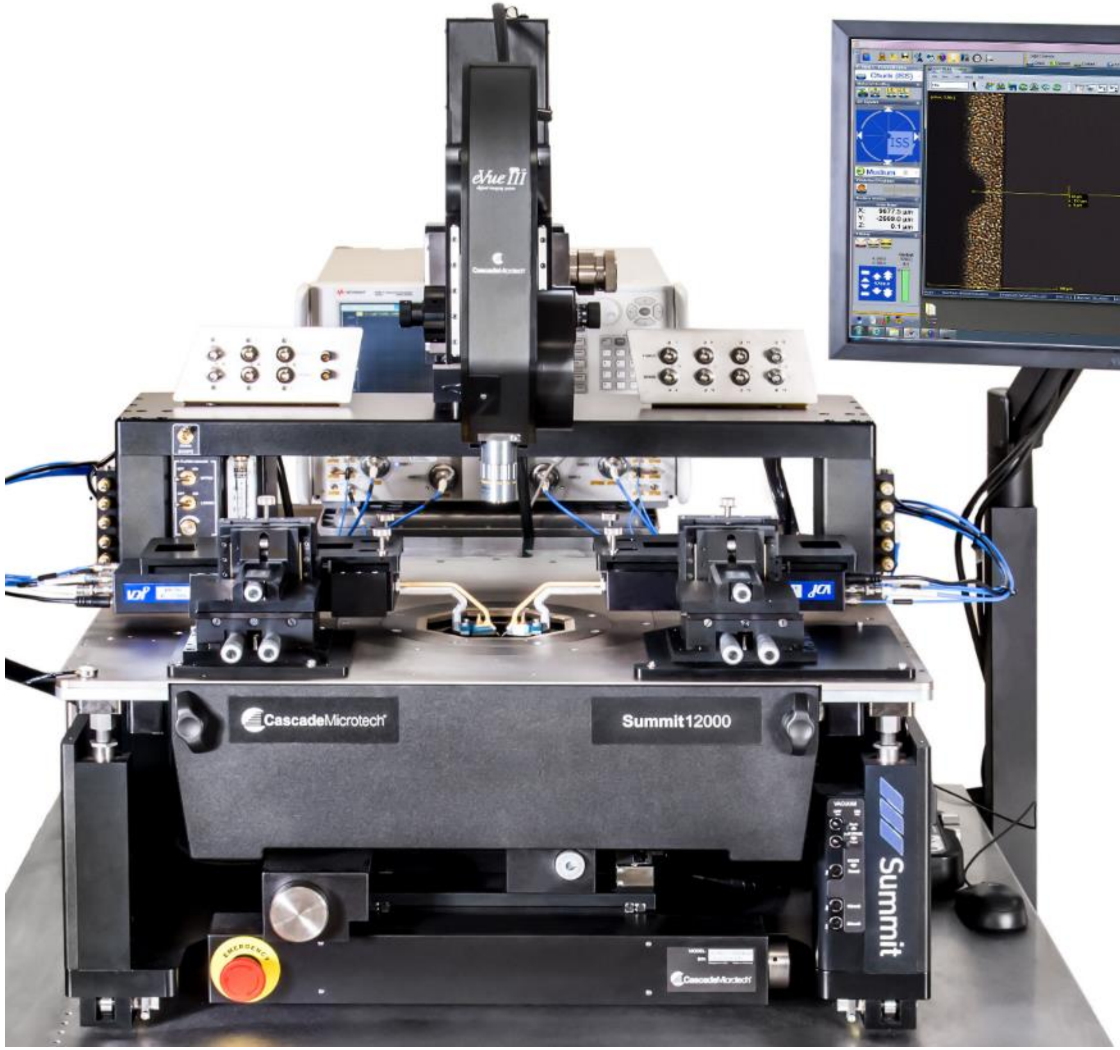
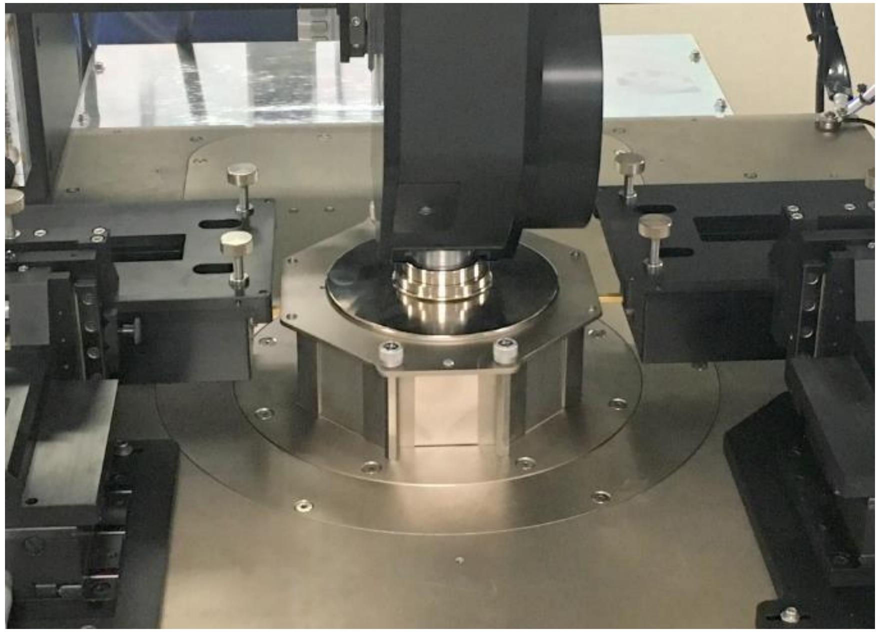
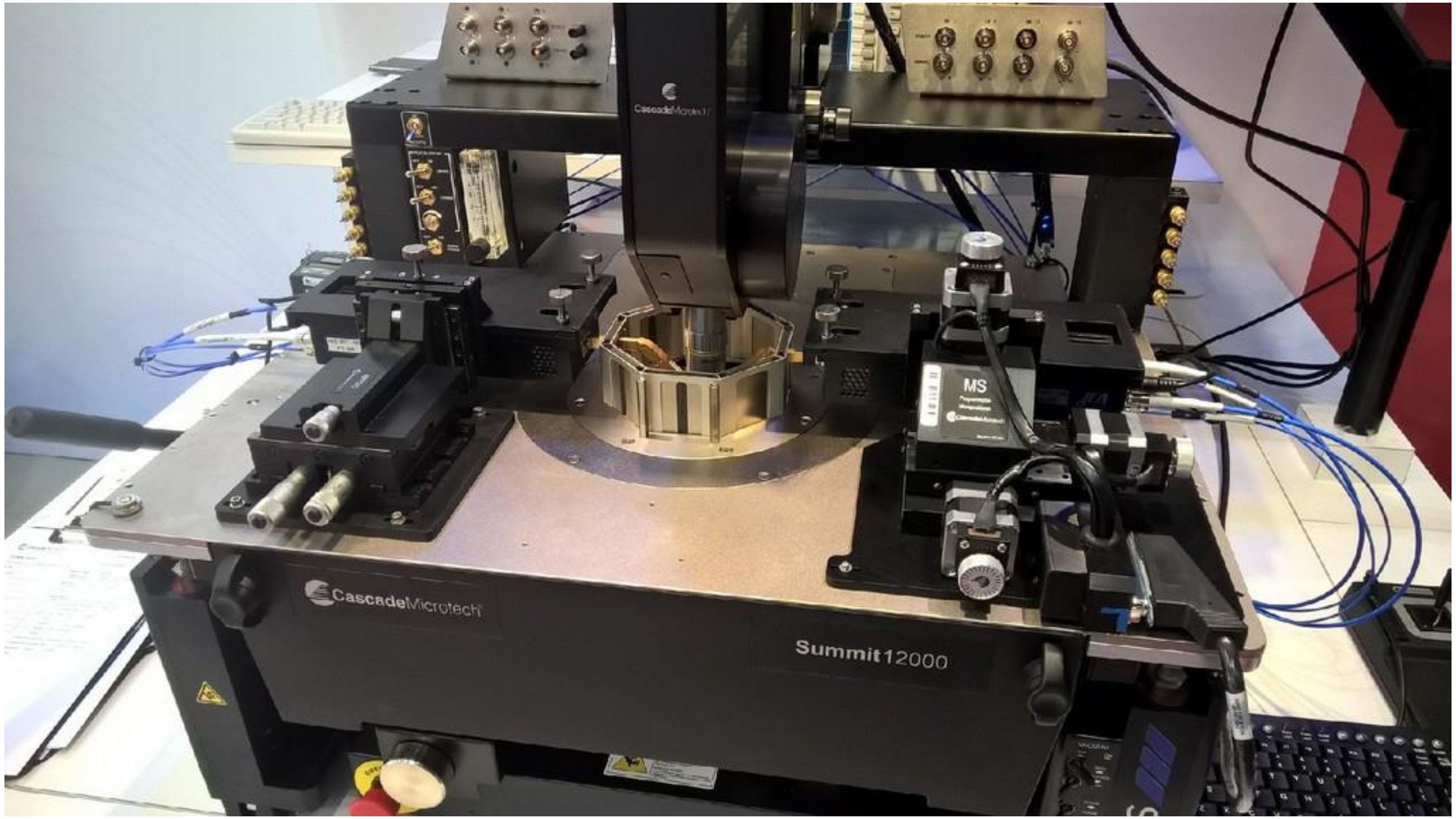
Semi-automatic, Thermal – Manual Positioner Bands from 50-330GHz Direct connect probe





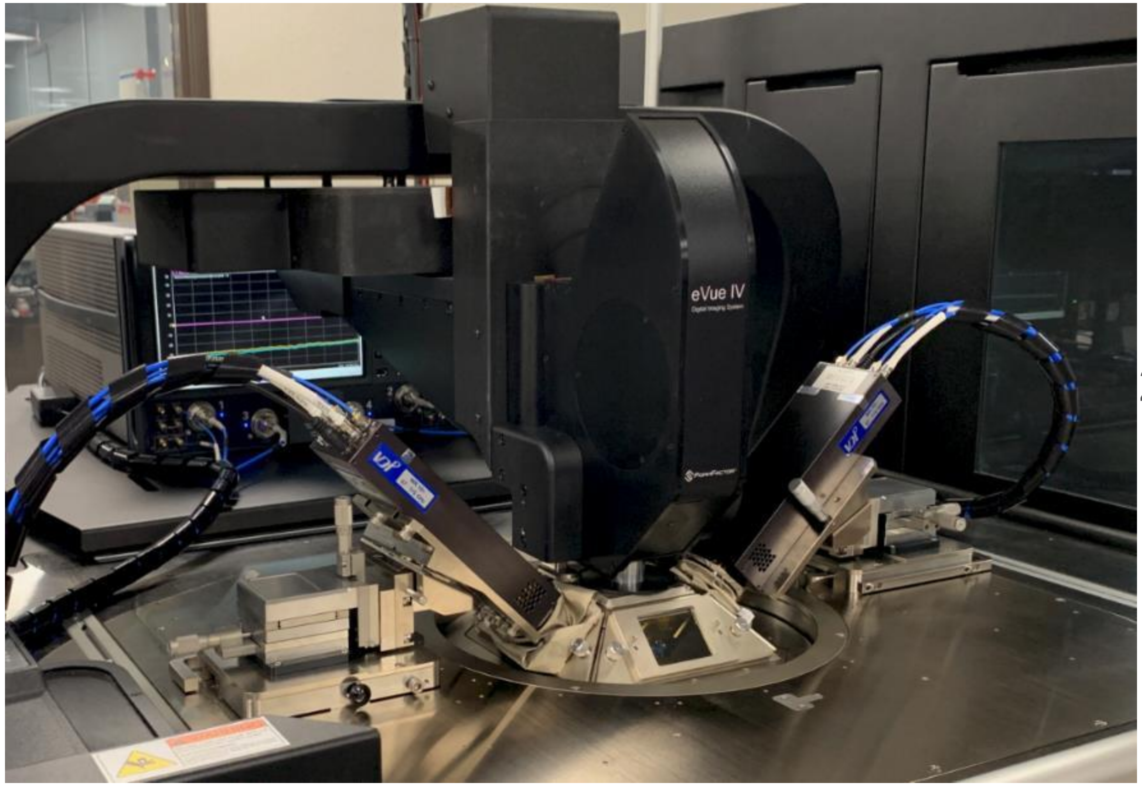
- This arrangement makes use of Tall geometry probes and small form factor of the Virginia diodes mini modules
- Probes connected directly to extender
- Reliant on shallow 14mm Chuck to platen height of Summit 12000
- Other stations in our ranges are deeper to improve thermal stability but which prevents use of this approach

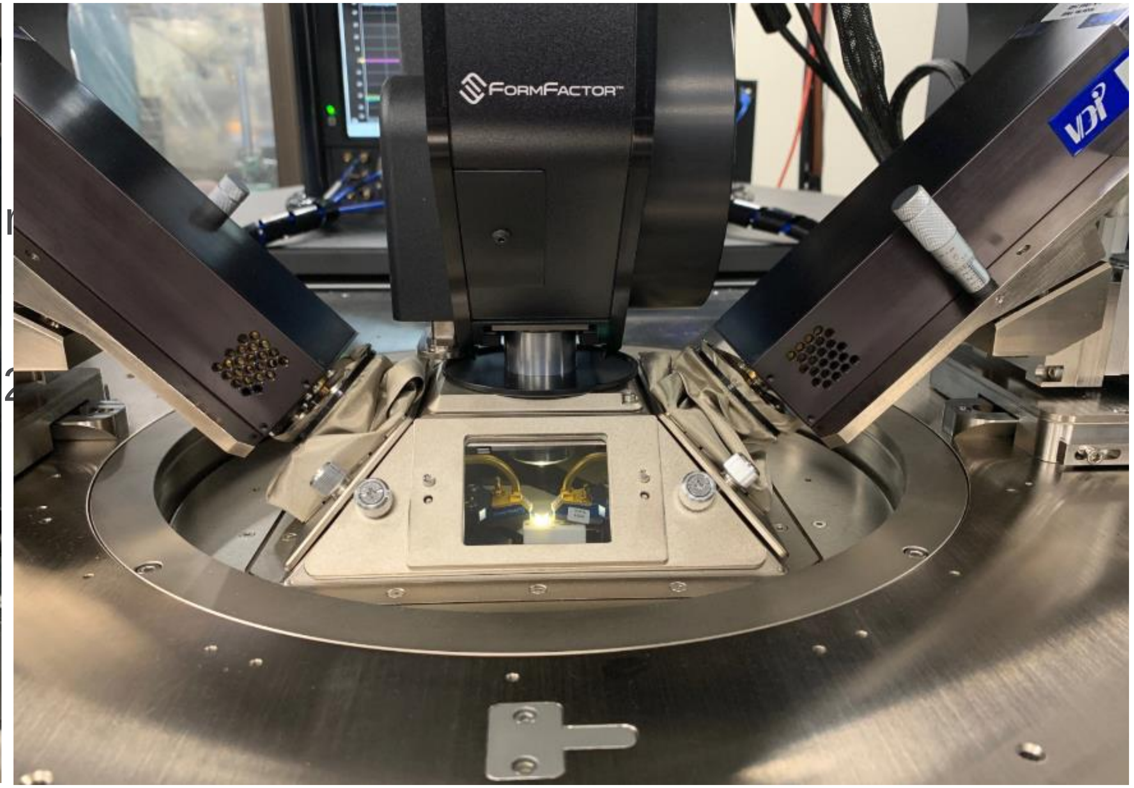
Station configurations – 200mm semi auto – Direct connect with thermal capability – Motorised positioner with Mini VDI



- Motorised positioner allows for use of automatic MLTRL calibration
- Motorised positioner improves placement repeatability on DUT even when using LRRM
- This shot shows tophat assembly
- Concept limited to WR3.4 at present but can extend warm only WR2.2 as special

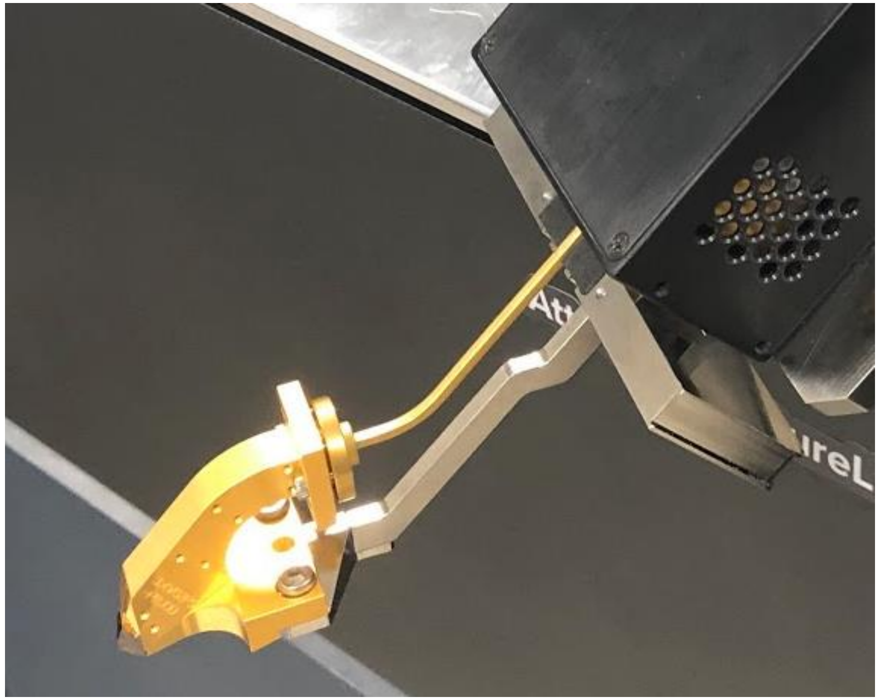
Angled VDI mini extender allows minimal path length for waveguide





Angled extender allows minimal path length

- Non chambered (left) and Chambered versions (right) available
- Non chambered version still capable of hot thermal measurements but has even shorter waveguide extension
- T-Wave / ACP and Infinity all supported for all implementations
- Length of short extension and probe is equivalent to T-geometry probe



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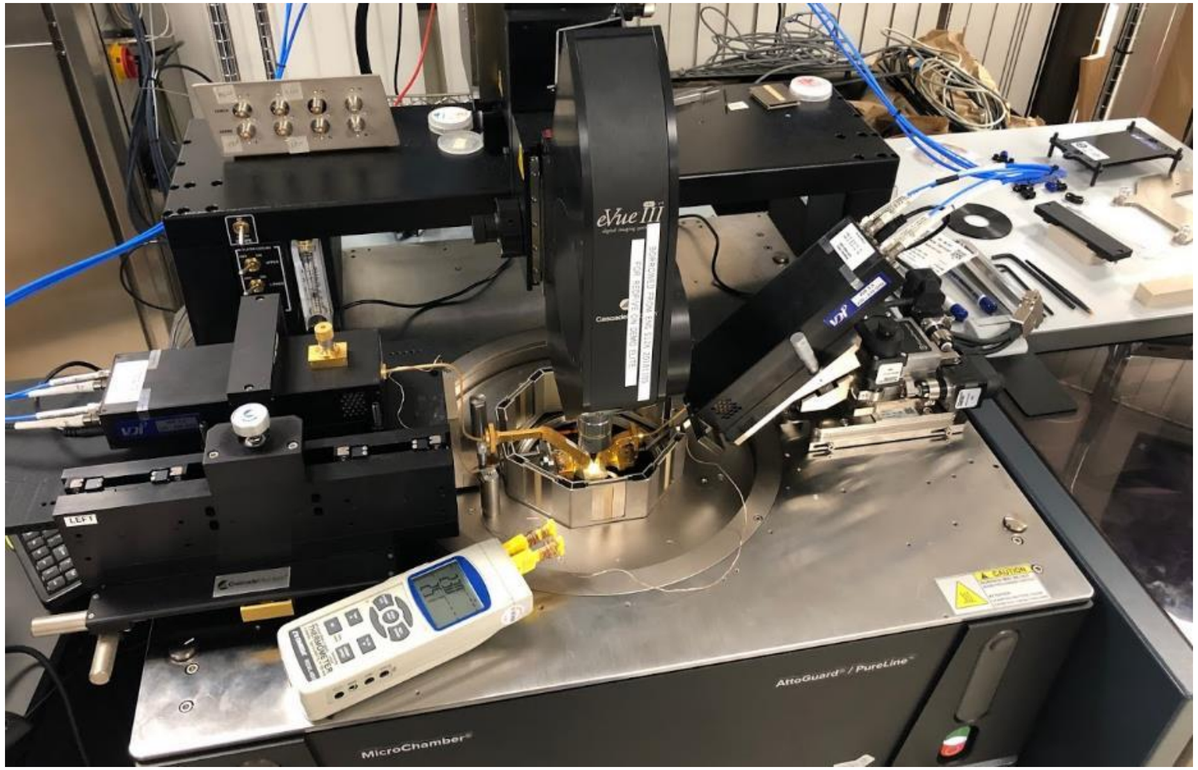
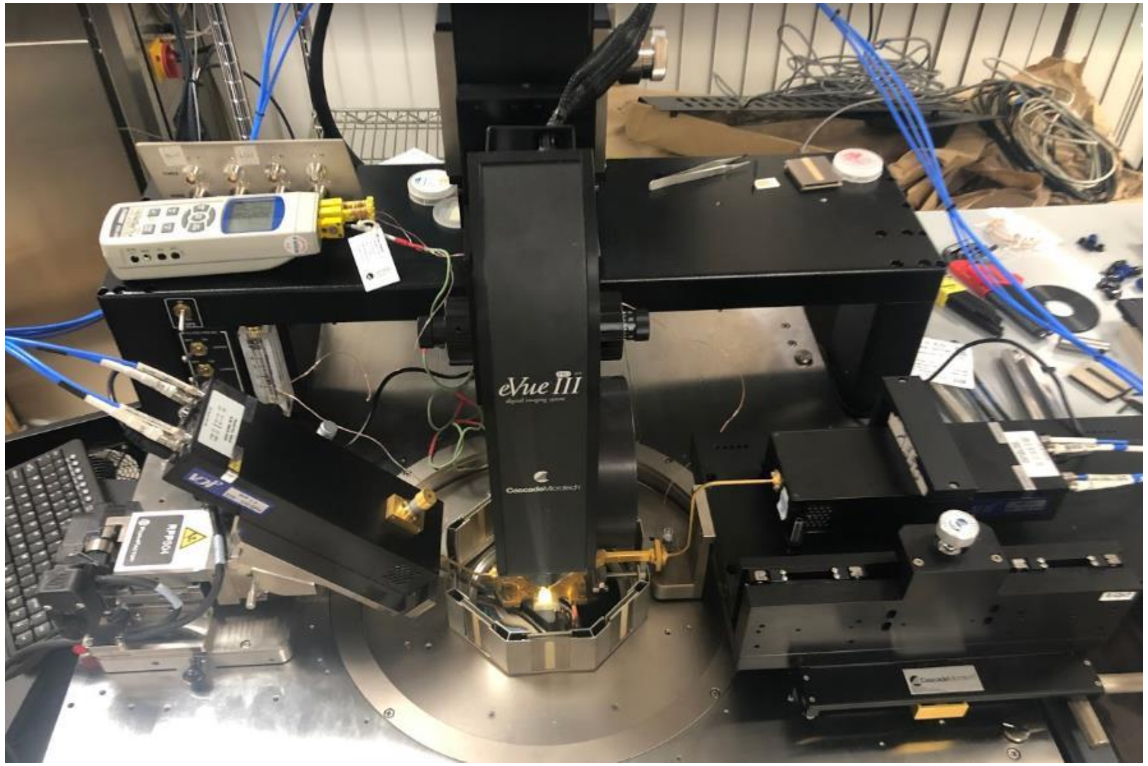
Drift Improvements – comparison experiment

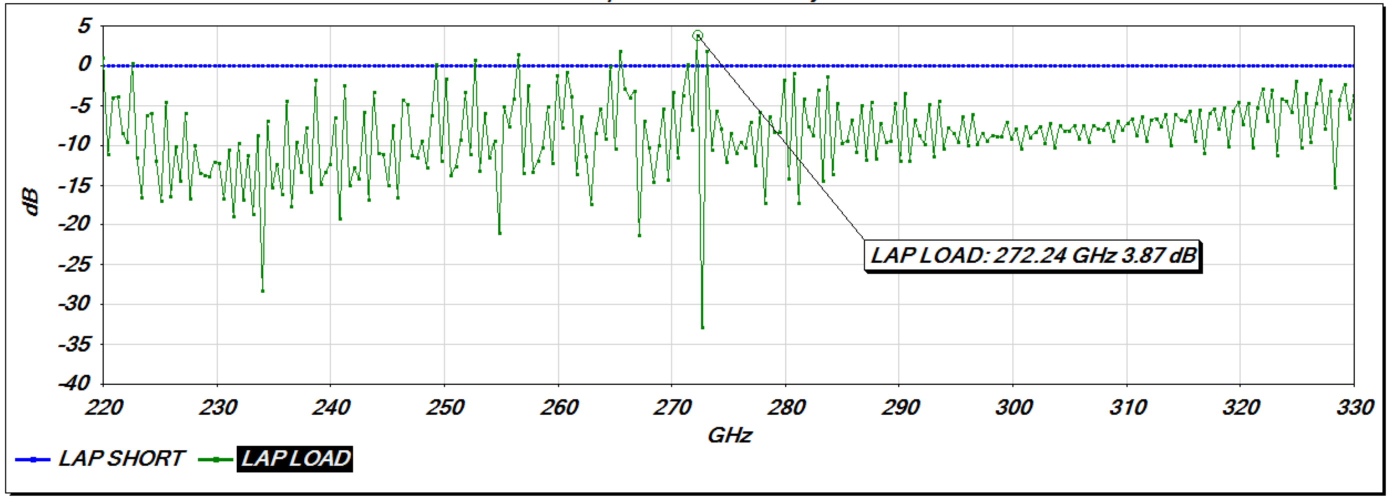




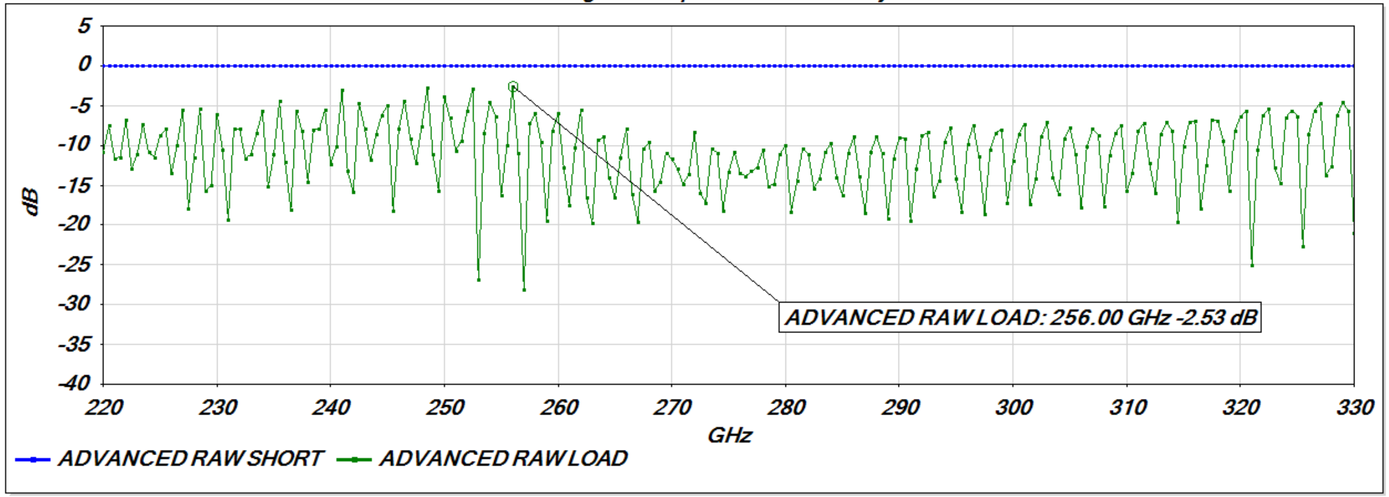
- Experiment done to see if drift is better for reduced path case
- First case is Long path setup left using Tall geometry and Angled Right short geometry
- Second case is with sides swapped Angled left, Long path right
- Calibrated Open measurements taken every 5 minutes and normalised to first

Angled mini extender compared to conventional– Directivity estimate (Load normalised to Short)

LAP Setup Load normalised by Short



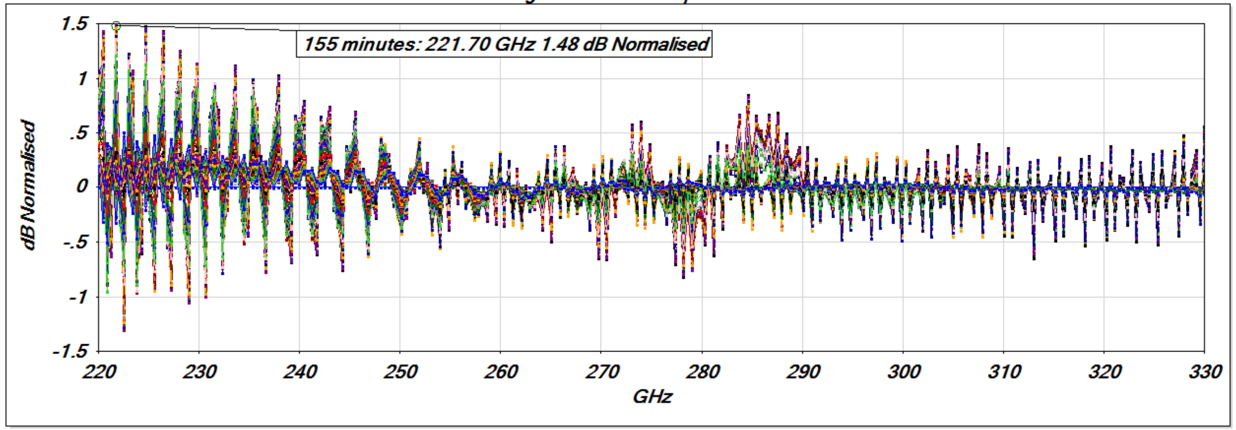
Advanced Angled Setup Load normalised by Short



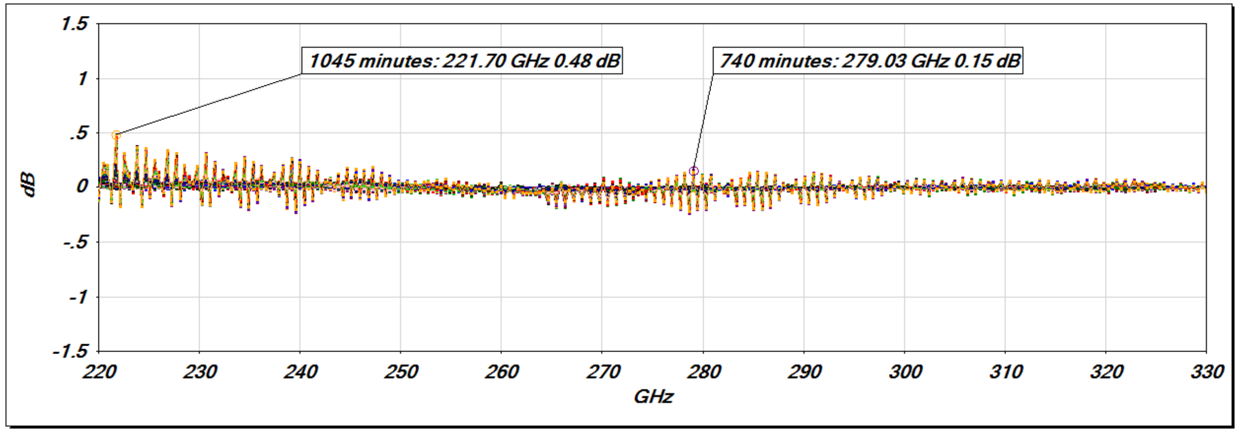
- LAP = Large area positioner with extended S Bends
- Worst case for LAP load actually have +3.87 dB w.r.t Short
- Angled case worst case -2.53 dB
- In general around 5 dB better off...which can make a big difference

Drift comparison – Normalised Magnitude

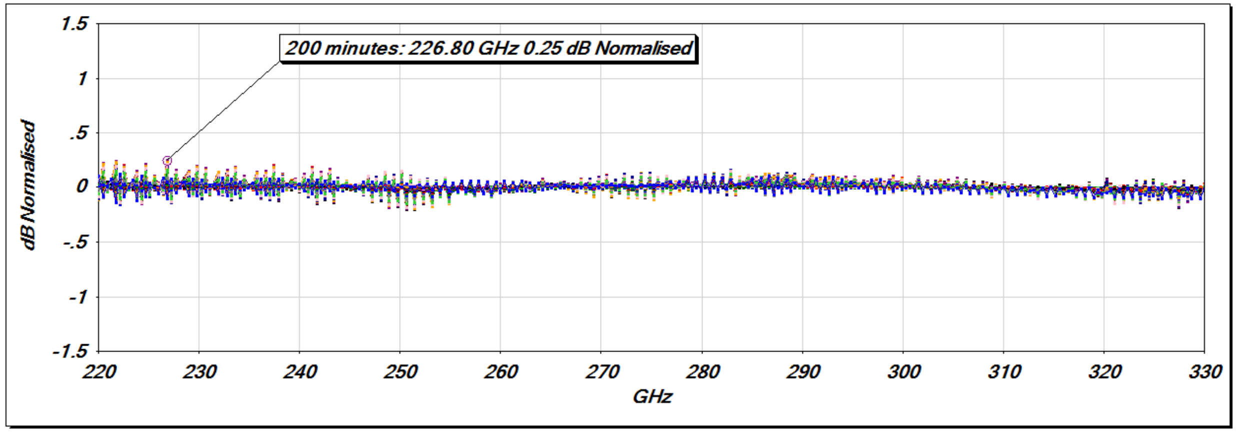
Conventional Waveguide Probe Setup - Attenuator head Port1



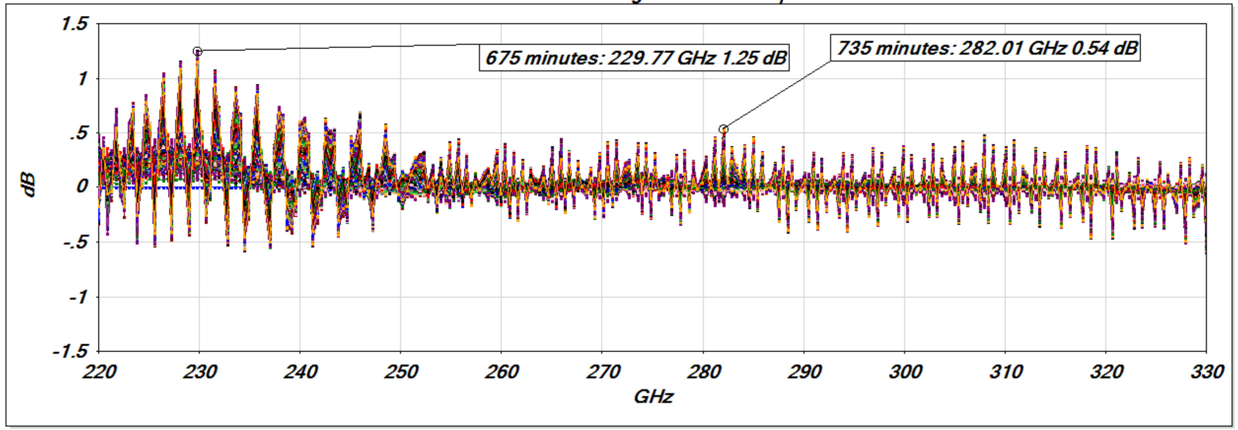
FormFactor's advanced mmW and THz solution



FormFactor's advanced mmW and THz solution - No attenuator Port2



Conventional Waveguide Probe Setup



- Heavy drift characteristics clearly follows the setup
- Both setups left overnight

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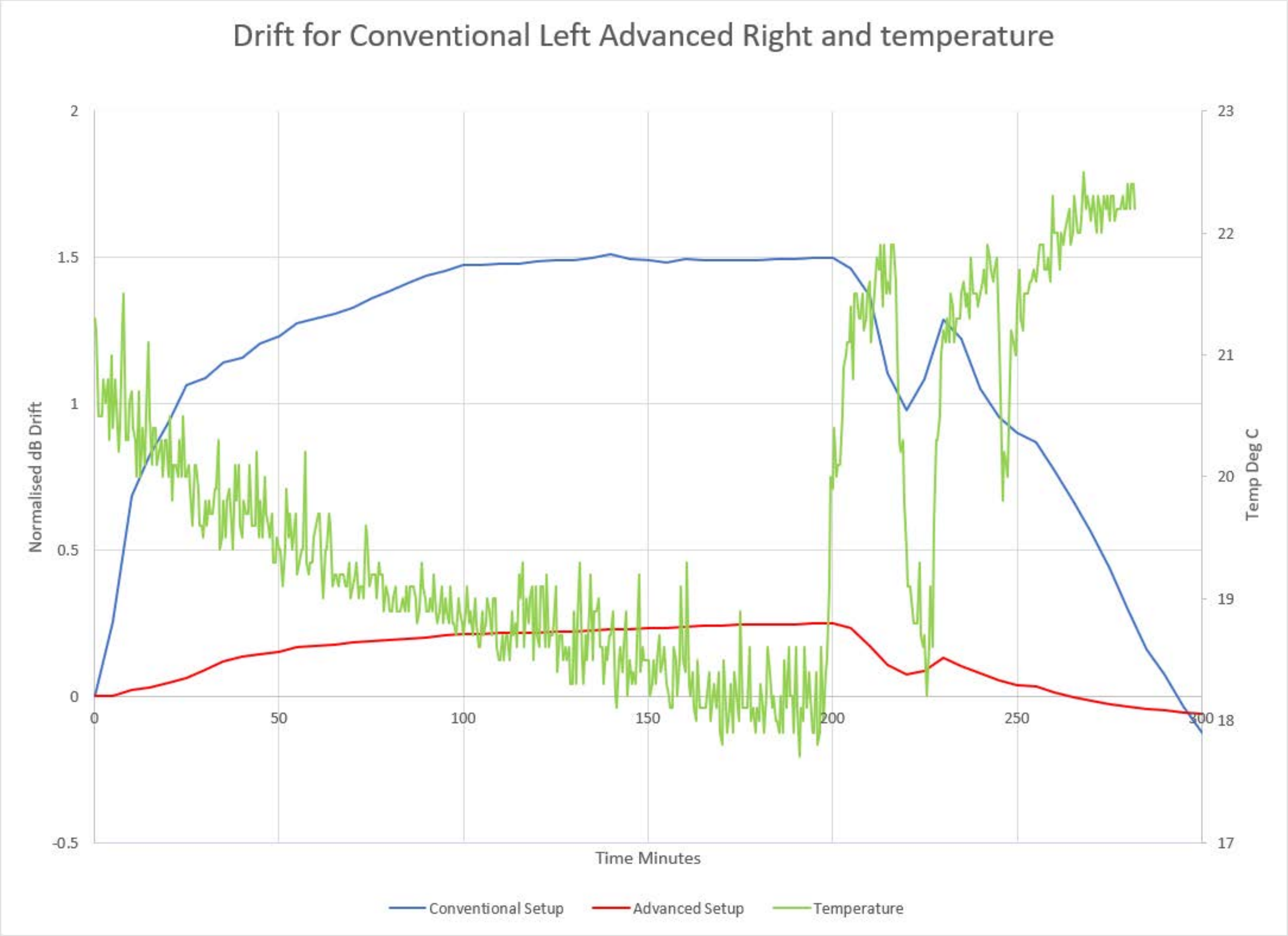
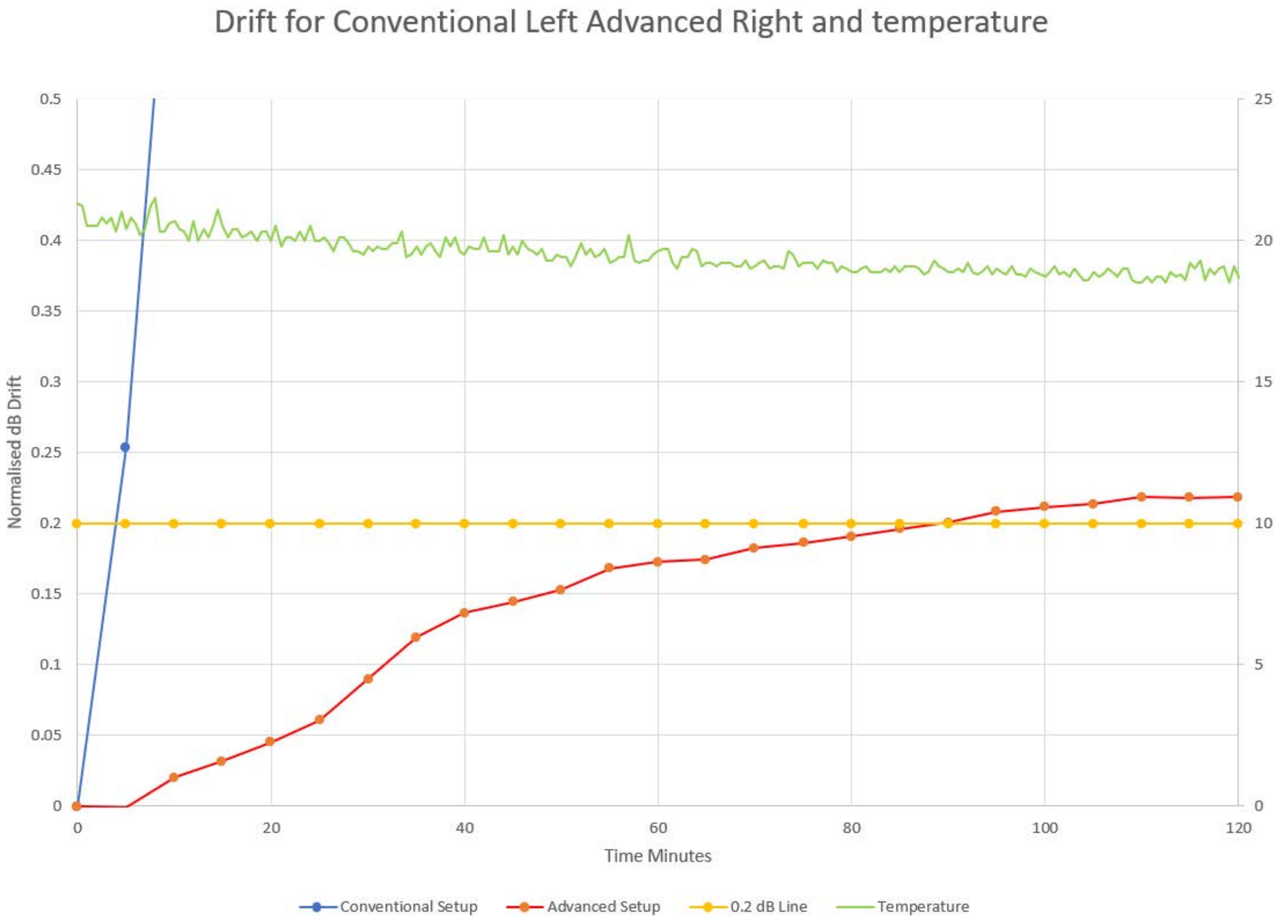
Drift as a function of temperature



- Thermometer batteries fail after 5 hours
- Previous graph used to assess point of maximum drift
- Red trace advanced angled, Blue trace conventional, Green temperature
- Drift characteristics follow room temperature

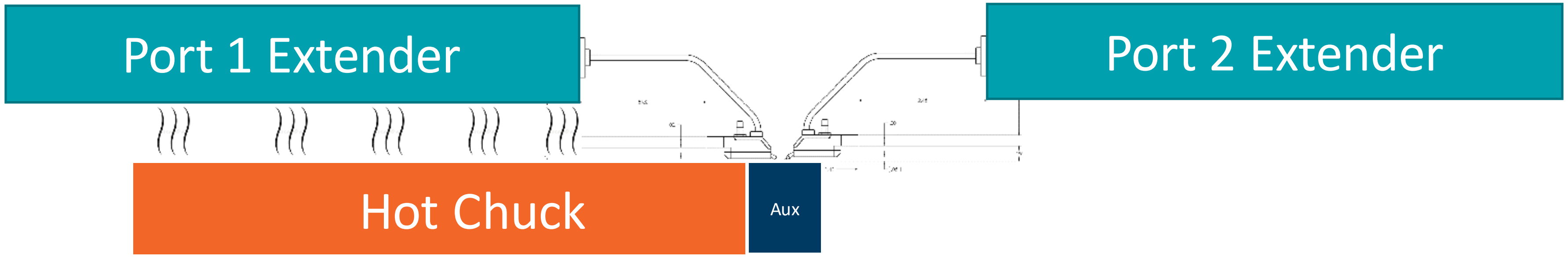
Drift comparison – Time to recalibration



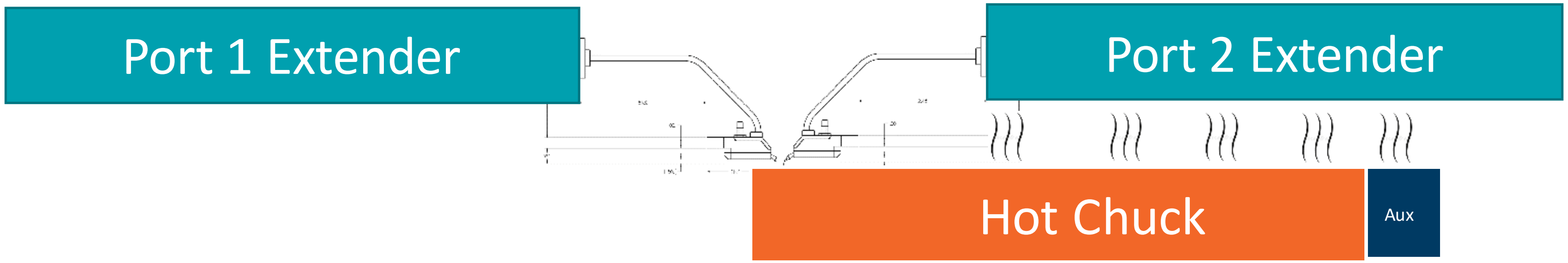
- Zooming into the data
- If a tight 0.2 Db window is selected this is 90 minutes in comparison to just 4

Challenges of Calibration Drift for thermal applications

Calibrating on Aux Chuck or measuring DUT on Right side

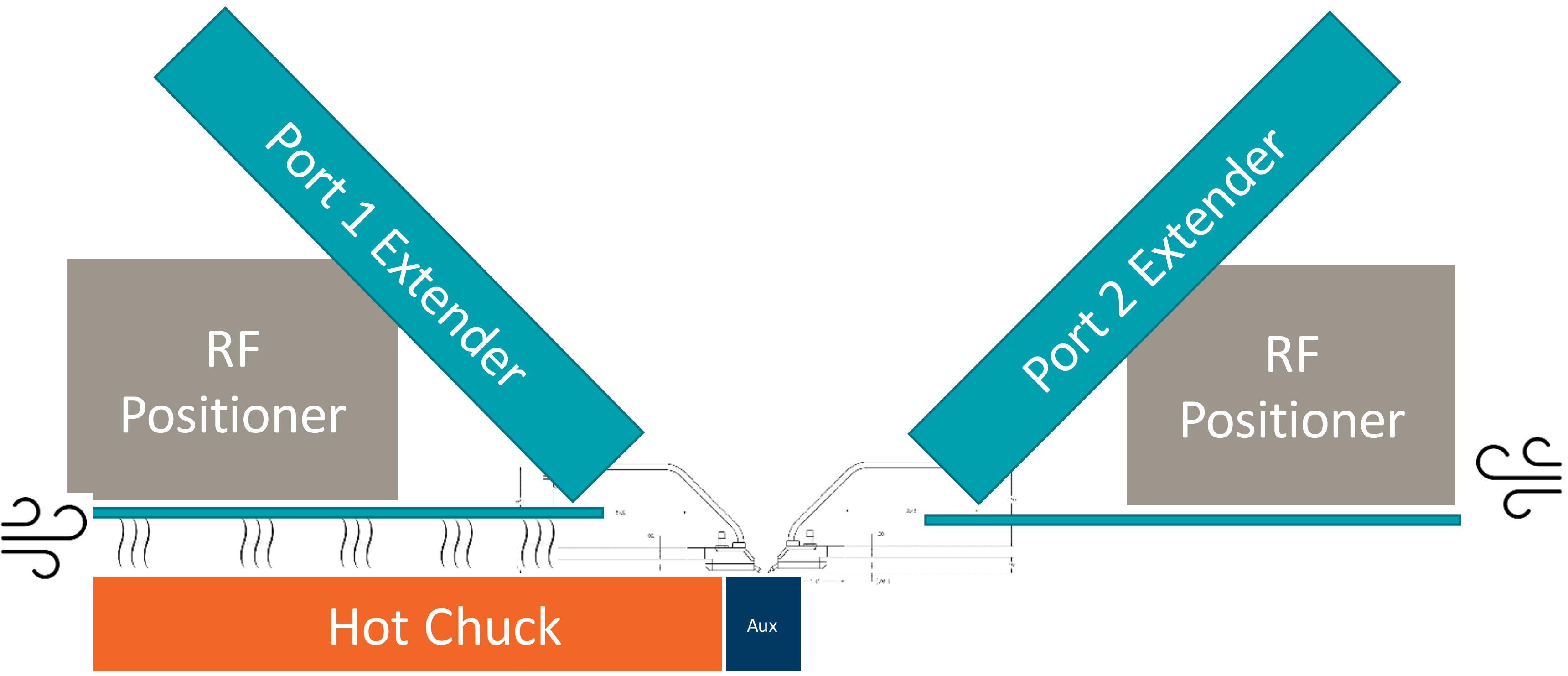


Measuring DUT on left side



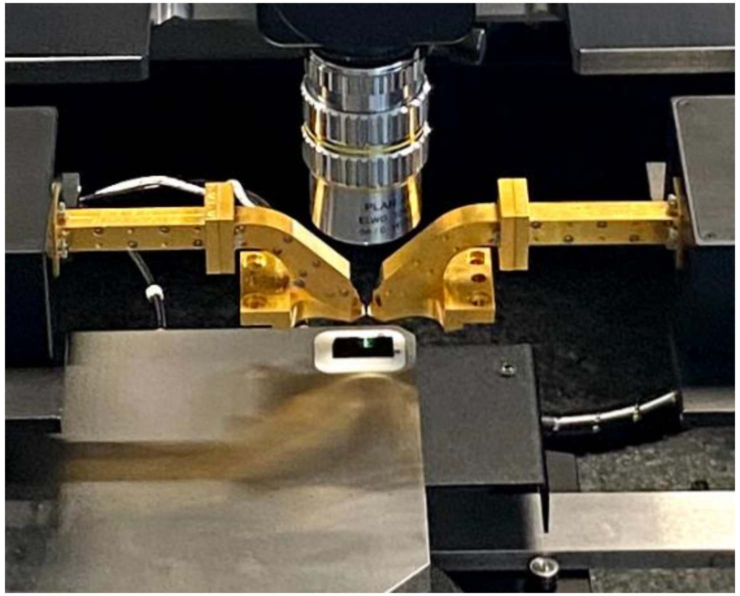
Thermally Isolated Extenders

Inclined – Thermally Isolated Extenders

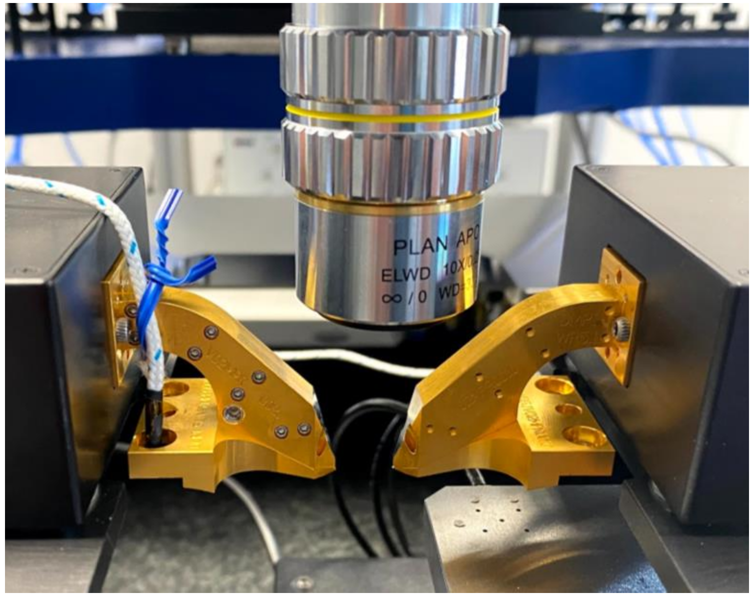


- Having the extenders inclined offers naturally improved thermal isolation
- Air jets improve cooling of platen surface
- Result is extenders stay at ambient temperature and not affected by thermal chuck
- This greatly improves drift stability regardless of chuck location

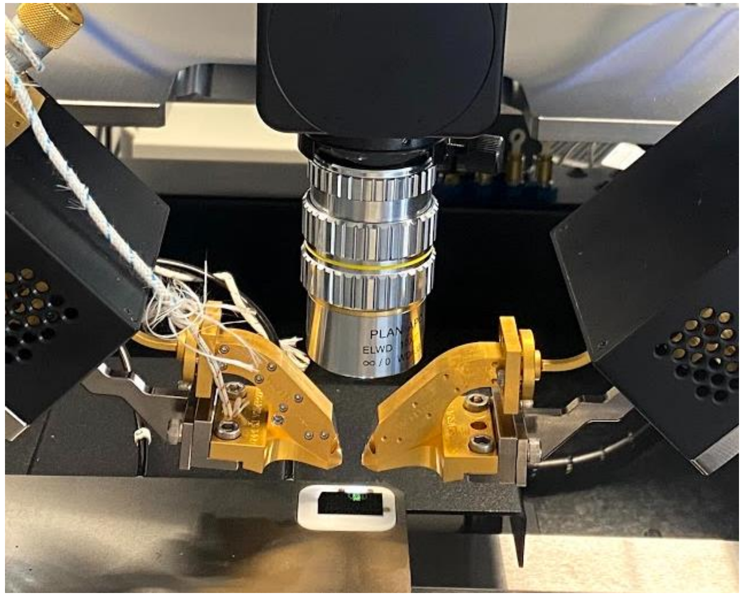
Comparison Between Extender / Probe Integration



Horizontal Extender – 50mm VDI WG - Probe

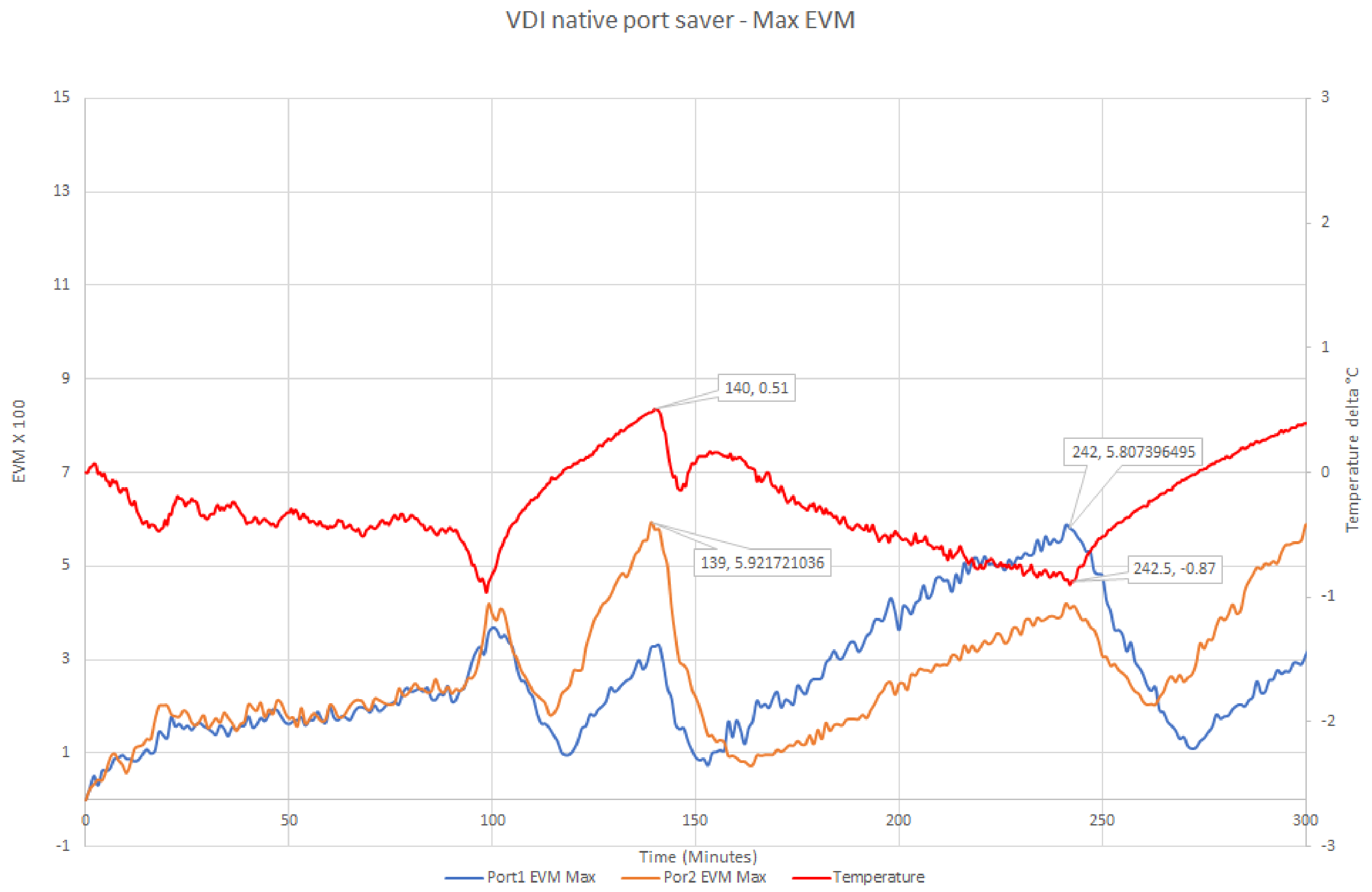


Horizontal Extender – Direct Connect - Probe

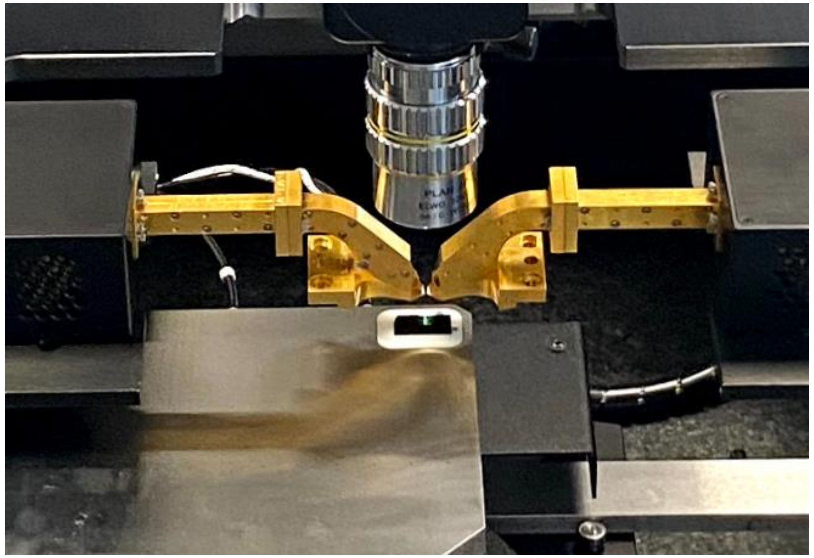


Inclined Extender – 45deg WG - Probe

Drift comparison – Horizonal Extender – 50mm WG - Probe



	PORT 1	PORT 2
Max EVM	5.8	5.9
∆°C at Max EVM	-0.87	+0.51
Max EVM per ∆°C	6.66	11.5



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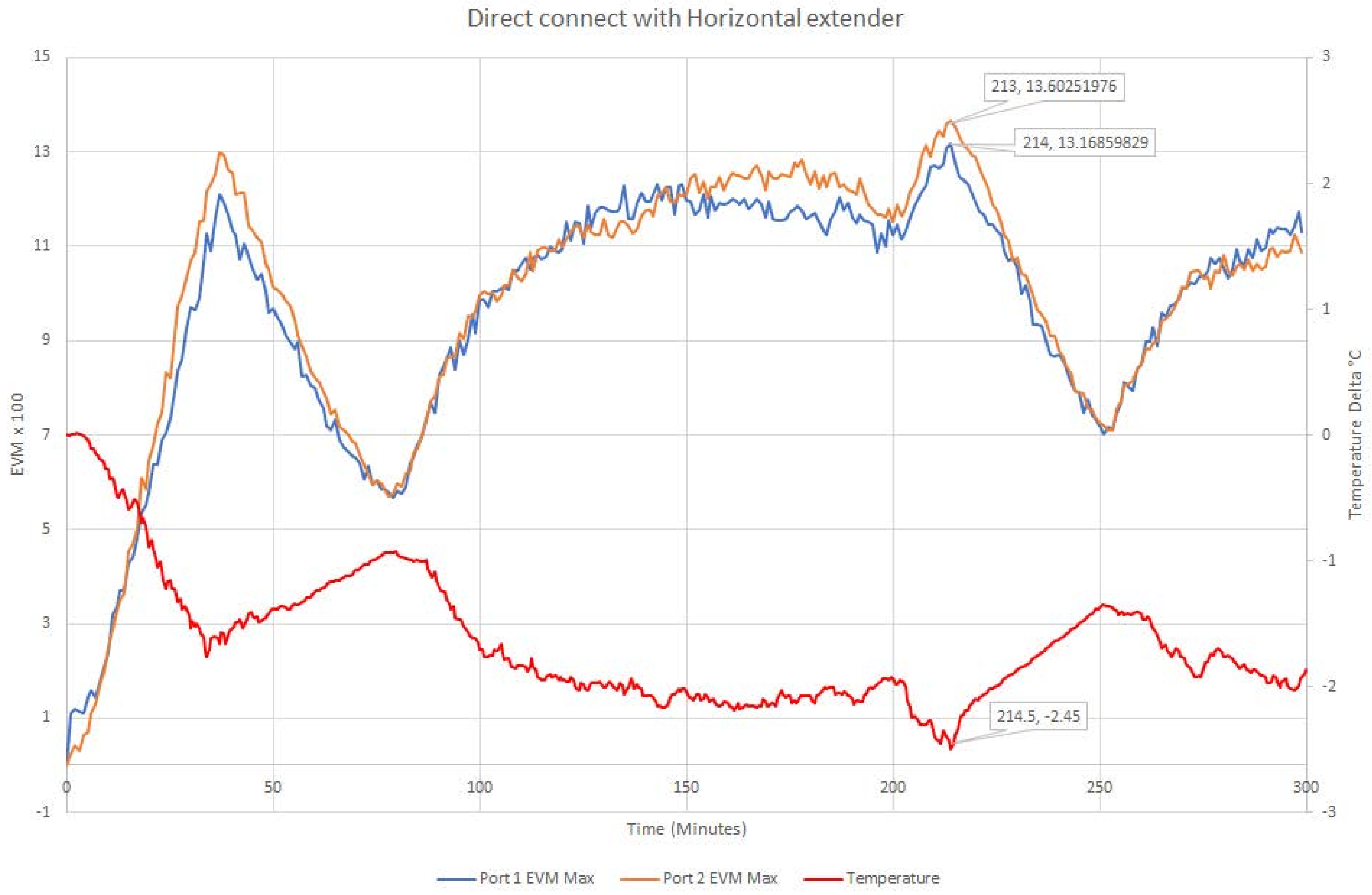
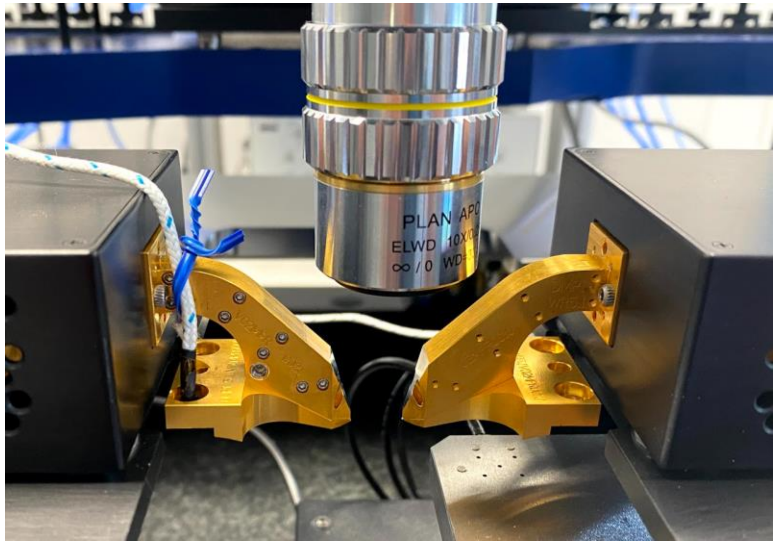
Drift comparison – Horizonal Extender – Direct Connect - Probe



	PORT 1	PORT 2
Max EVM	13.16	13.6
Δ°C at Max EVM	-2.45	-2.45
Max EVM per **Δ**°C	5.37	5.55



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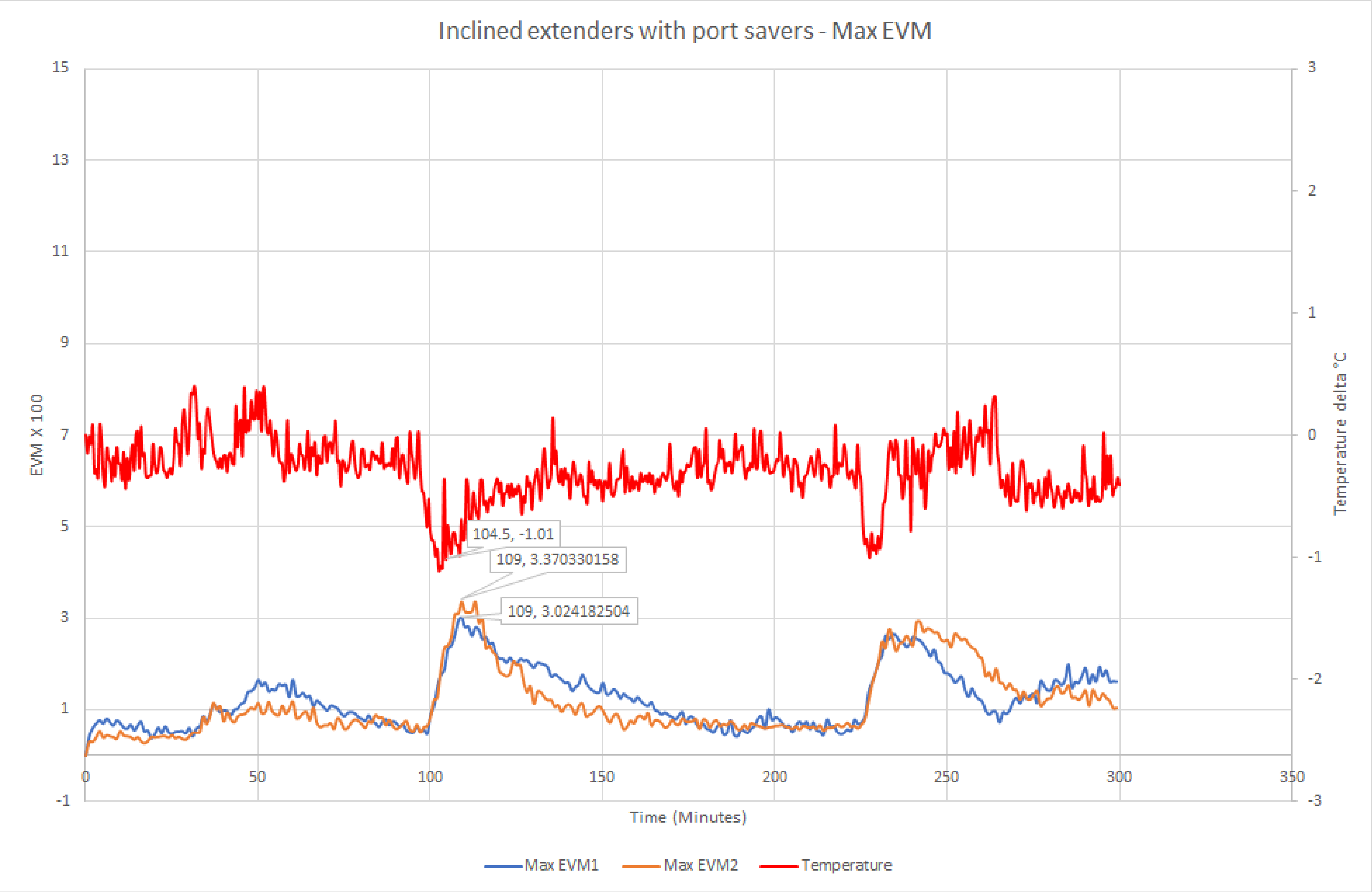
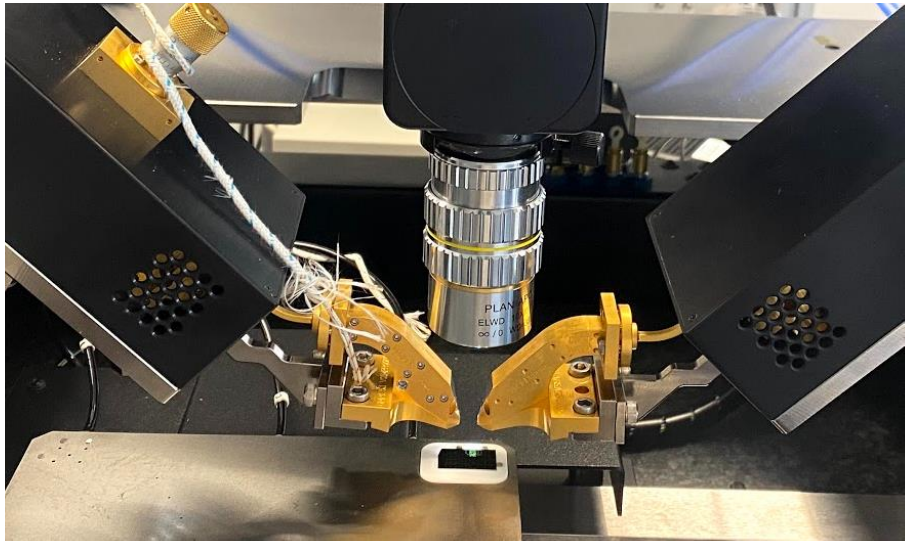
Drift comparison – Inclined Extender – 45deg WG - Probe



	PORT1	PORT2
Max EVM	3.02	3.37
∆°C at Max EVM	-1.01	-1.01
Max EVM per ∆°C	2.99	3.33



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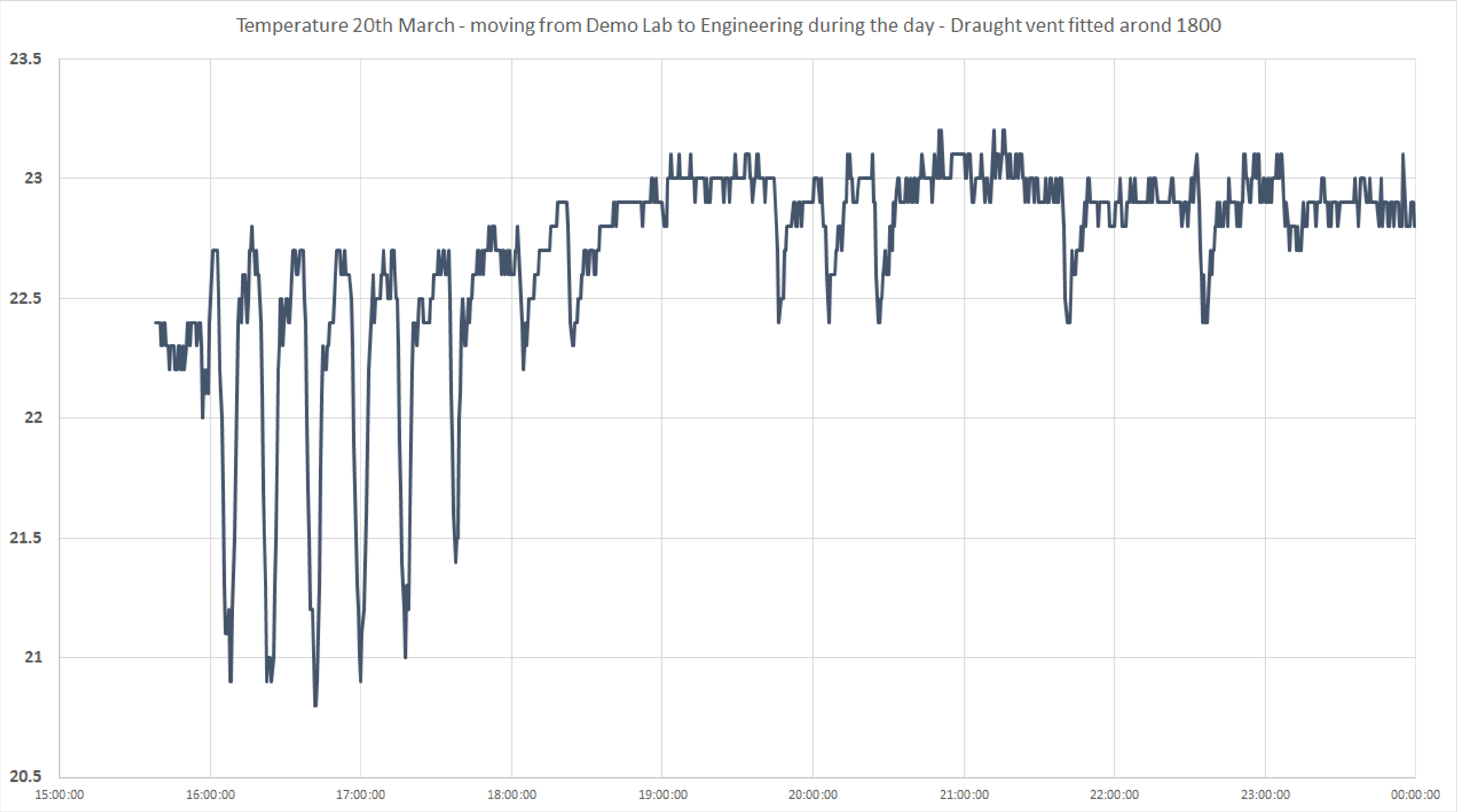
Drift – Temperature control

- Direct draughts from air-conditioning should be avoided
- We now fit vent covers near the stations and block apertures that would drop air directly down onto station
- Avoid direct sunlight –block off windows that illuminate stations
- Stable and a little warm is better than cool with spikes

Drift – Temperature logging

- For all measurements temperature is logged but this is especially important during drift measurements
- We specify maximum temperature as 25°C with max delta +/- 1 degree
- Air temperature probe is used which has some mass to reduce noise due to air currents
- The more stable the ambient conditions the longer the calibration is valid

Effect of fitting vents – Vent control fitted at 18:00



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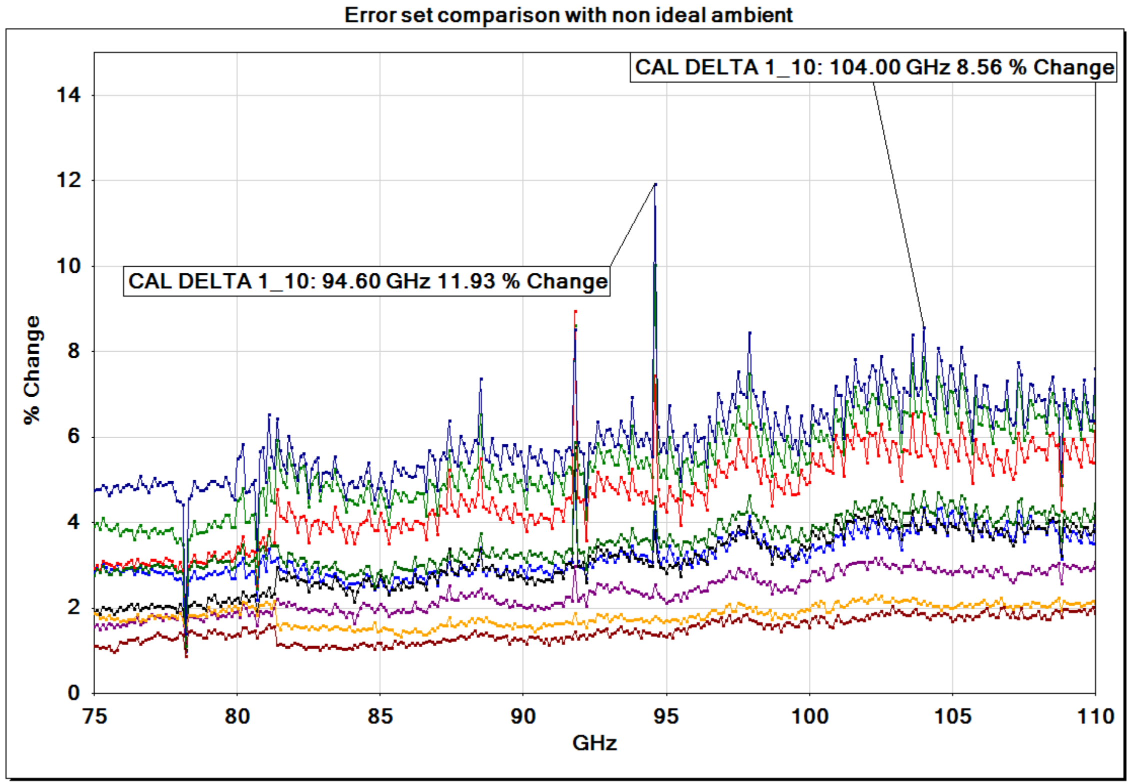
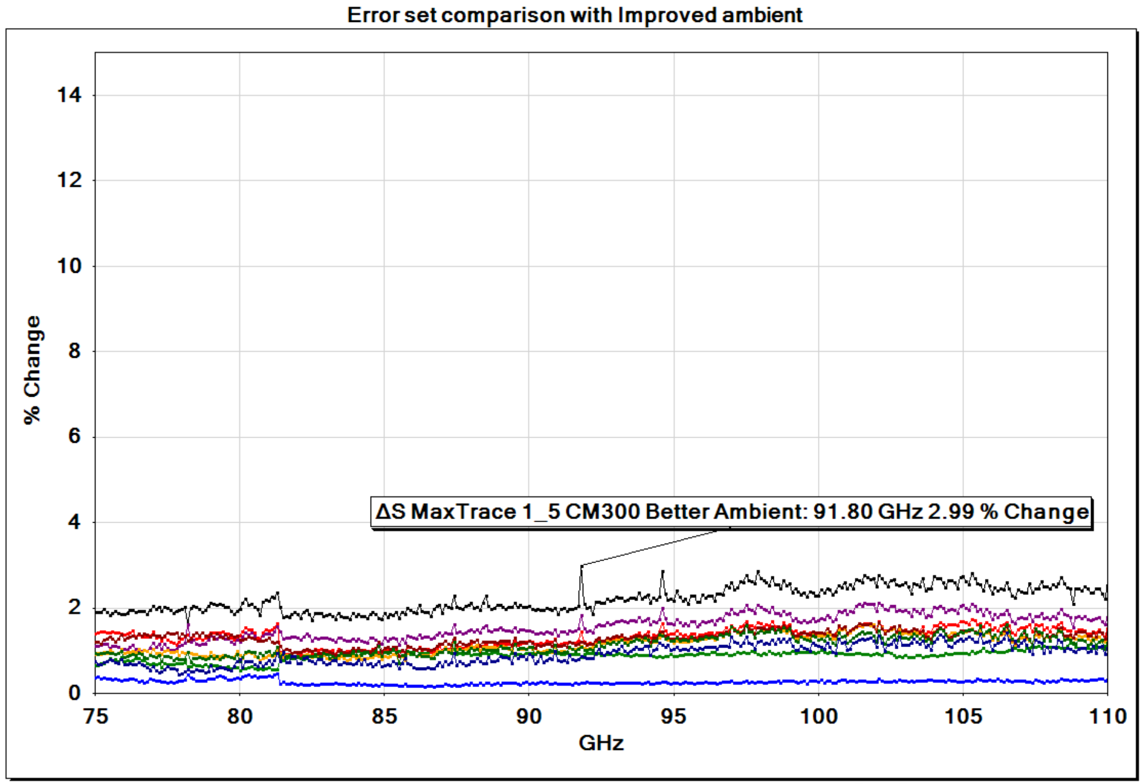
Error term variation with and without vents

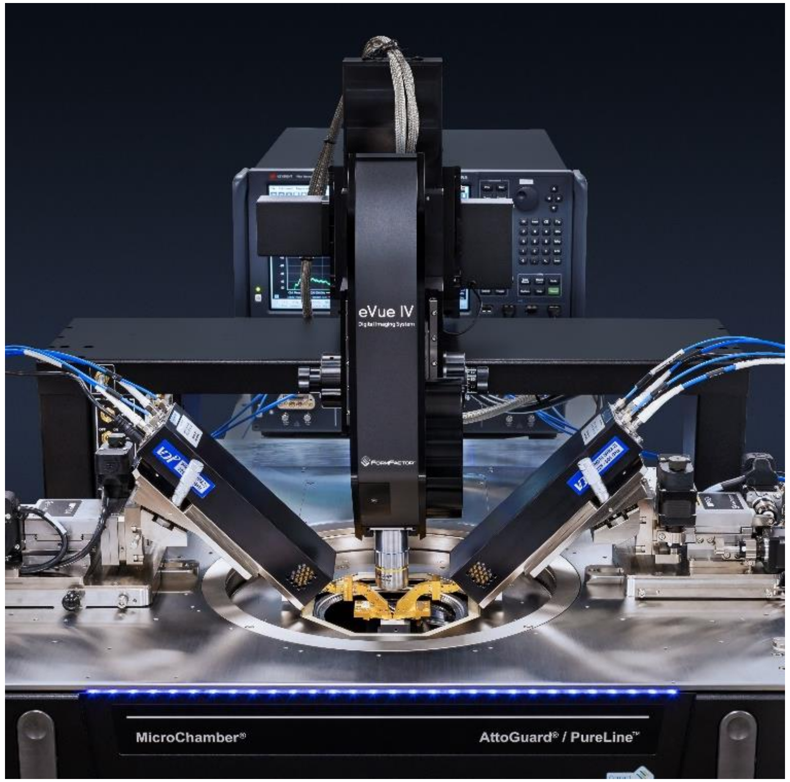
- Series of calibration was done sequentially at WR10
- Stability problems were noted as seen in left hand chart and control vent fitted
- Improvement seen in right hand chart





Challenges of Broadband Measurements (other than calibration)

+



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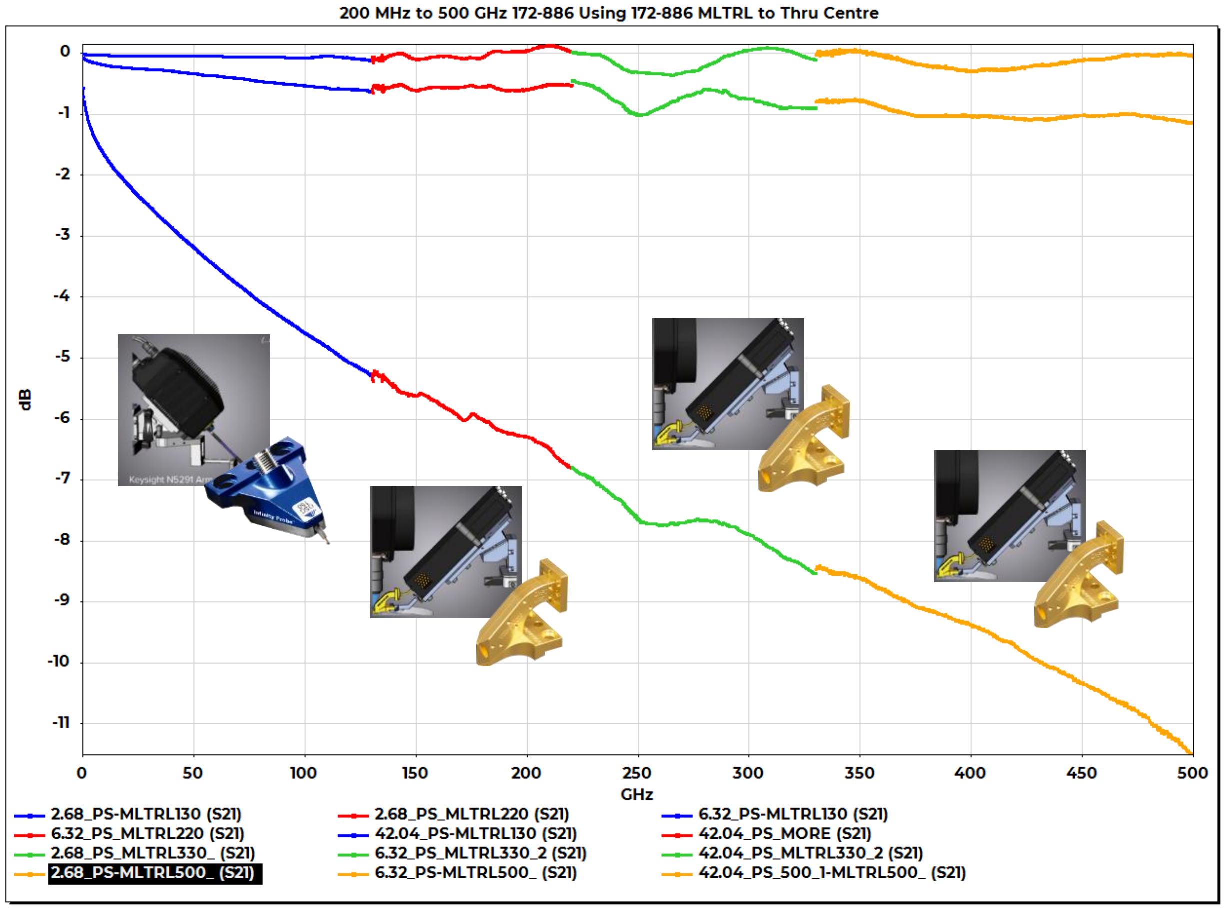
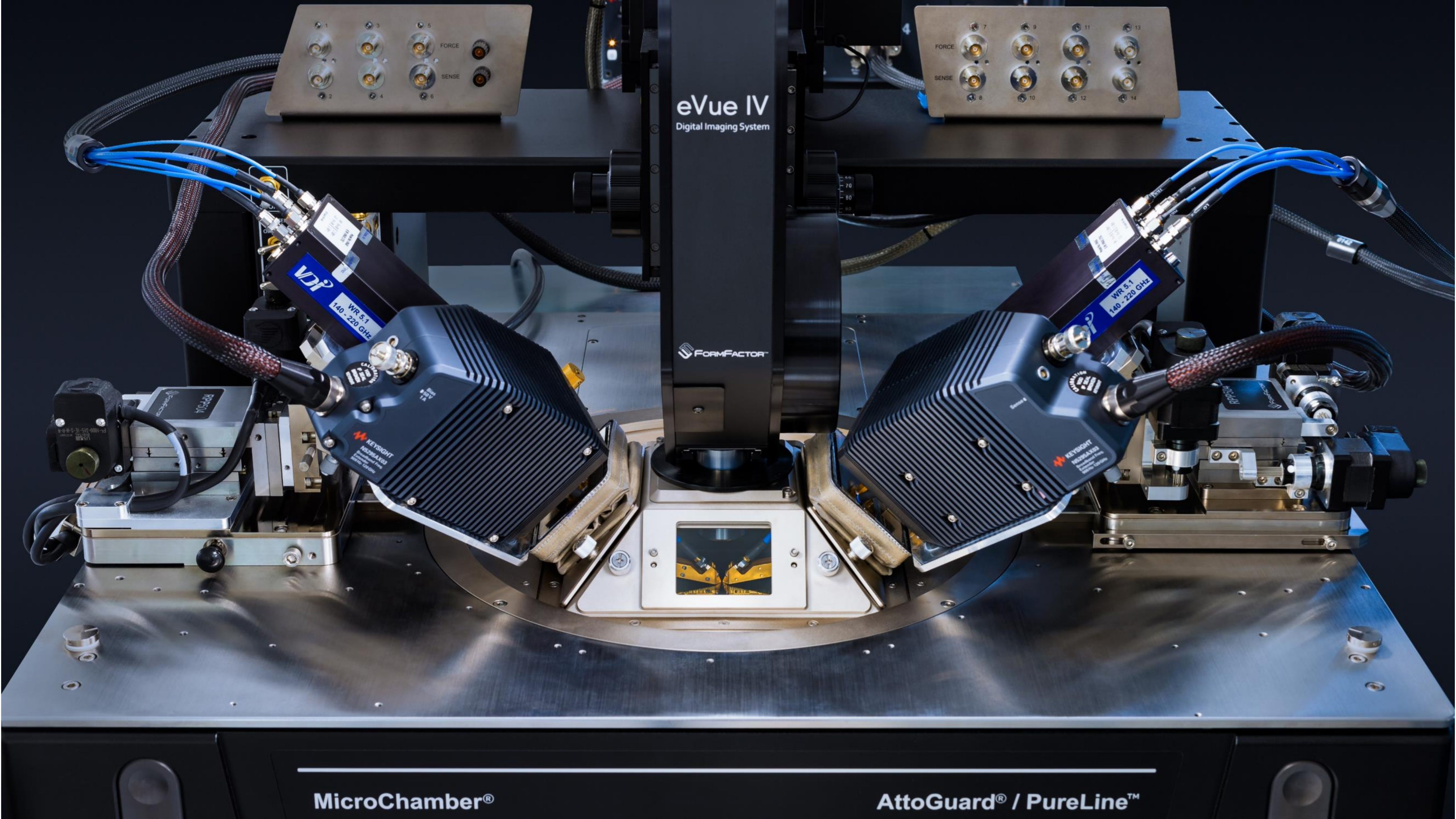
Challenges of Broadband Measurements to 220GHz

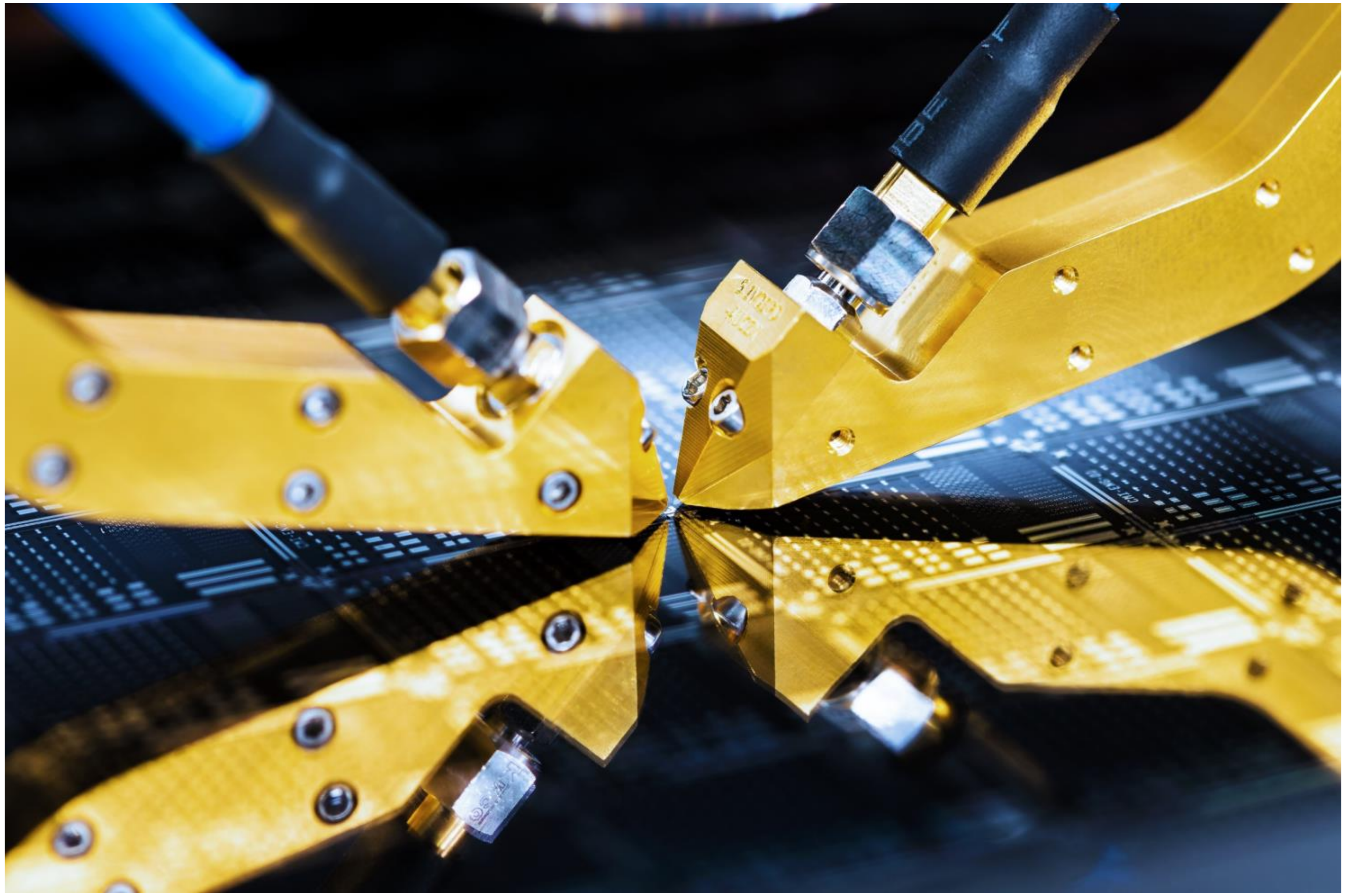
- Broadband solutions typically require
  - Multiple probes
  - Multiple extenders
  - Multiple calibrations
  - Multiple measurements
- Then the data needs stitching together
  - Discontinuities
- Whole process is time consuming, manual and intensive





eVue IV
Digital Imaging System
FORCE
SENSE
WR 5.1
140 - 220 GHz
FormFactor
KEYSIGHT
MicroChamber®
AttoGuard® / PureLine™

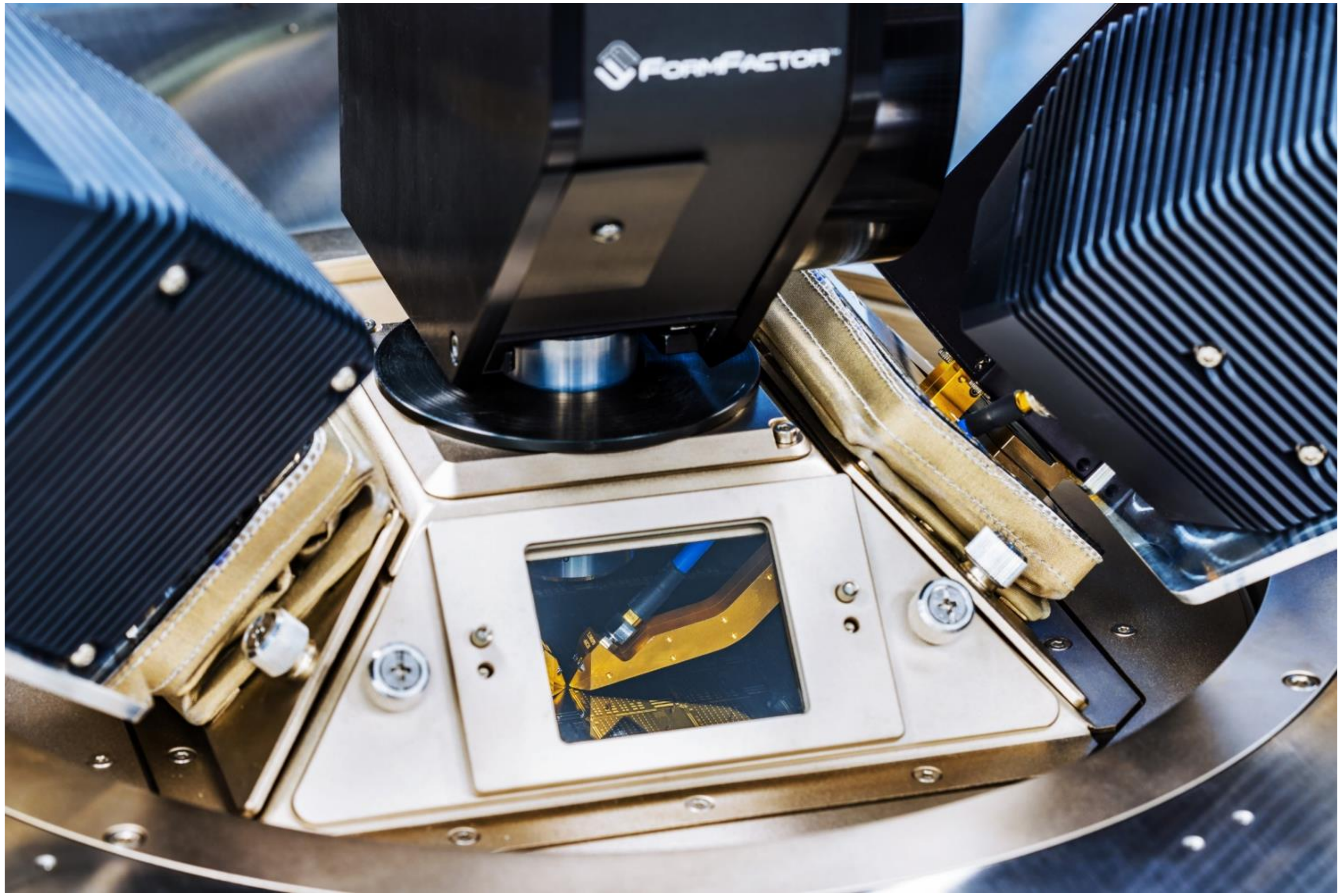
New Dual Band 220GHz Integration



- Combines coax and waveguide bands via diplexer integral to the probe
- Single sweep measurements
  - One set of probes
  - One Calibration
  - One Measurement

Features & Benefits of Dual Band

- Re-use existing tools
  - Probe station, extenders, positioners and tophat enclosure
- Manual, semi-auto or fully-auto systems
- Full thermal capability
- Dark, EMI Shielded and dry measurements
- Allows an existing N5291A to be extended to 220 GHz



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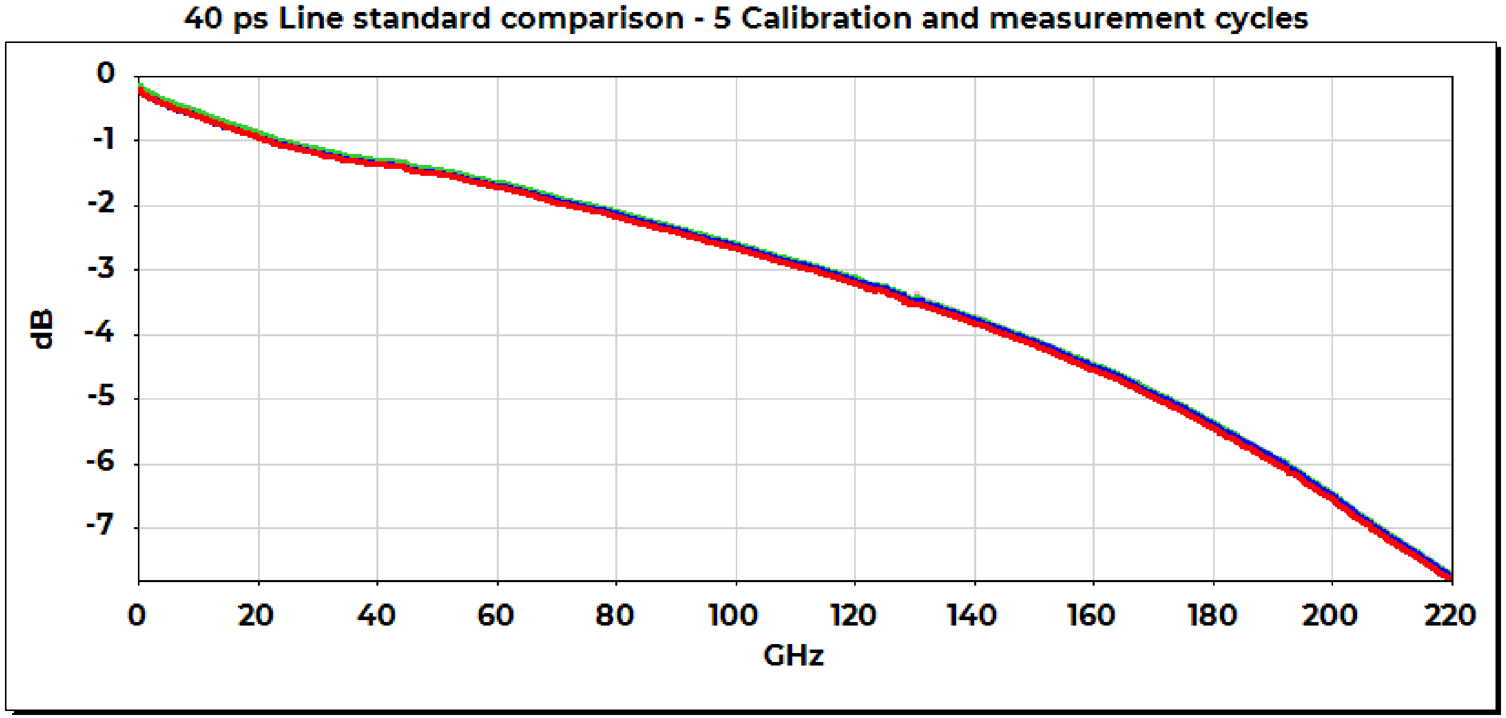
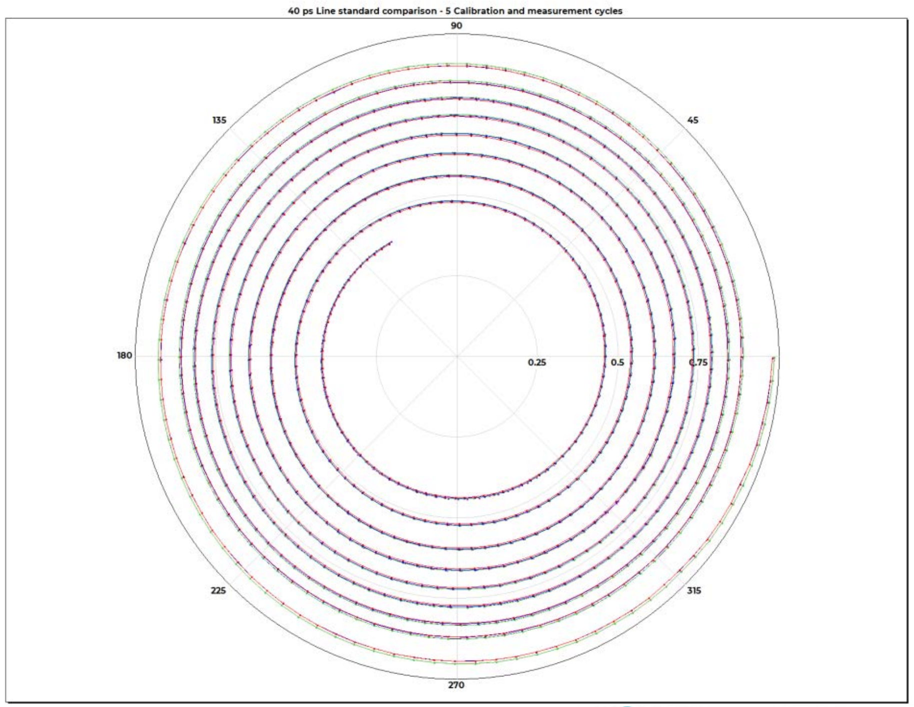
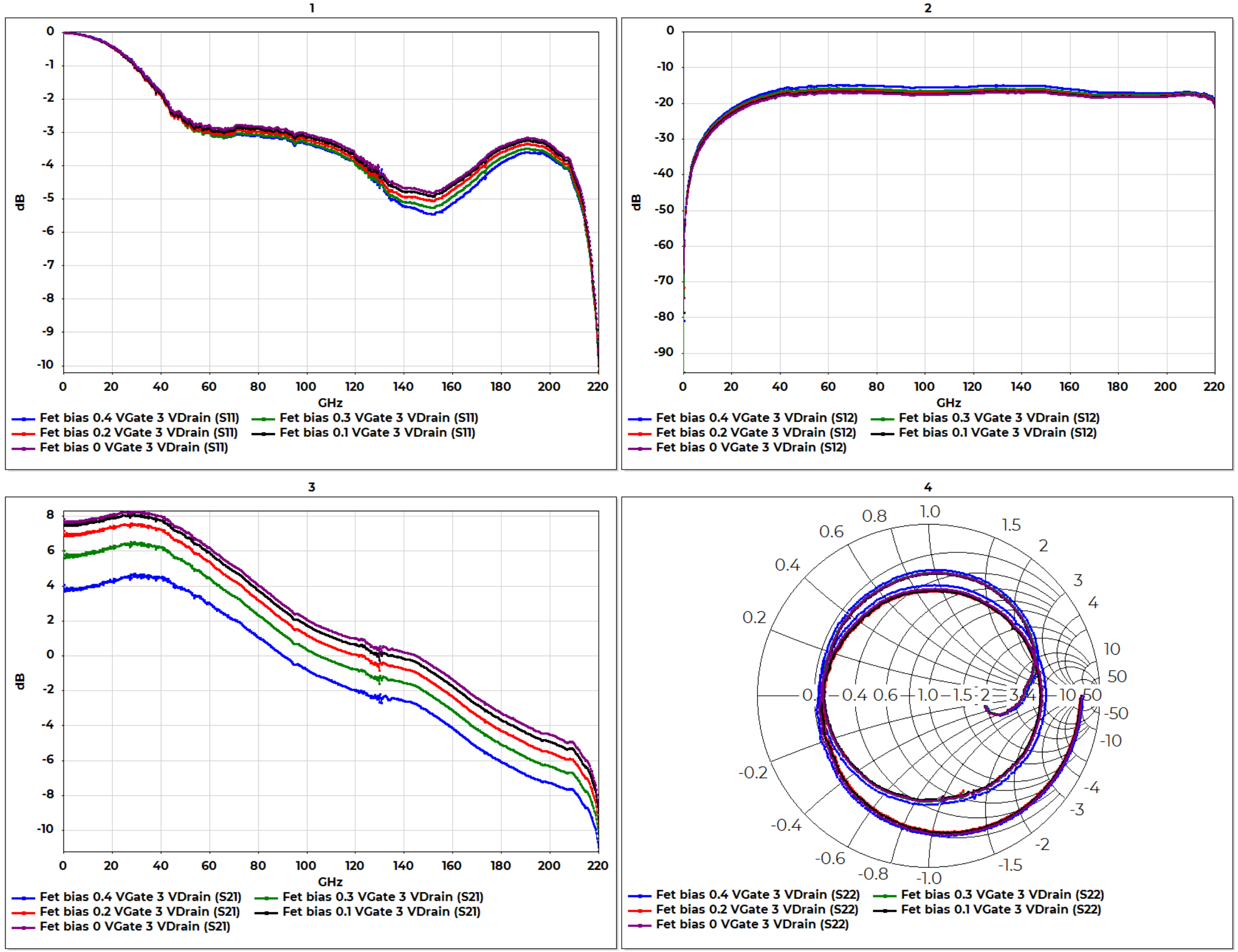
Calibration / Measurement repeatability

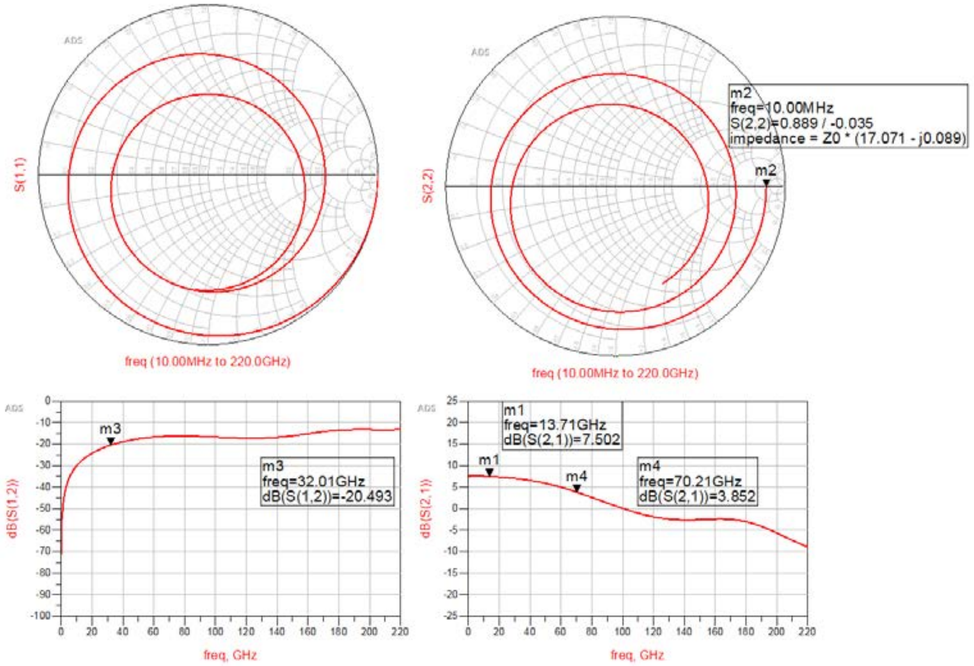
- 100 Hz IF
- 10 MHz to 220 GHz
- 40 ps with 5 cycles on 185-400 50 um specific iss with LRRM





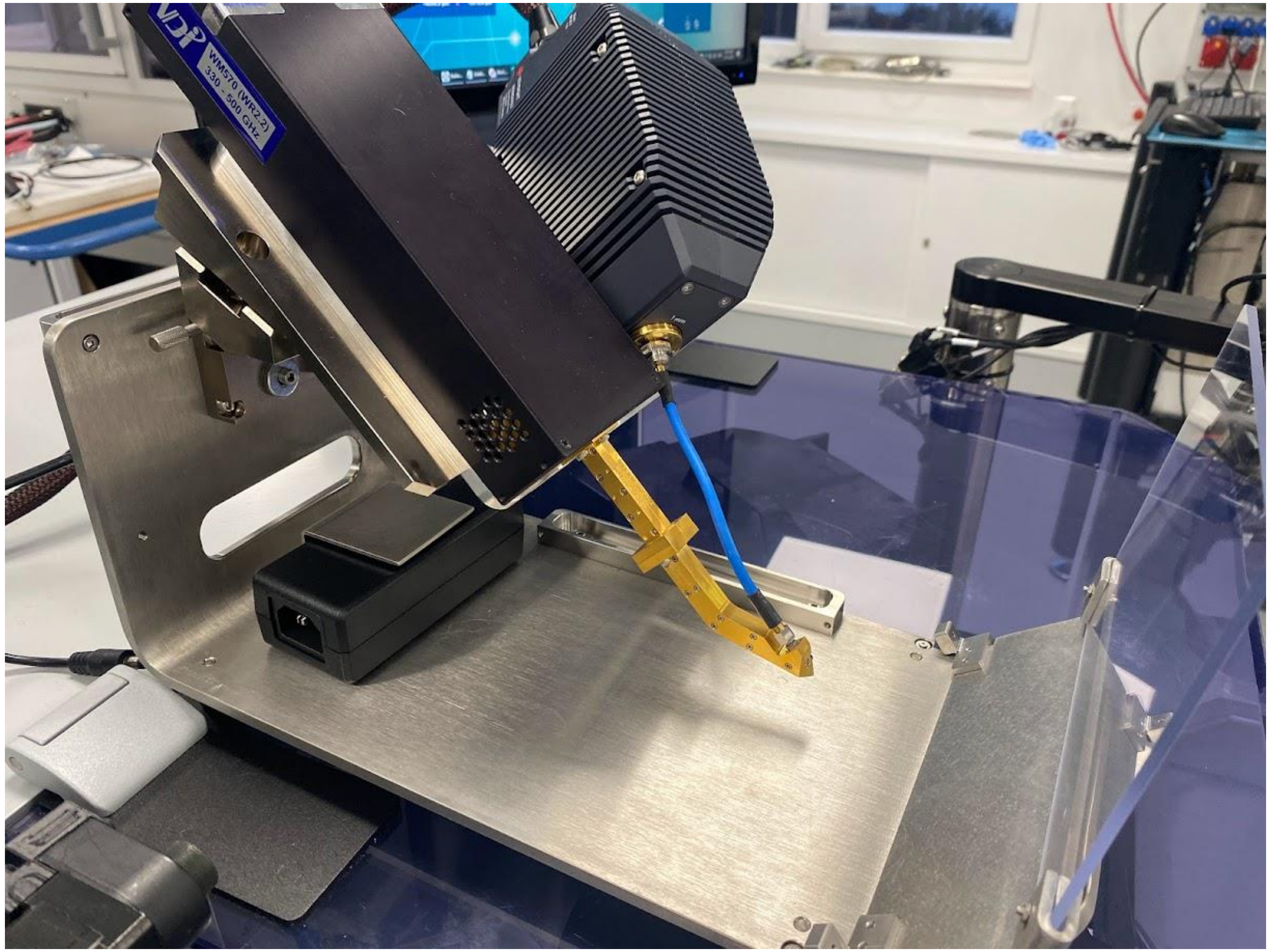
Active demo device measured at -30 dbm





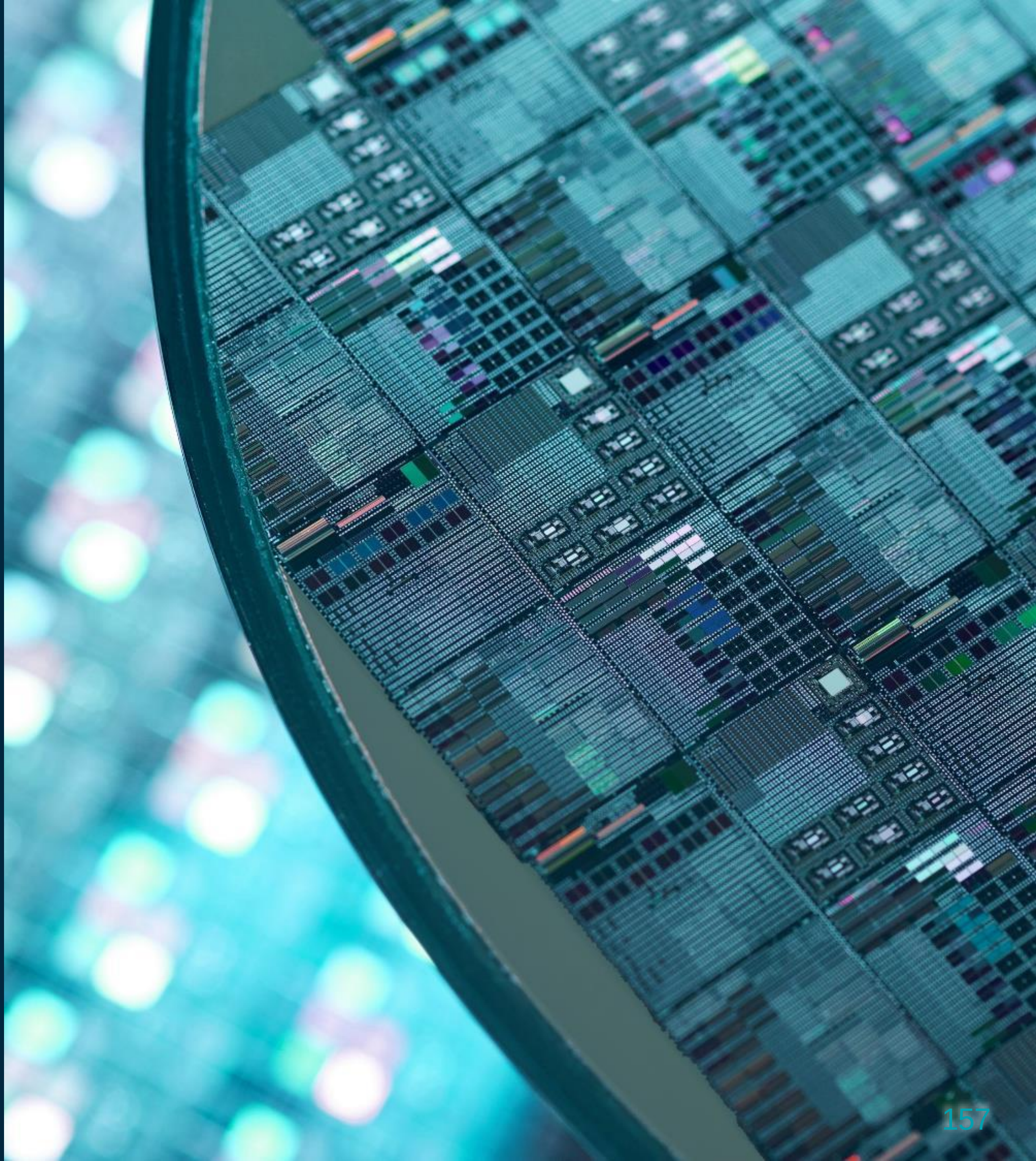
- Thanks to Rob Sloan for designing and providing the demo device...

Storage pod

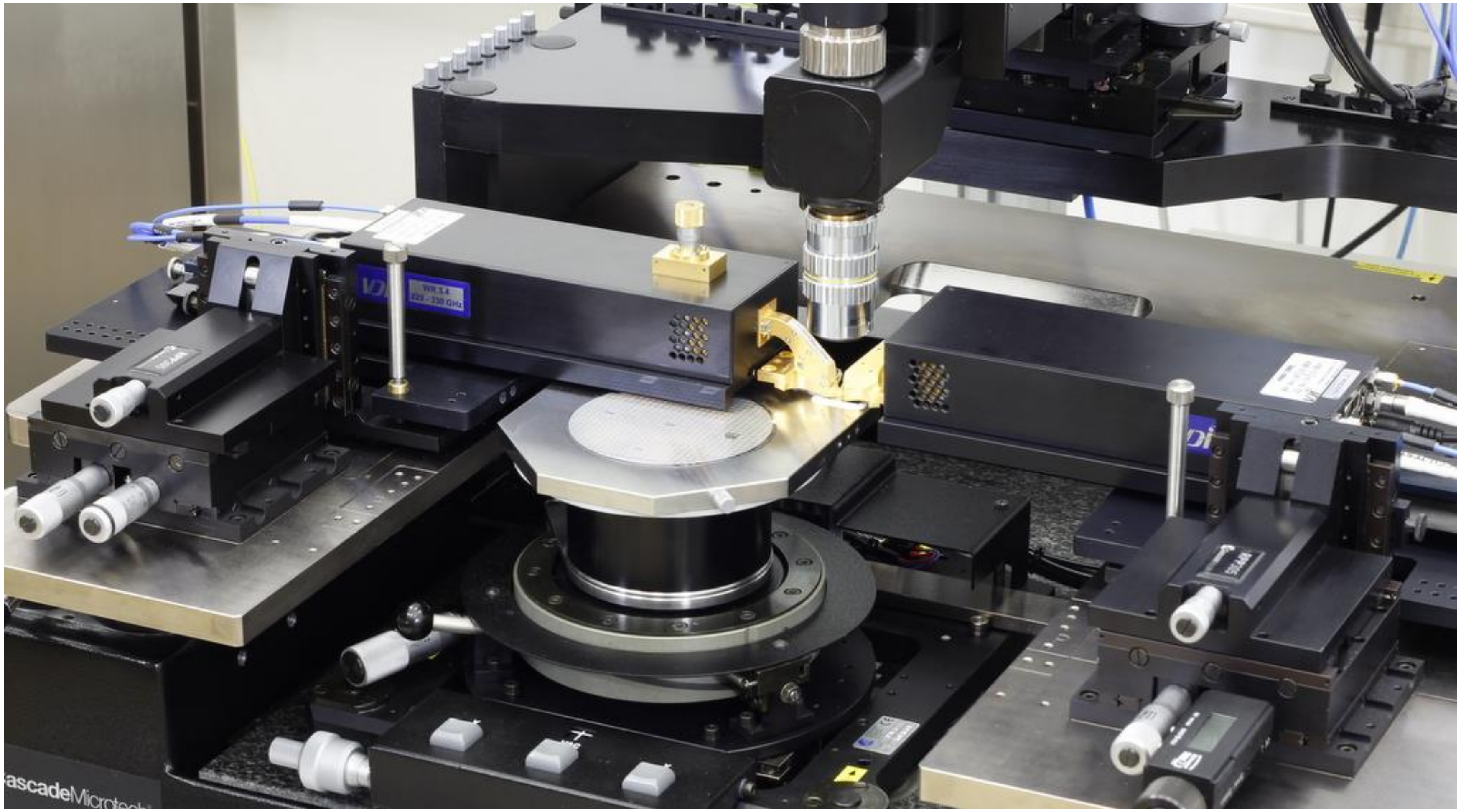


- When mounted with Wideband probe and extenders

Manual systems

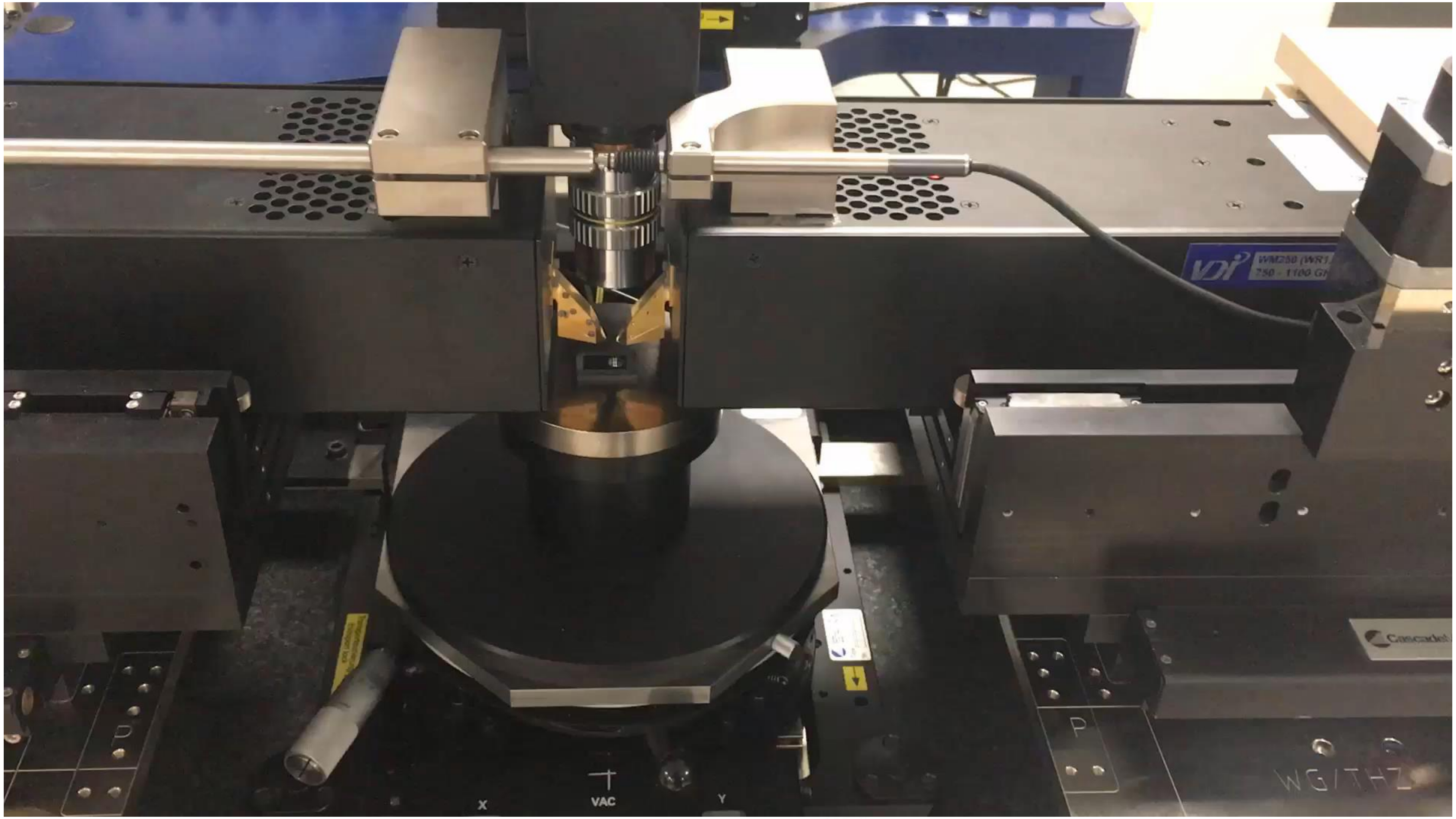


200mm Open manual – Direct connect to WR2.2 using VDI Mini, Manual

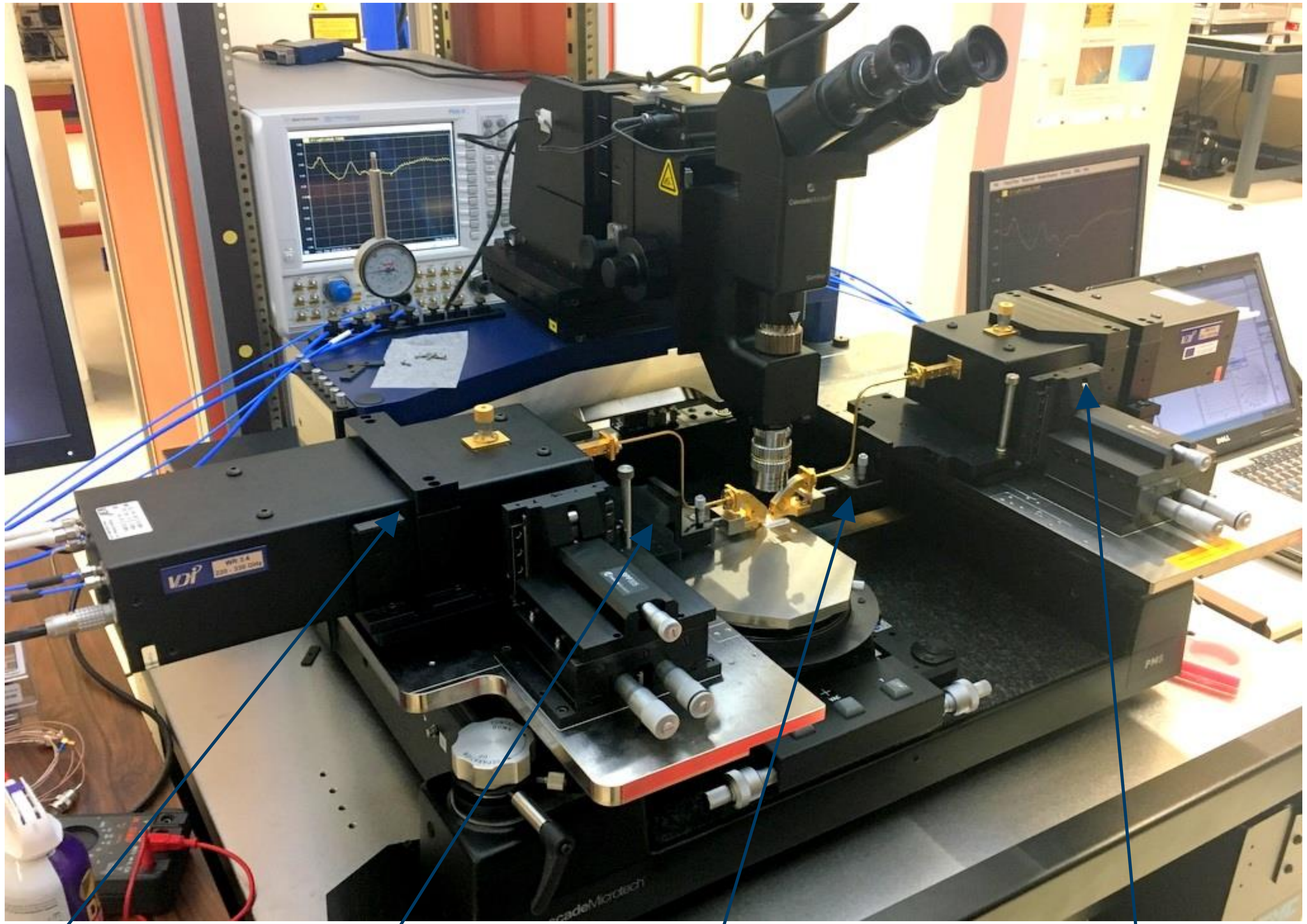


- Mini heads are shorter and need extension to get them to centre.
- It does not matter if extender has attenuator
- Best performance on the EPS station for banded

Direct displacement differential gauge video



200mm Open manual – Using Waveguides to WR3.4



West "Forklift" positioner

Probe planarsation mount (West)

Probe planarsation mount (East)

East "Forklift" positioner

- Typically we like to avoid the use of the S Bends although at low frequency contribution less significant
- Solution is actually more expensive as it needs a slightly more complex sigma kit and also there is the cost of the bends
- In this instance we have full format Virigina diode extenders

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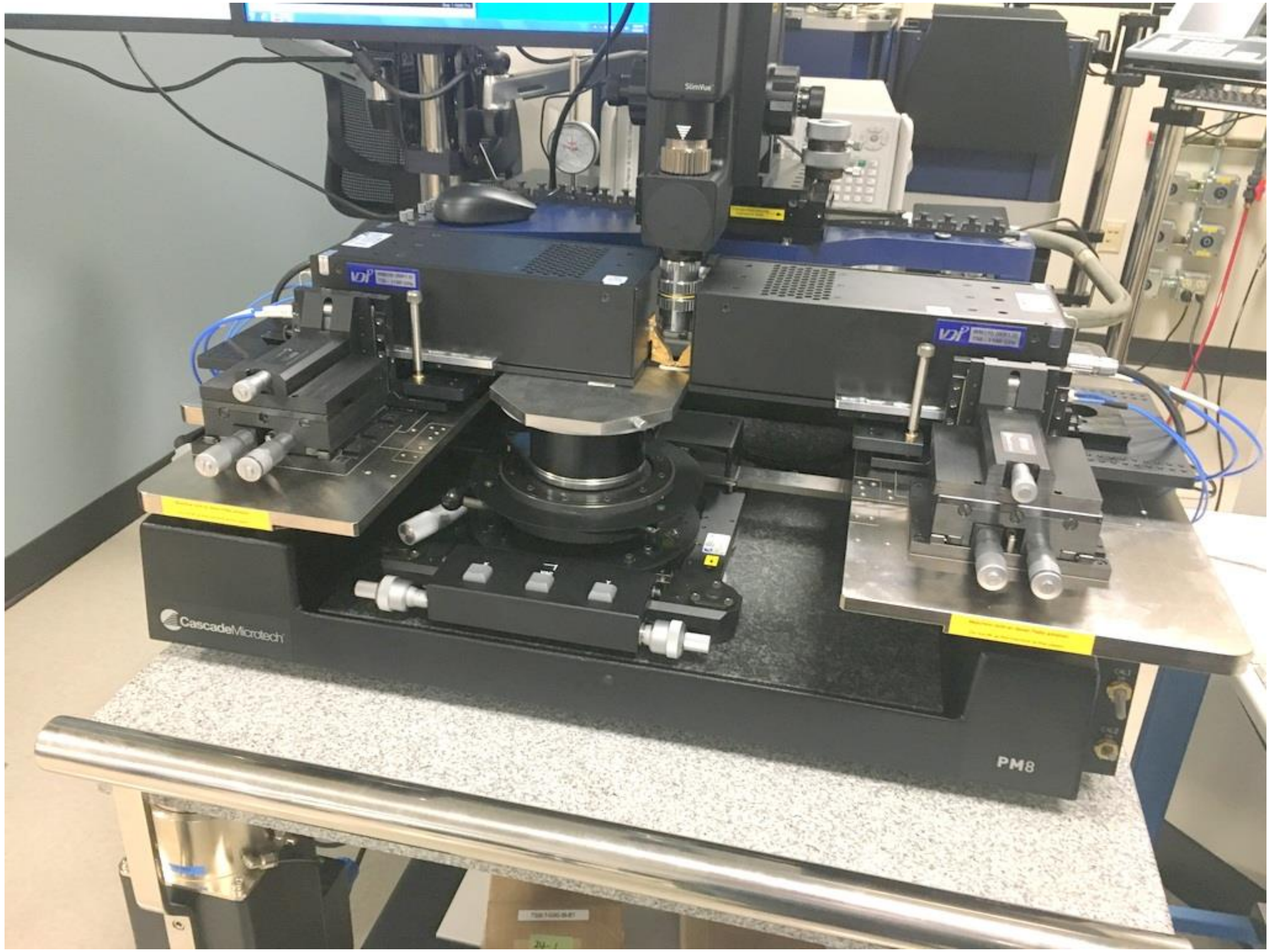
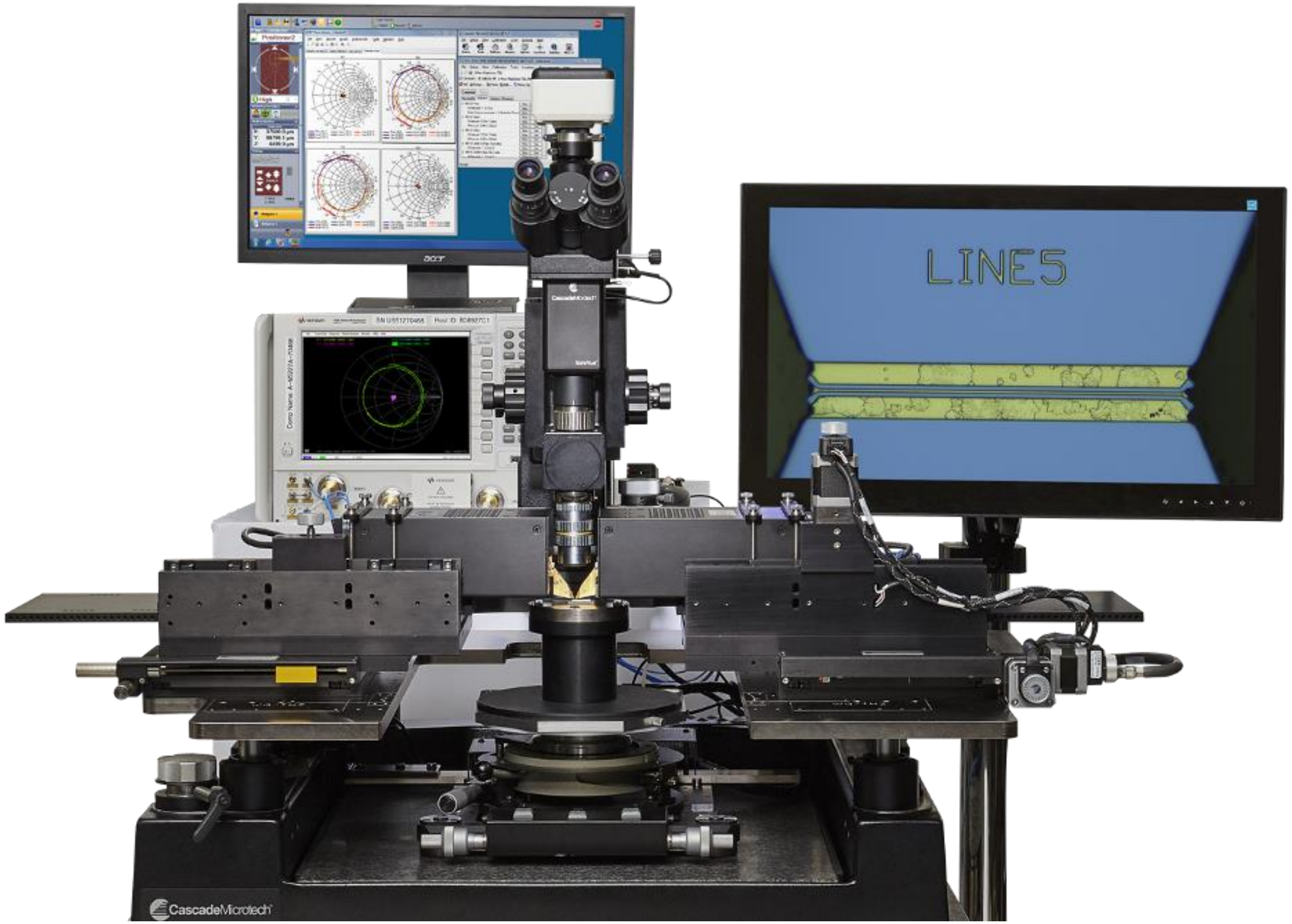
200mm Open manual– Fully manual 1.1 THz



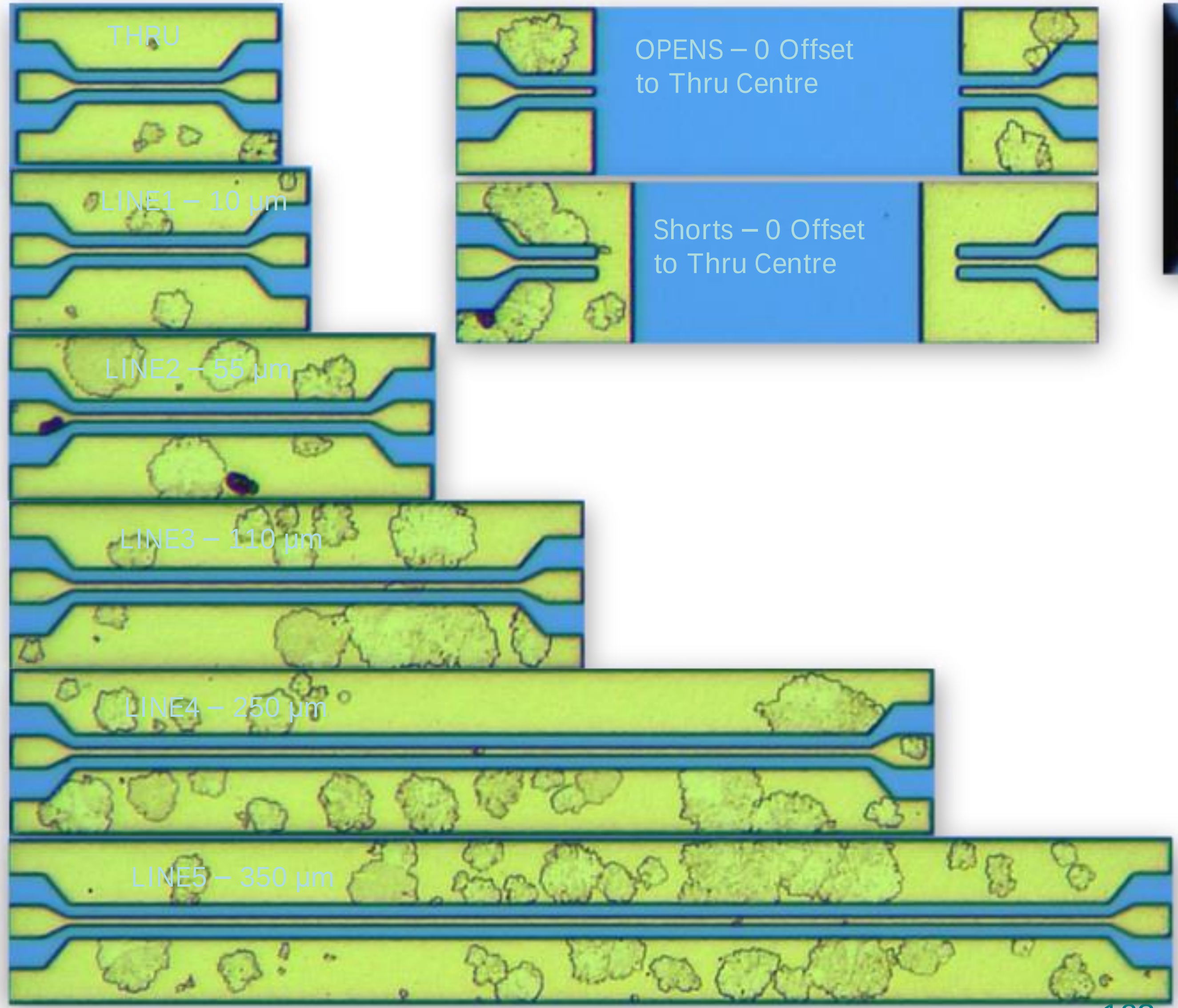
- 1.1 THz manual must be done with great care
- ISS has alignment marks for every location to aid positional accuracy
- Uses slight modification to regular THz Sigma

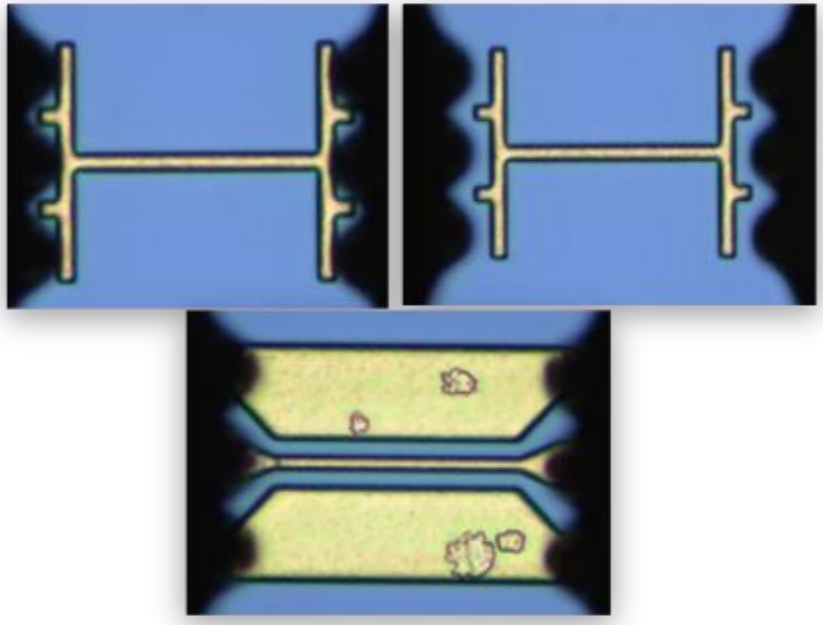
200mm Open manual with motorised positioner 1.1 THz



- Motorised positioner helps with speed of calibration and accuracy
- Not essential but very useful

1.1 THz Impedance Standard Substrate (172-885)



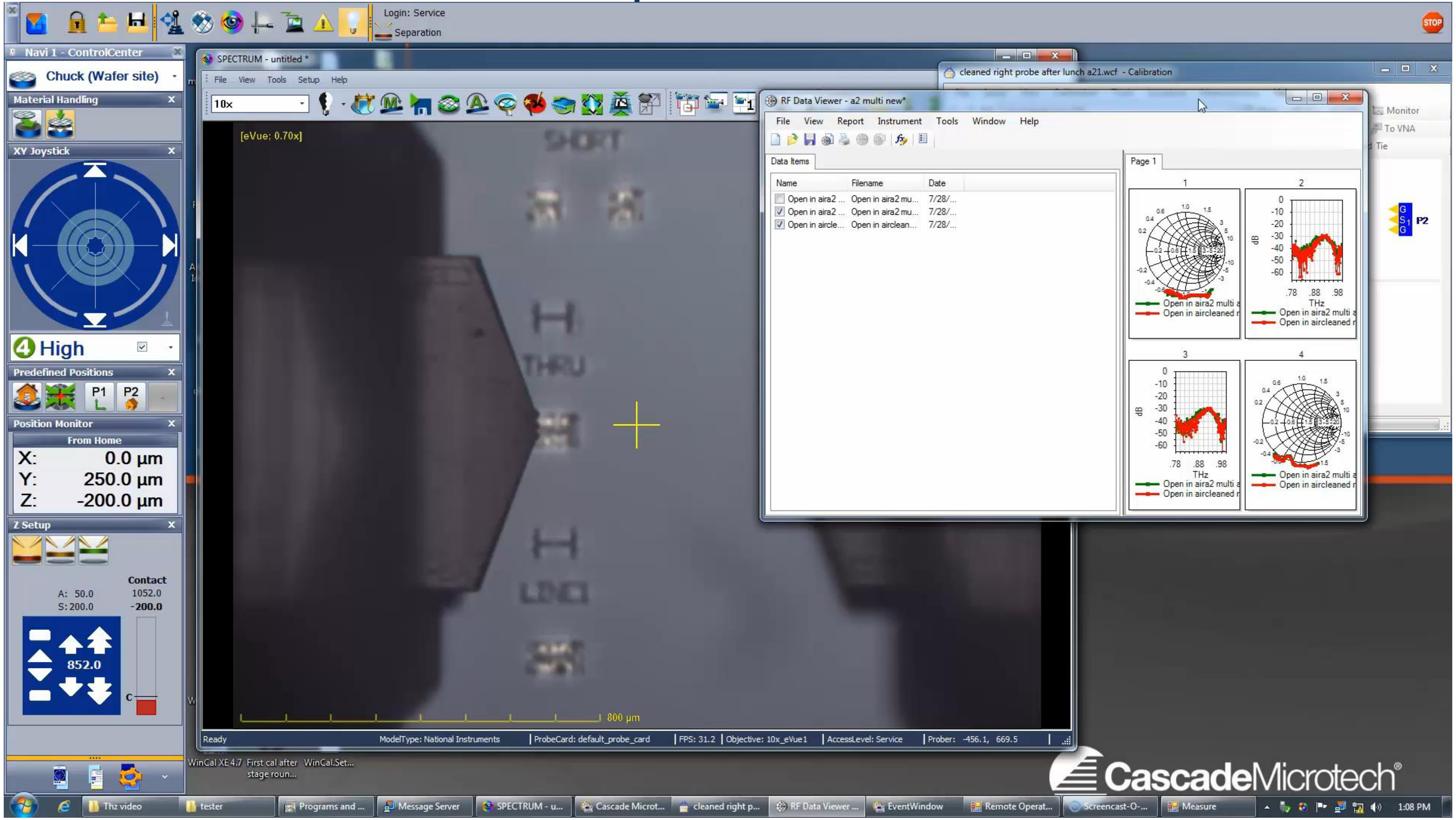


- Every standard has its own precision alignment marks – almost essential for manual probing
- 10 Cal lines, Open, Short
- 6 different validation shorts (also used for 1 Port cal)
- 5 different validation opens
- Listed iss in WinCal
- On wafer MLTRL standards handled with location manager (ideally device cal will be done on wafer)

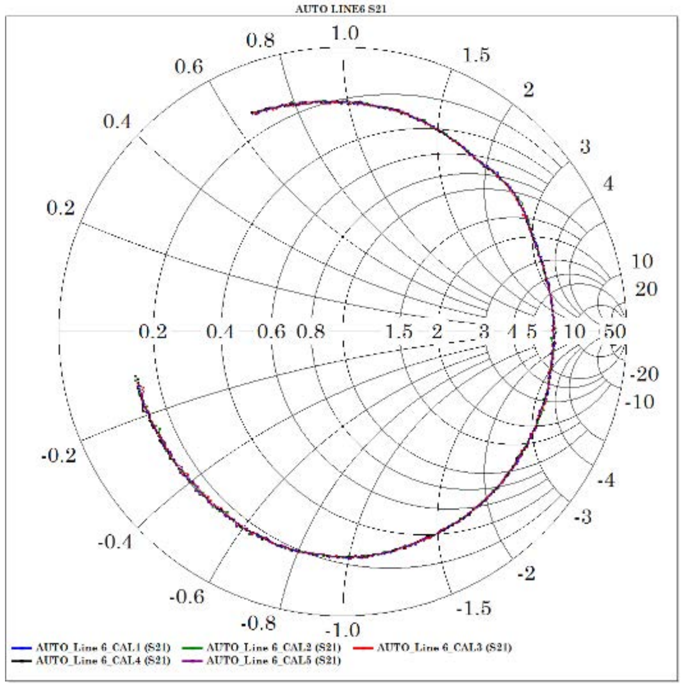
Case Study – How important is Motorised Positioning at 1.1 THz

- EPS Station used for Manual and Motorised manual
- Summit used for fully automatic – there is a fourth case of semi auto station but manual positioner but this is not covered in this session

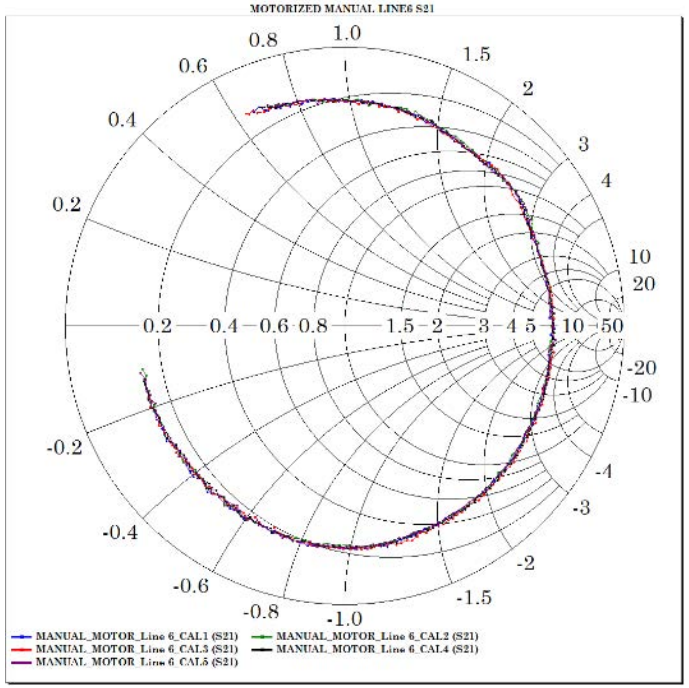
THz Calibration setup – Calibration run video



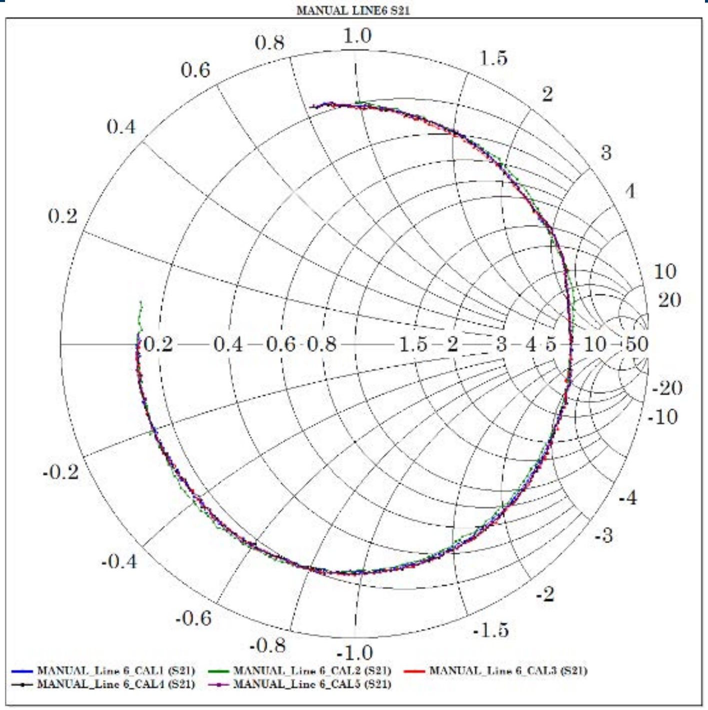
Results - corrected line standard



Fully Auto



Manual stage / Motorised positioner



Manual stage / Manual positioner

- Line 6 - 475 um long
- 3 Lines used for Calibration
- Start 780 GHz Stop 1000 GHz
- 100 Hz IF – Absorber used beneath ISS

- Data from calibration computation report
- Normalised next slide w.r.t first cal

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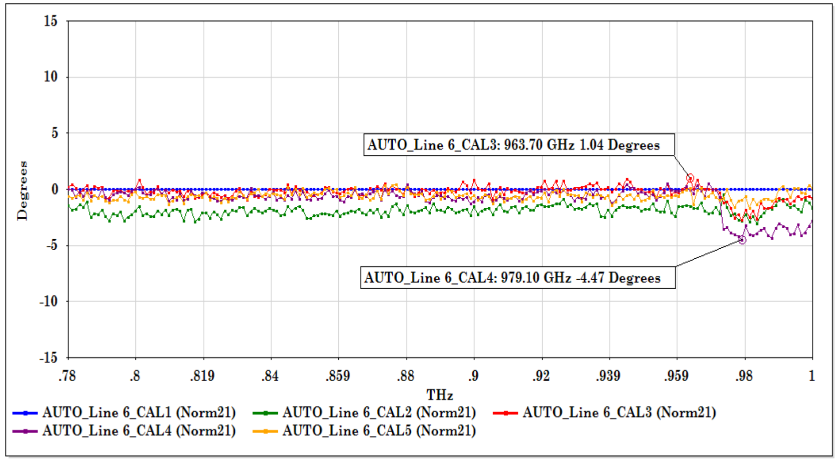
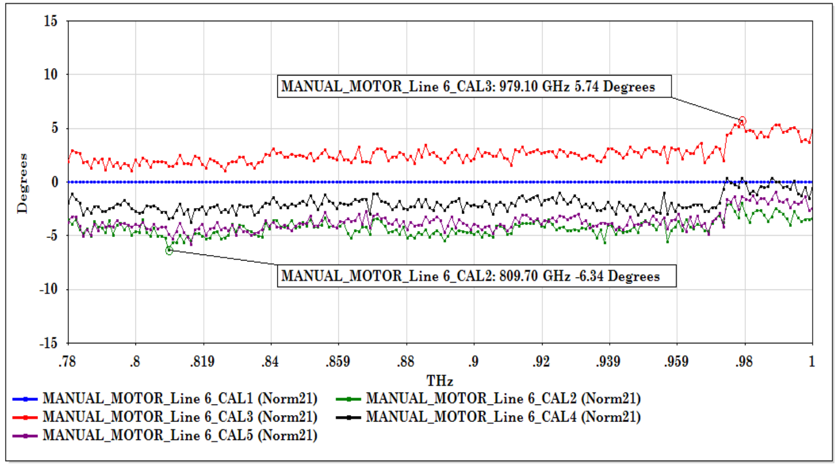
Results - Phase / Magnitude normalisation – Line 6 S21

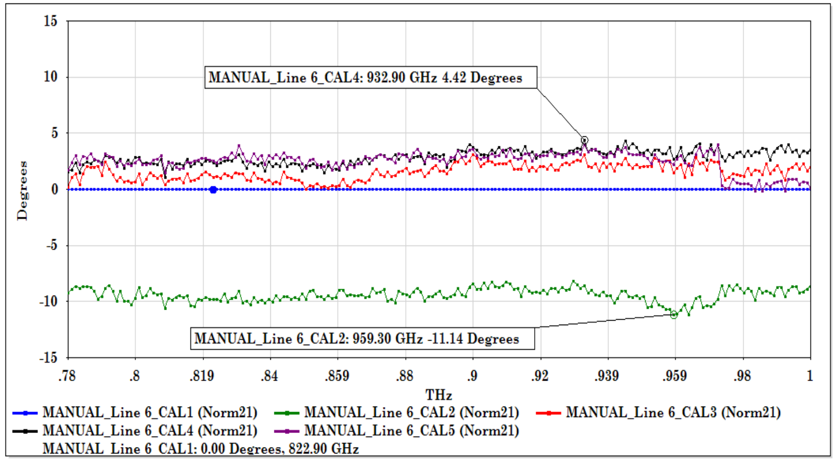
AUTO LINE6 S21 NORMALIZED PHASE



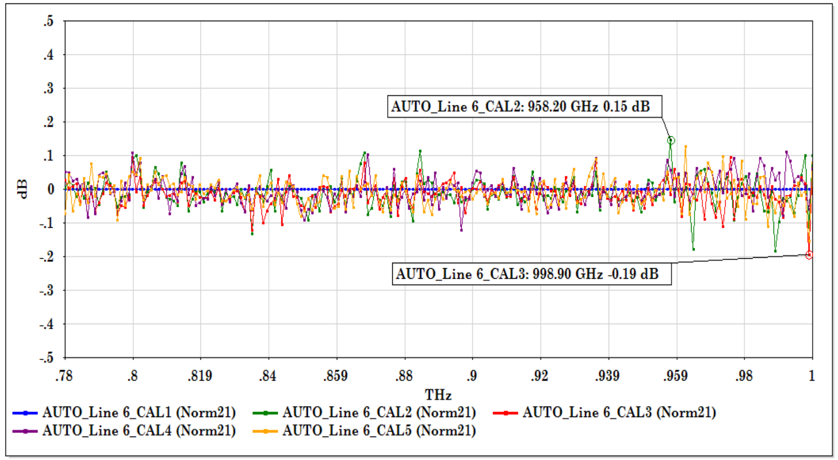
MANUAL MOTORIZED LINE6 S21 NORMALIZED PHASE



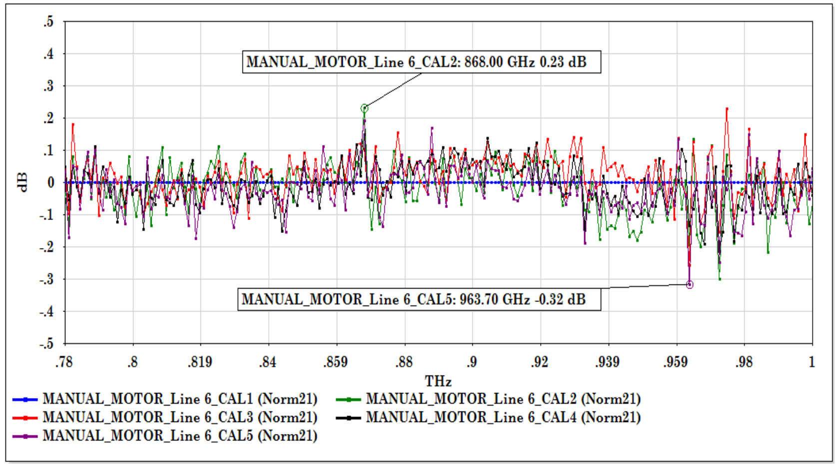
MANUAL LINE6 S21 NORMALIZED PHASE



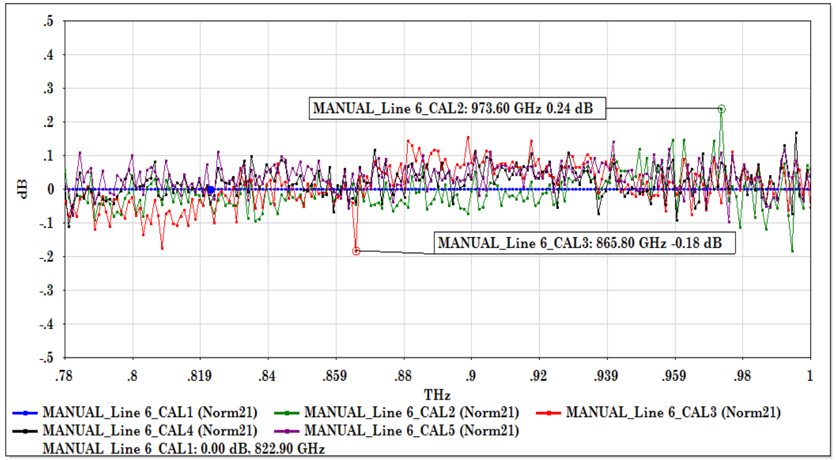
AUTO LINE6 S21 NORMALIZED MAGNITUDE



MANUAL MOTORIZED LINE6 S21 NORMALIZED MAGNITUDE



MANUAL LINE6 S21 NORMALIZED MAGNITUDE



Fully Auto
Phase +1° -4.5 °
Magnitude +0.15dB -0.19 dB

Manual / Motorized
Phase +5.7 ° -6.3 °
Magnitude +0.23dB -0.32 dB

Fully Manual
+4 ° -11 °
+0.24dB -0.18 dB

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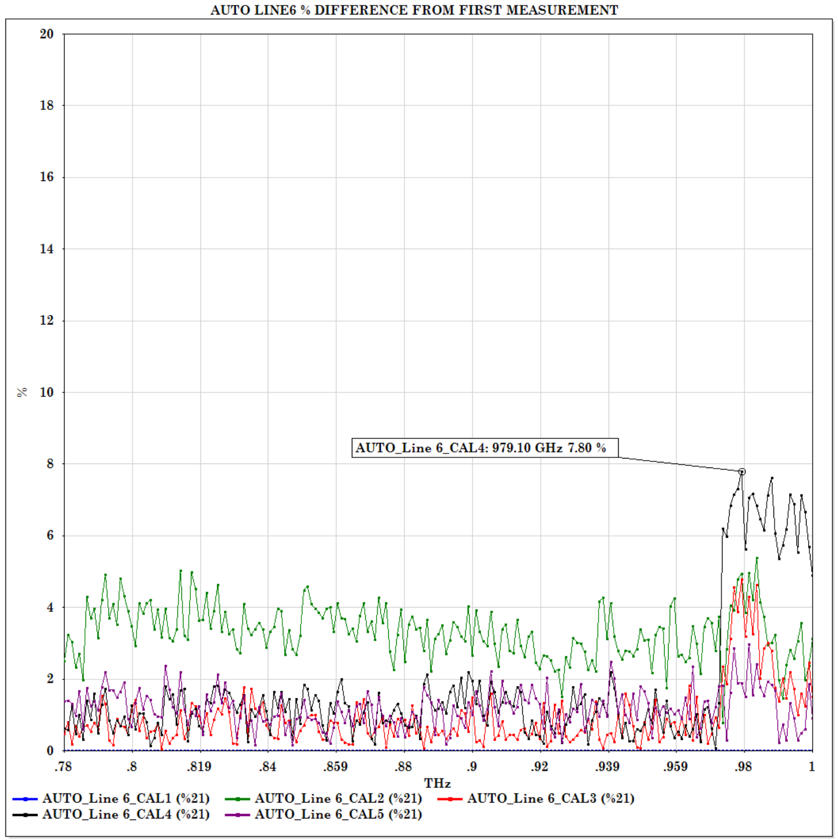
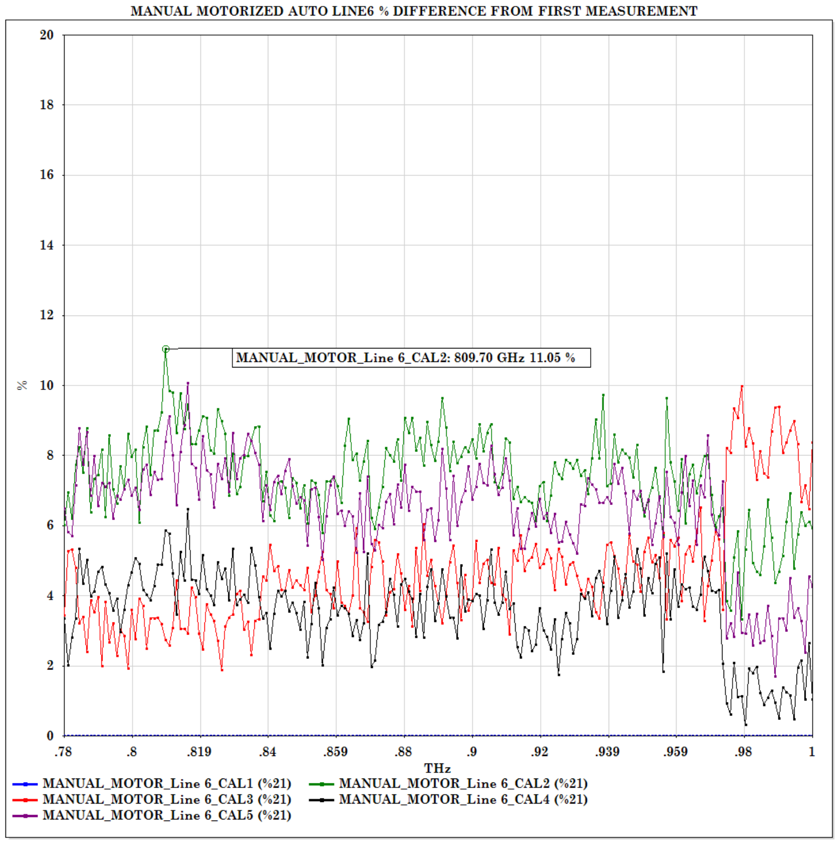
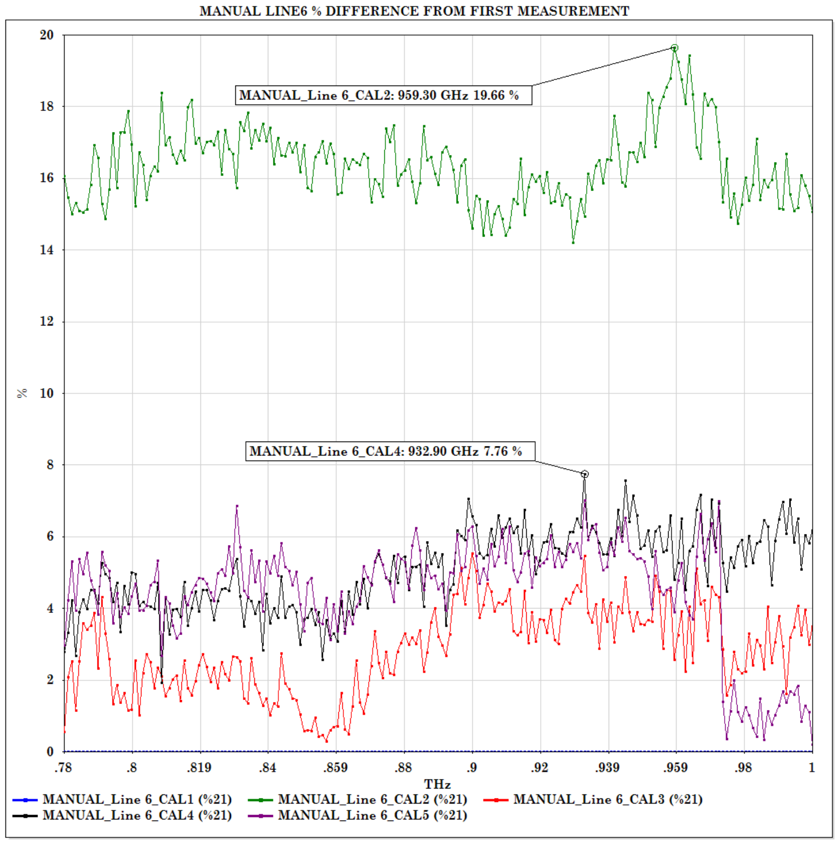
Results - %Change – Line 6 S21



Fully Auto
Standard deviation 1.4%
Mean Delta 1.8%
Max delta 7.8%



Manual / Motorized
Standard deviation 2%
Mean Delta 5.5%
Max delta 11%



Fully Manual
Standard deviation 5.5%
Mean Delta 7.2%
Max delta 19%

Delta Calculation (|VectorN – Vector1|/|Vector1|)*100

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Auto vs Manual Motorised v Manual

Method Used	Time 100 Hz	°+	°-	Δ°	dB+	dB-	% Delta Mean	% Delta Std. Dev	% Delta Max
Full Auto	2:00	4.6	-6.7	11.3	0.17	-0.29	1.8	1.45	7.8
Manual / Motorized	5:45	11	-15	26	0.3	-0.34	5.5	2	11
Manual	6:15	2	-13.9	15.9	0.13	-0.38	7.2	5.5	19.7

- Full auto gave most consistent results over 5 calibrations
- Manual cal = 3 x duration Auto cal
- Cal time = drift time
- Manual results aided by ISS position marks hence great result
- Manual based stations need much more care and time than semi-automatic
- Two motorized positioners on manual platform could act like semi auto station
- Skilled operator needed throughout
- True manual station can get better results than motorised manual if great care taken
- Timing for motorised manual less than Manual but not as much as expected

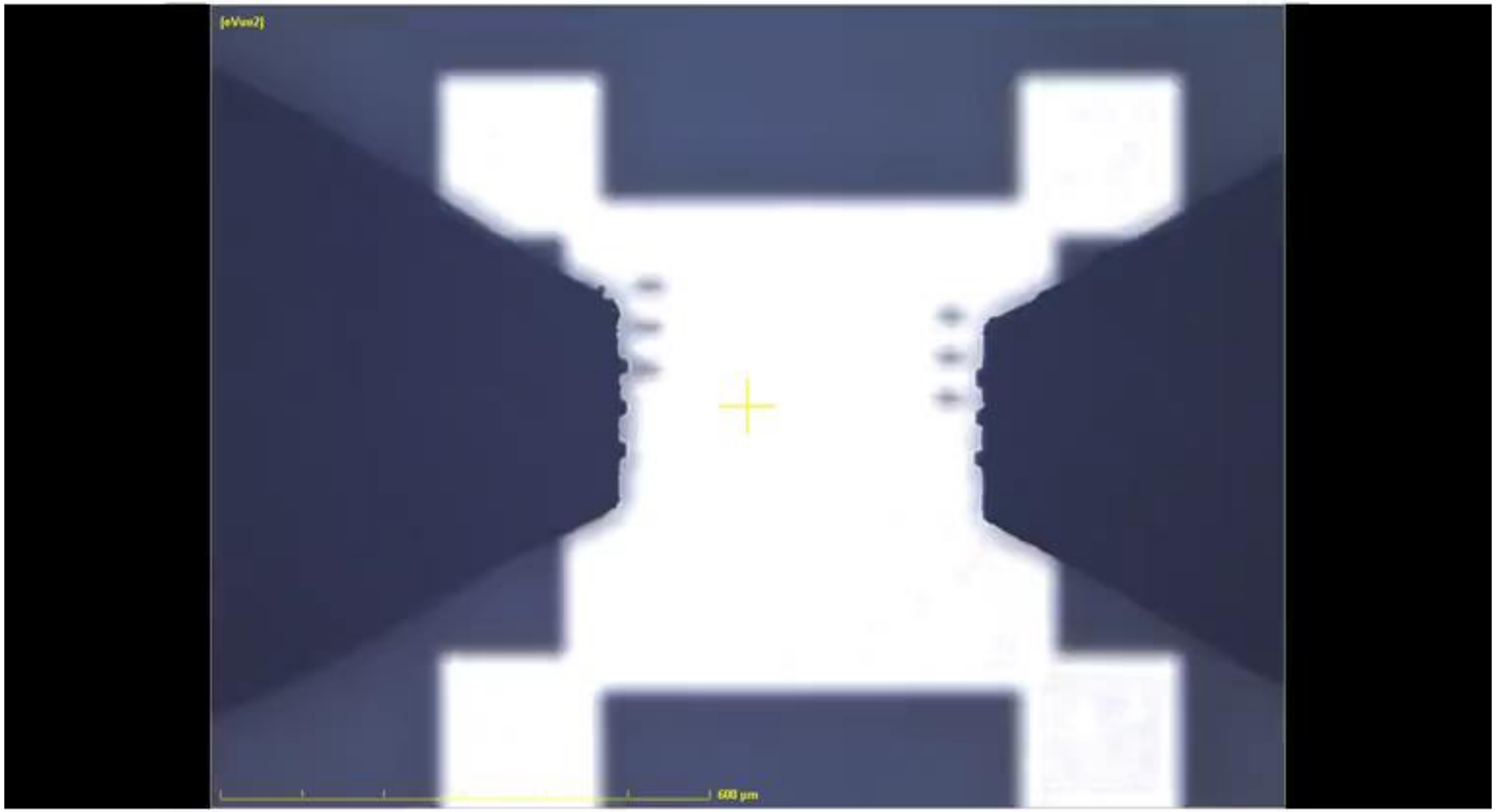
Thermal optimization

Mechanical effects of growth

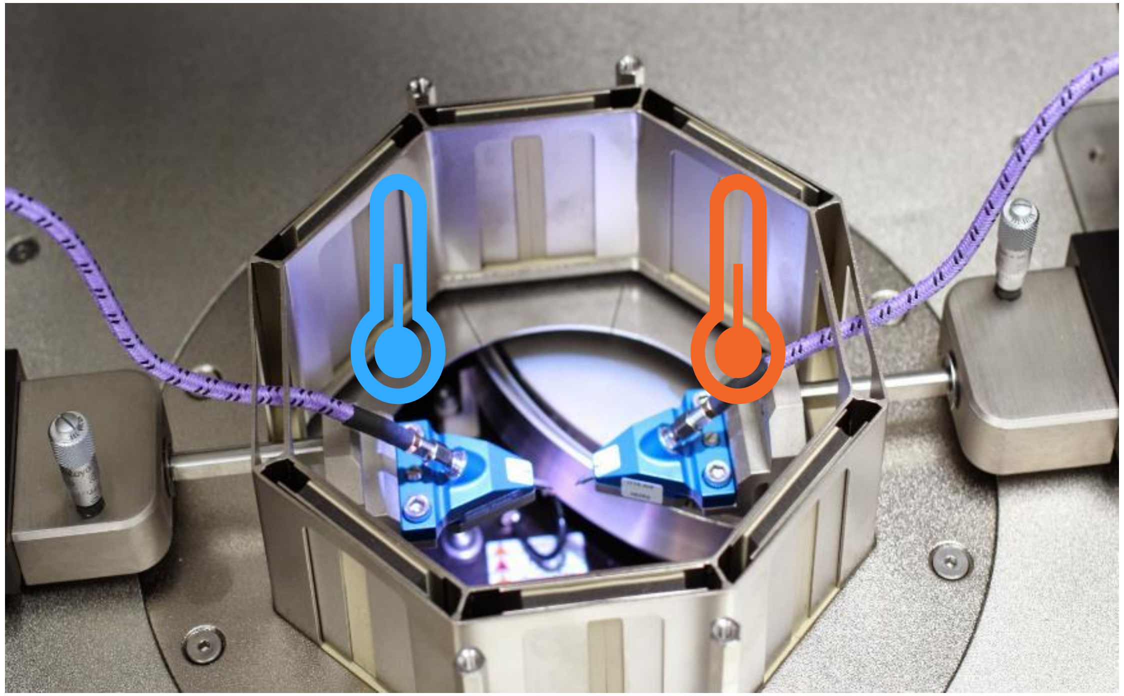
- Probes grow / retract with temperature in X and Z
- Some movement in Y but comparatively minimal
- For significant thermal changes evaluate theta also
- Chuck expands in XYZ as a function of displacement from centre and also shifts axially

Probe expansion from Ambient to 125 degree Summit

Video

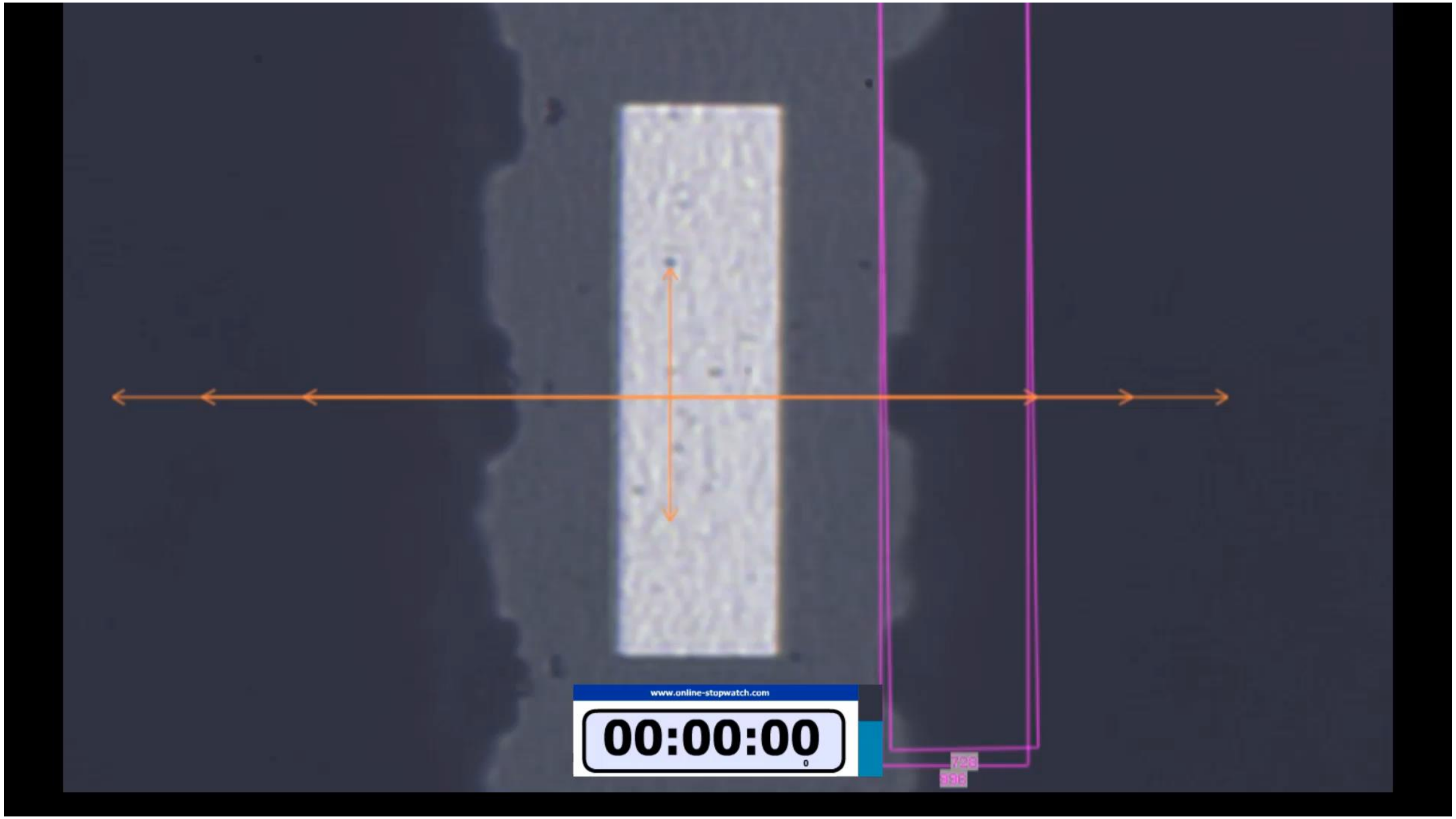


What happens when there is no autonomous but IS XYZ Automation?



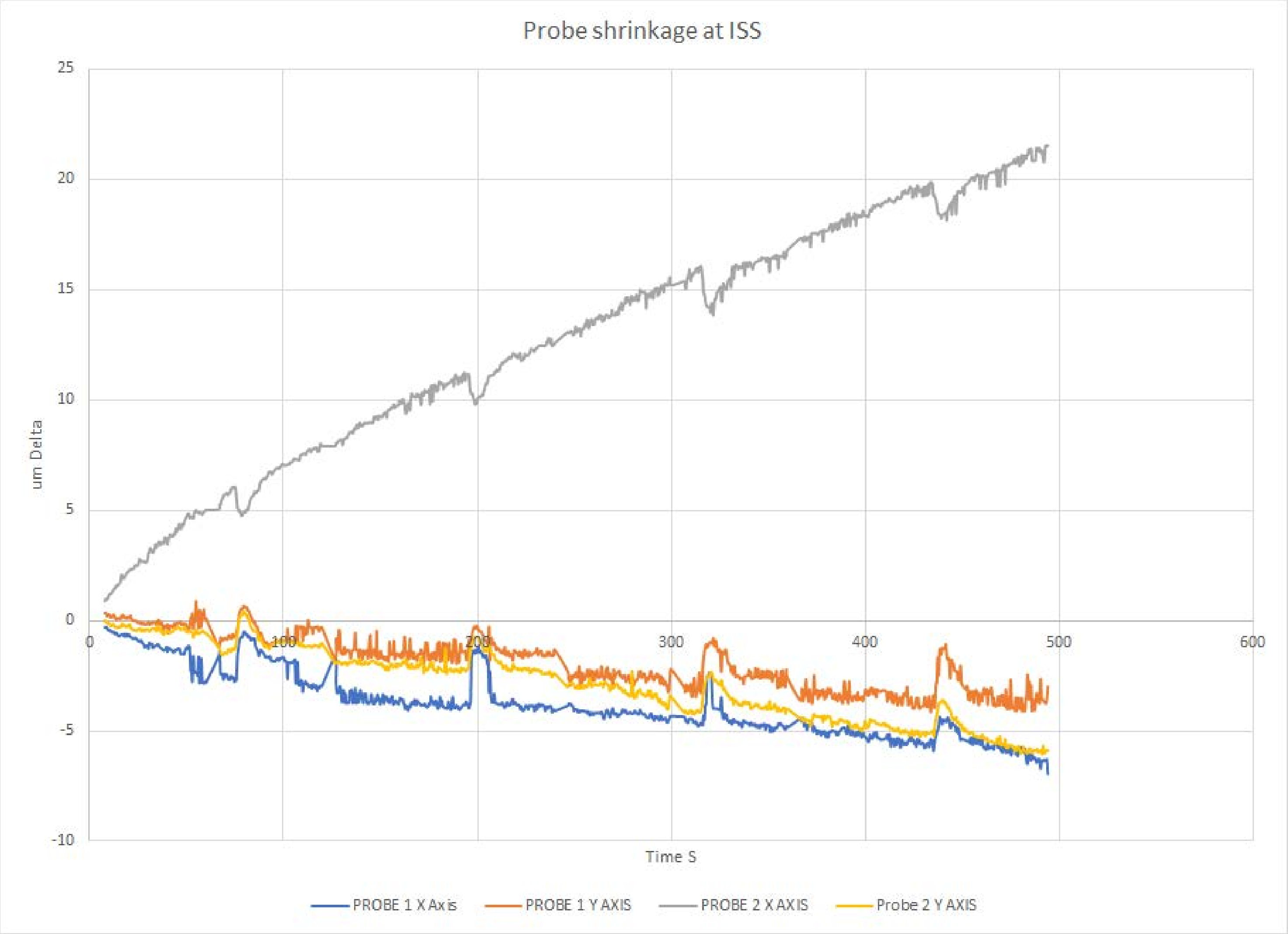
- Chuck can be corrected w.r.t the scope but if the probe movement isn't taken into account probes and positioners move.
- Fixed positioner Vuetrack can correct some of this but not differential growth
- When chuck reaches wafer edge one arm and probe is heated and the other cooled (differential)
- Vuetrack has no algorithms to deal with recalibration

Probe movement with time spent at Aux chuck – Chuck temp 125



- Cal done and system stabilised
- Probes moved to ISS and a probe align done
- Probes left to sit at Aux chuck and an Open measurement is done every 2 minutes
- Pink boxes are find feature to analyse

Probe movement with time spent at Aux chuck – Chuck temp 125



- This experiment took a configured machine and deliberately let it sit there
- The dips are the chuck moving to separate to do a drift measurement every 2 minutes
- On a 12k Port 1 is still partially heated by the Chuck

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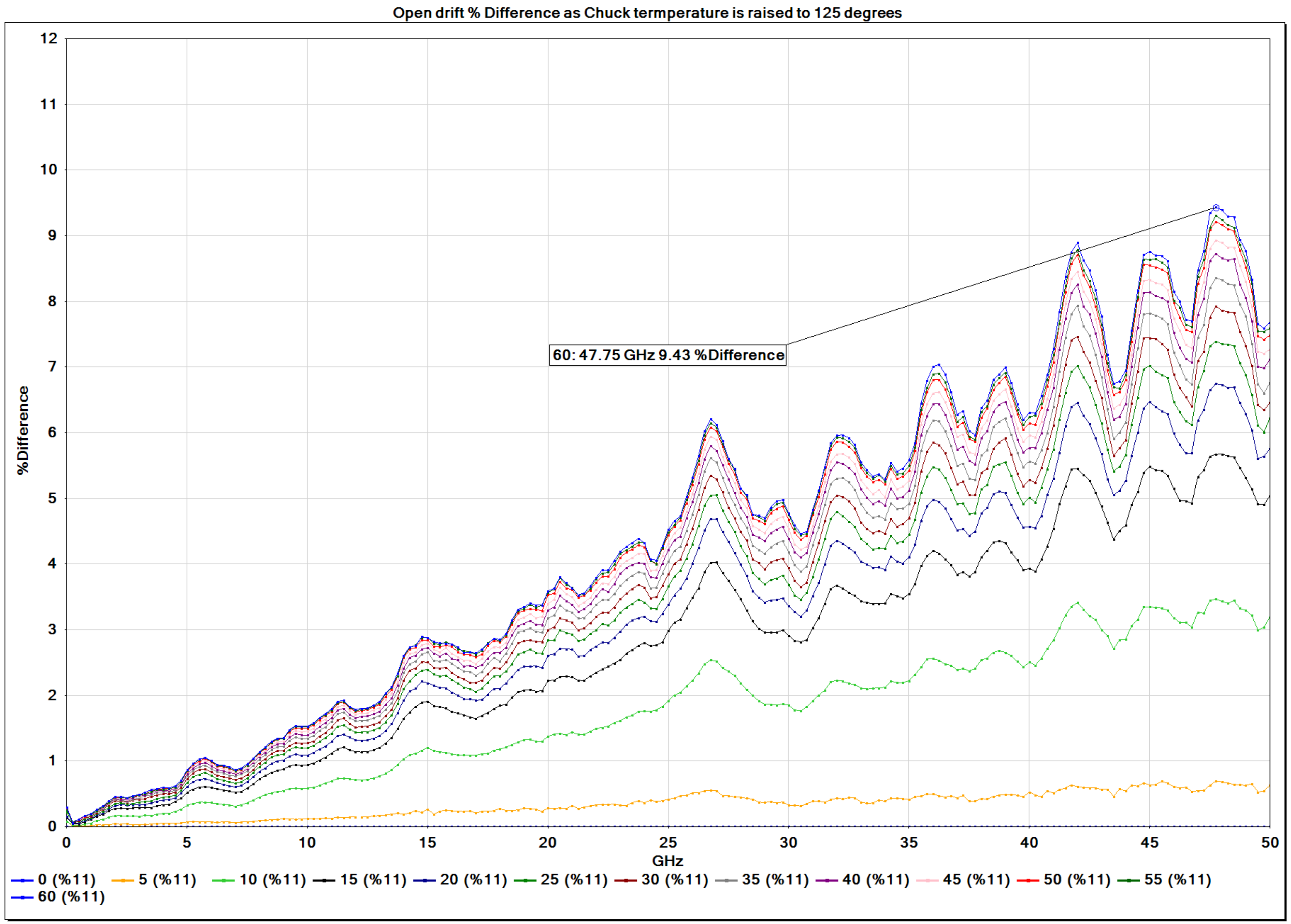
Calibrated S parameter change during warm up

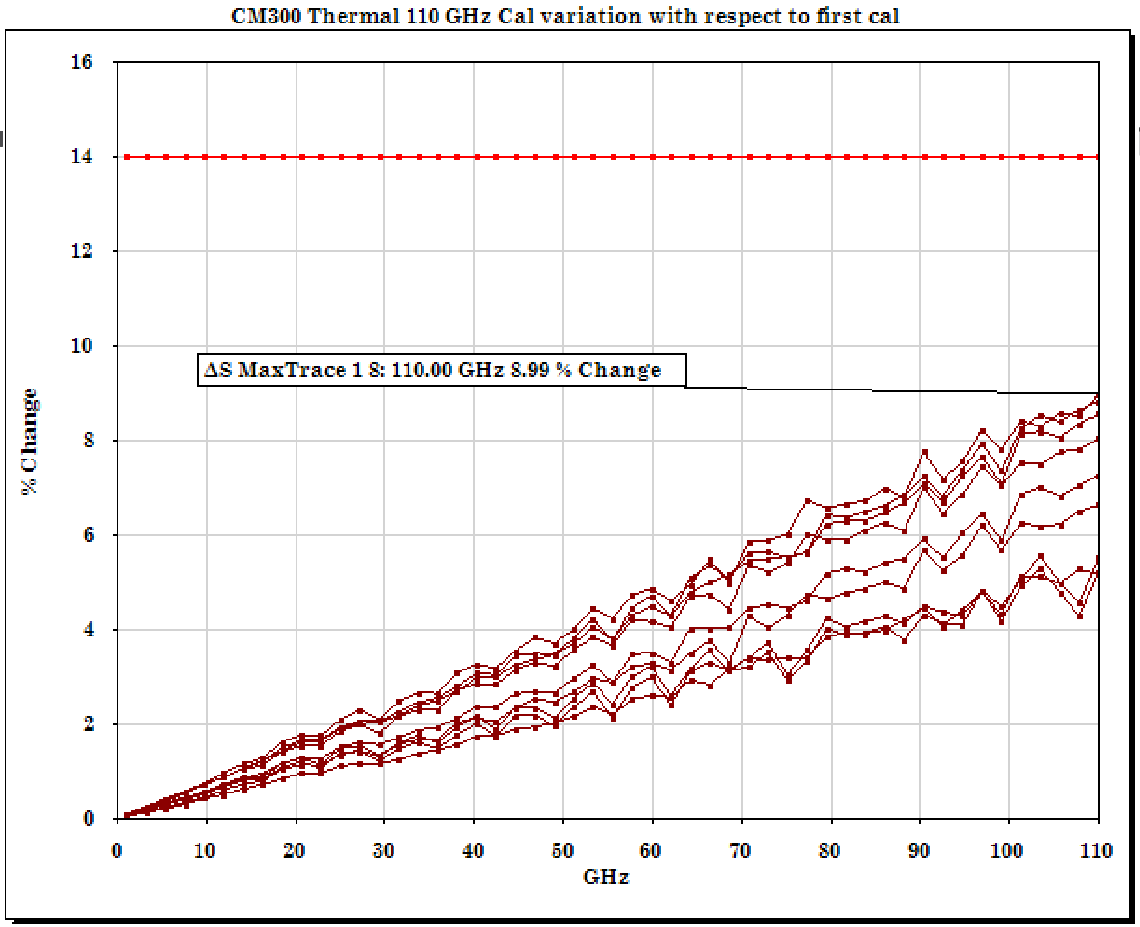


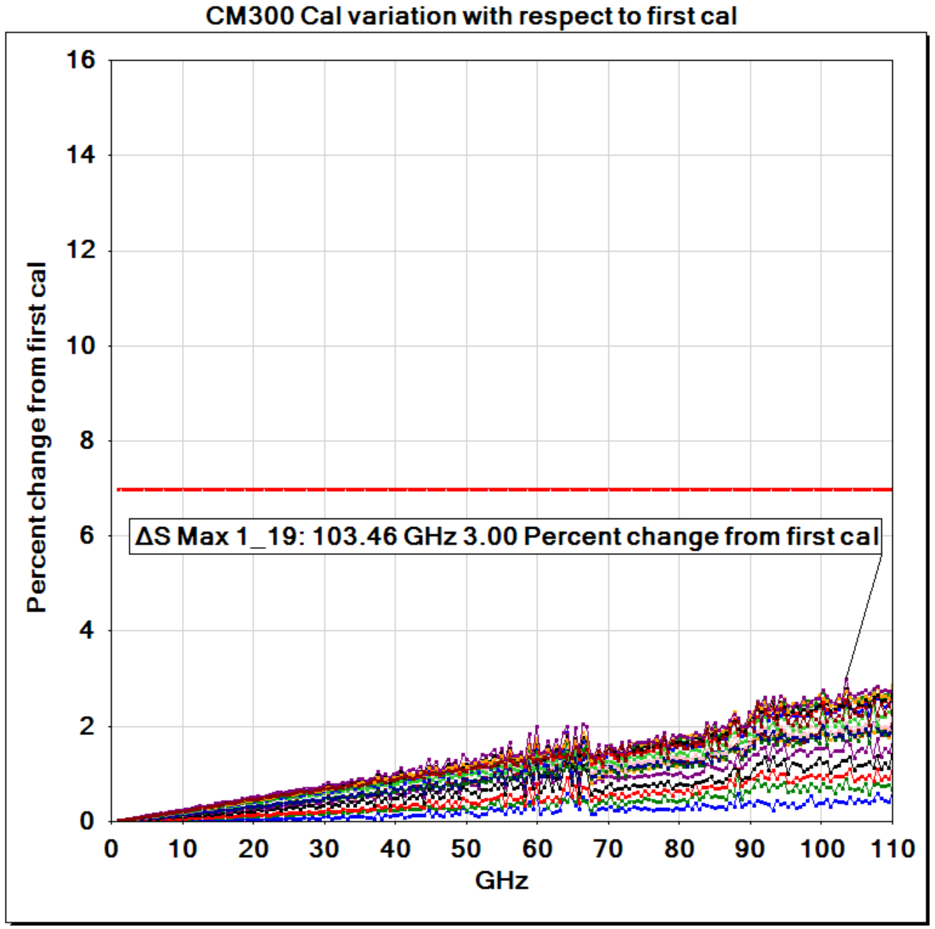
- This was a 50 GHz example
- System was calibrated and probes left above chuck
- Chuck temperature raised to 125 degrees
- This is the change during warm up without contact to the chuck

How to minimise calibration duration?

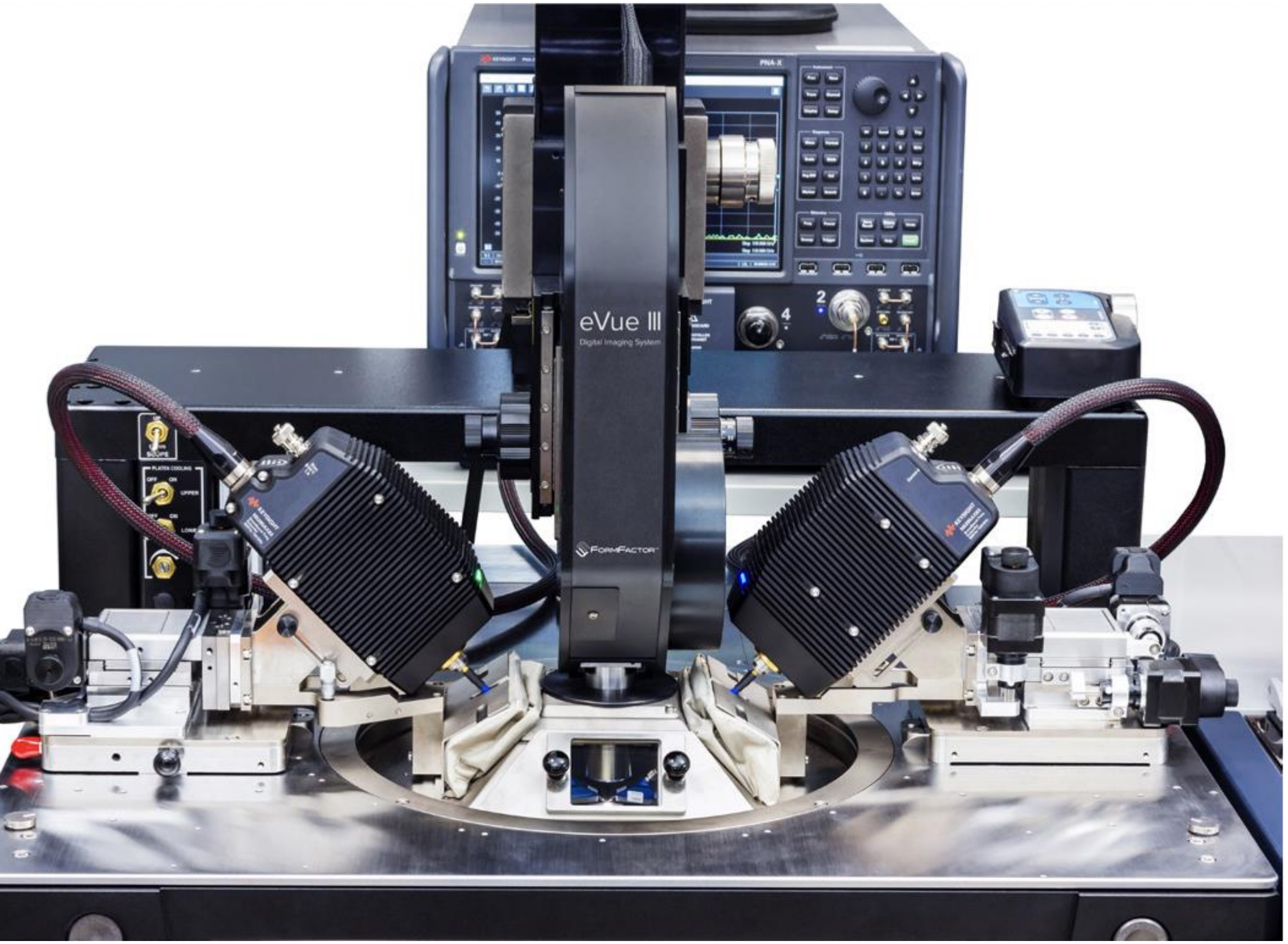
- Limit Number of points (Typically we use between 50 and 111)
- Limit if practical lowest IF bandwidth
- Total time away from wafer ideally <1 Minute.
- For best results use ISS dimensioned structure at Hot chuck to pre-align probes without time pressure (I use actual ISS here)
- Onscreen markers can perform the same task as physical standards
- Unless there is intelligent automation all steps require human intervention typically

300 mm Automatic - Thermal v Ambient error set stability





Introducing – Autonomous RF Measurement Assistant



Contact Intelligence™

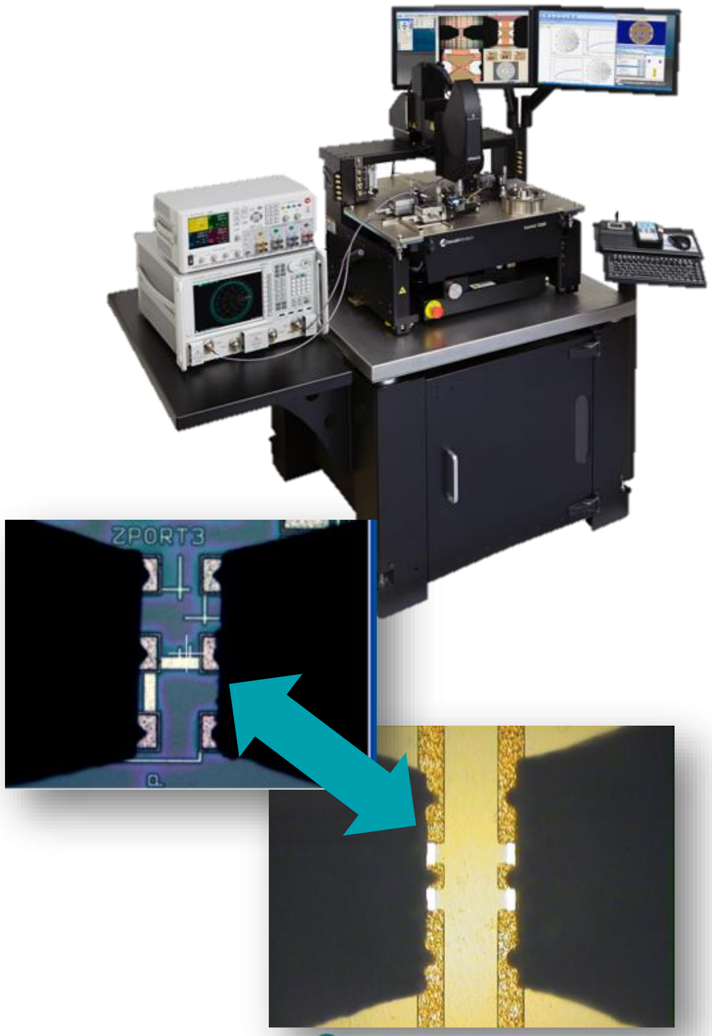
"Only the Autonomous RF Measurement Assistant, a combination of programmable positioners, a precise digital microscopy system and advanced pattern recognition algorithms, enables fully autonomous, hands-free calibrations and measurements of RF devices over multiple temperatures."

Autonomous RF – What it does..

- True Automatic, hands free calibration
- Monitors calibration drift, re-calibrates automatically
- Full thermal calibration management
- Save time & increase data accuracy

▪ Corrects "thermally induced" probe electrical errors

- All manual calibration steps are automated :
  - Moves any DC probes out the way
  - Moves to ISS calibration substrate
  - Aligns ISS and Probes with correct separation & over-travel
  - Performs full VNA calibration
  - Moves RF and DC probes back to DUT with correct pad layout



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Autonomous Rf Measurement Assistant
Compact High resolution Programmable Positioner

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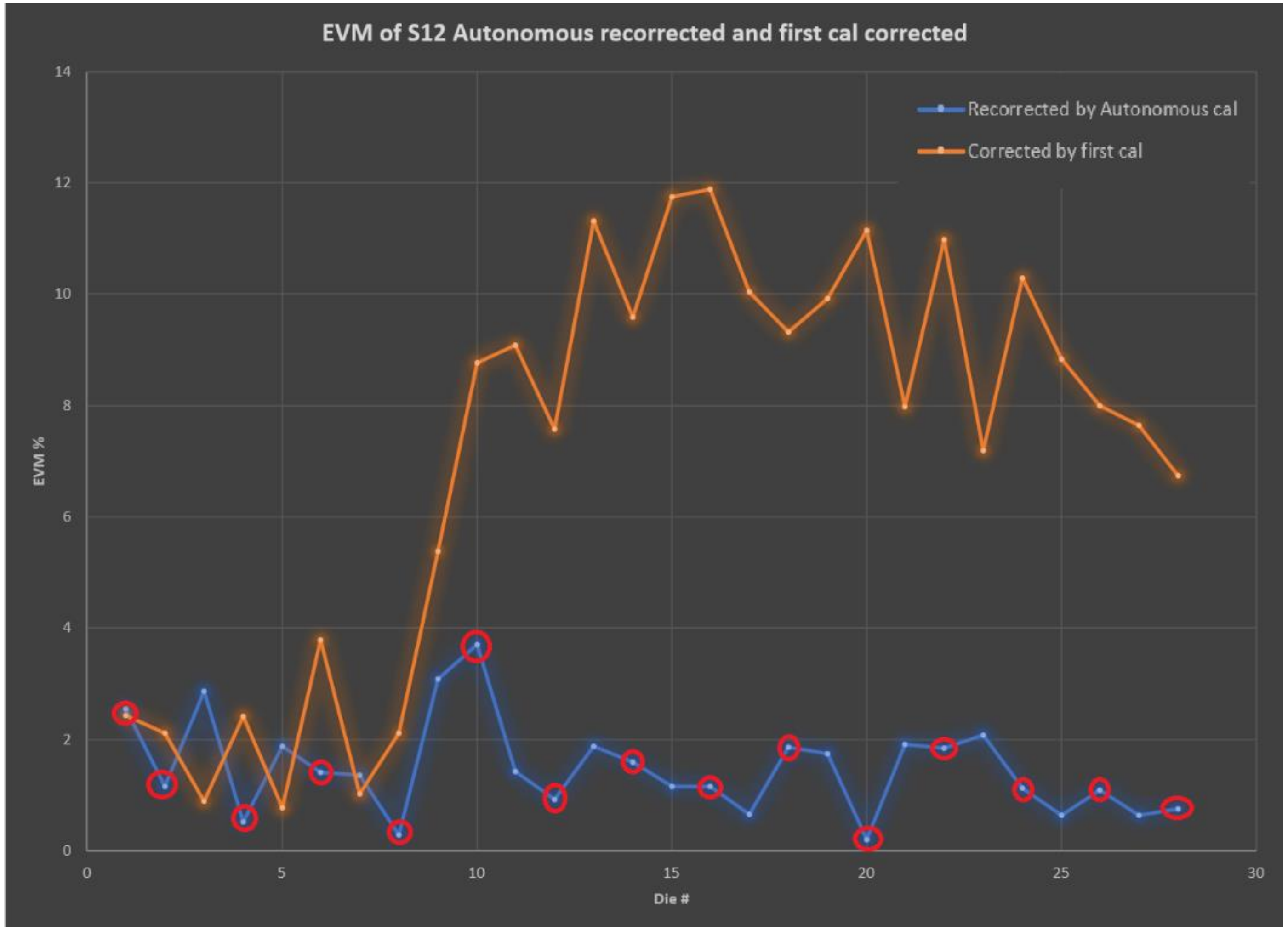
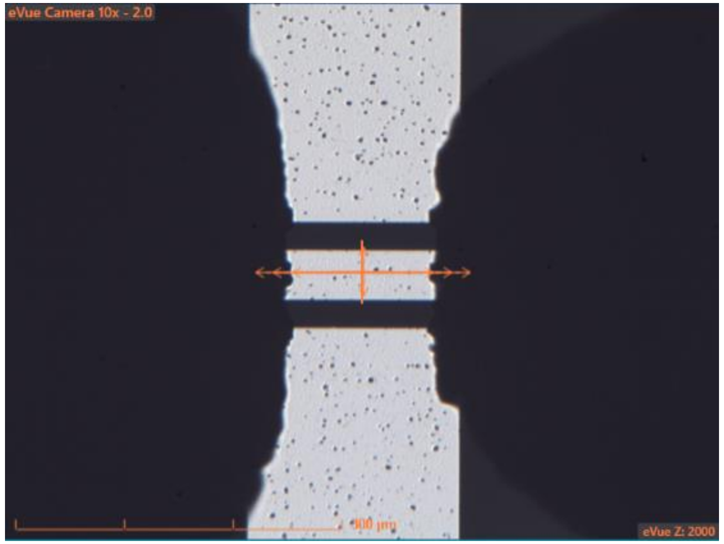
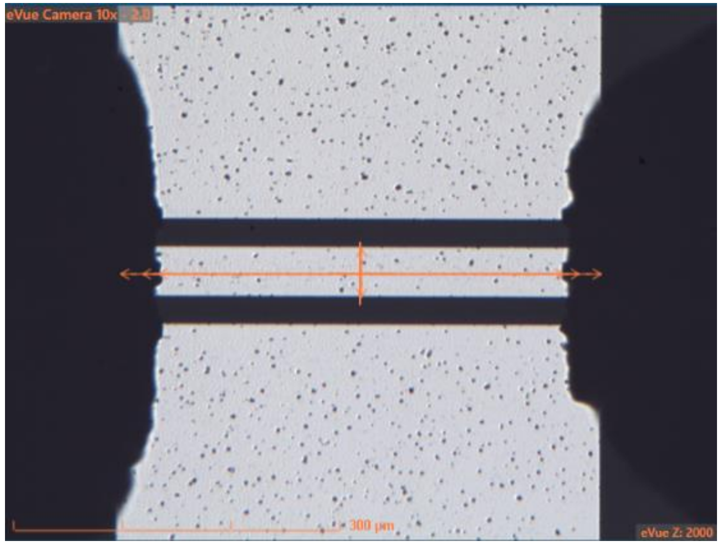
Variation as a function of Die



- Each point is from Max marker of WinCal report
- Orange is from processed data where the data is uncorrected and all recorrected using first cal
- Blue is recalibrated by autonomous
- Probes have been placed by autonomous – calibrations are the variable
- Rings indicate recalibration

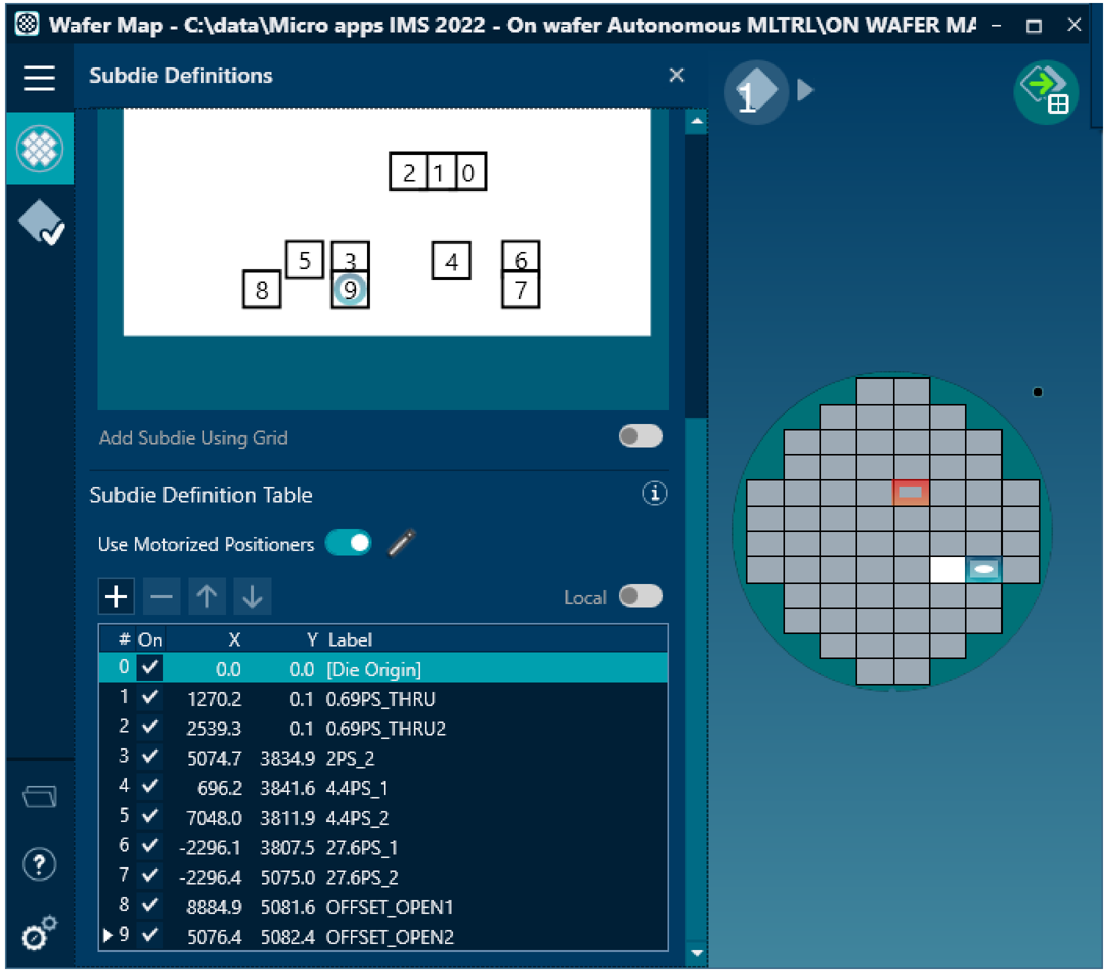
Problem - Multiple DUT Geometries

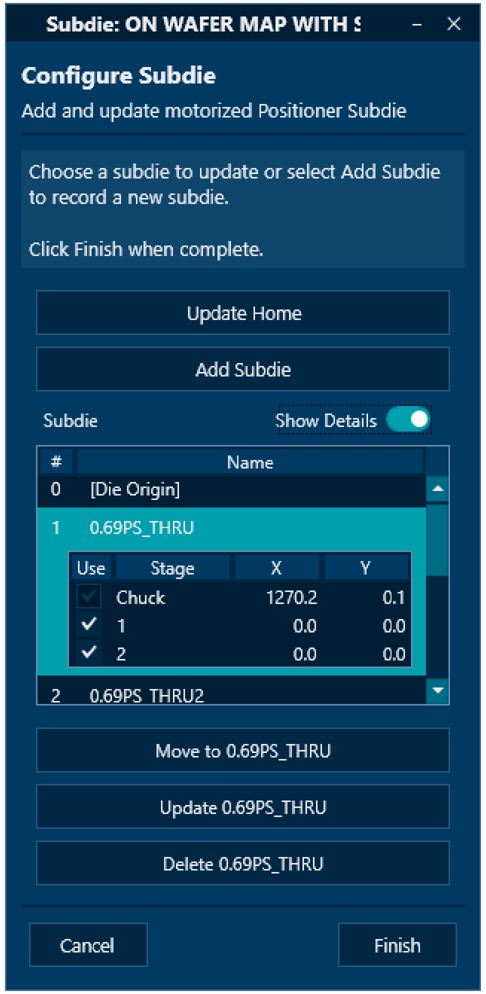




- Its common for customers to have multiple different sizes of device in a single die
- These different devices sometimes need different probes spacings
- Probe spacings are also generally different from calibration spacing
- The ability to test all the test devices in a single run is very attractive
- Without autonomous or at least a motorised positioner a user will need to manually adjust the probe placement for all different devices
- Motorised positioners also allow for autonomous MLTRL with WinCal automatically moving to required lines

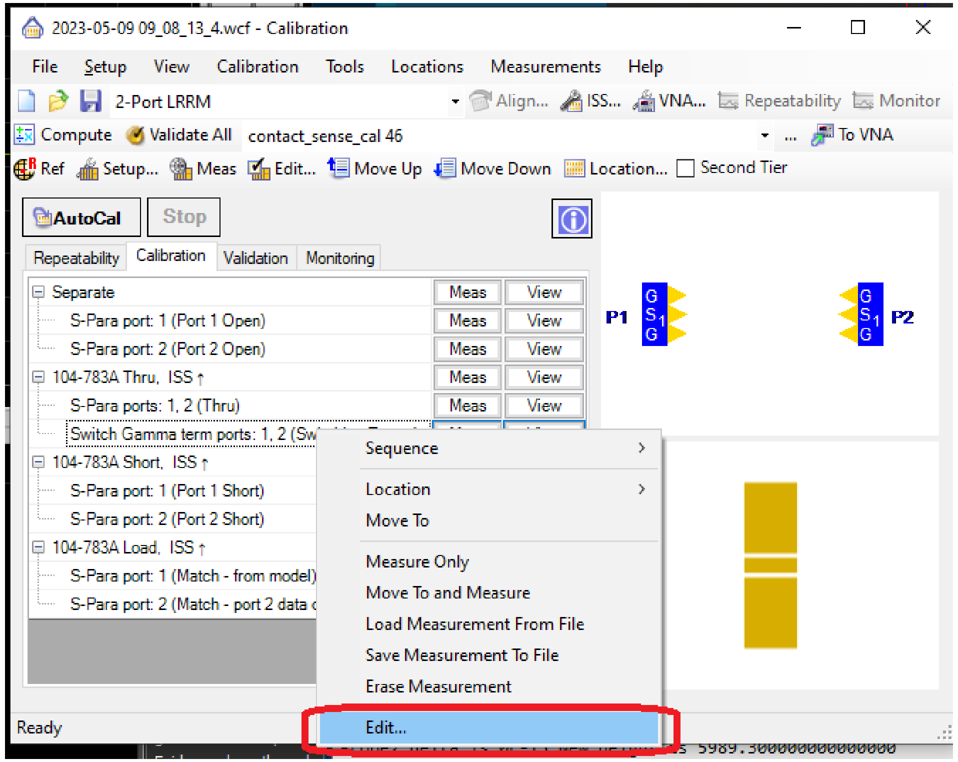
Native Multiple Probe Geometry Support

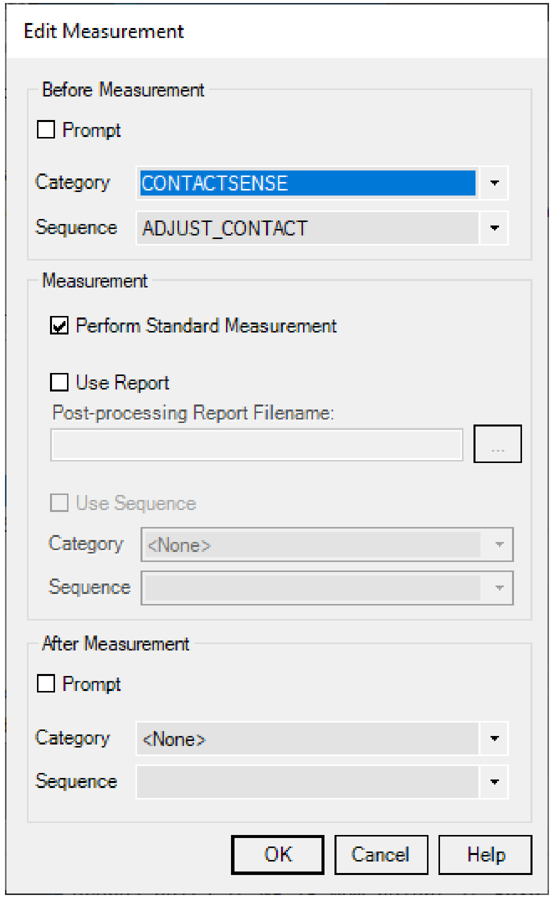




- Velox wafermap now supports moving motorised positioners as well as the wafer chuck via a click or via existing subdie step remote commands

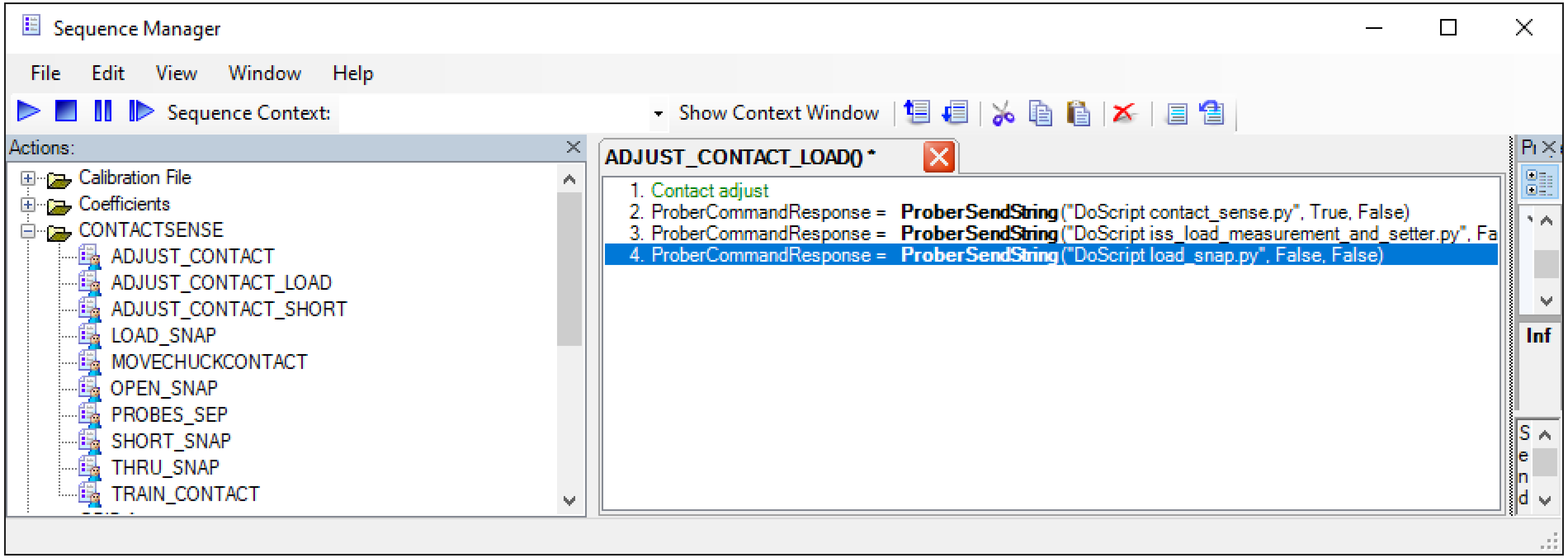
How to make python scripts work within Wincal





- Python direct approach could use Wincal as a slave but preference is to sense in the normal cal approach
- Wincal can invoke a “sequence” during the calibration sequence
- Calibration sequence can in turn invoke a python script using DoScript command
- Each measurement can have a sequence run before and after and even use a specified report for process work

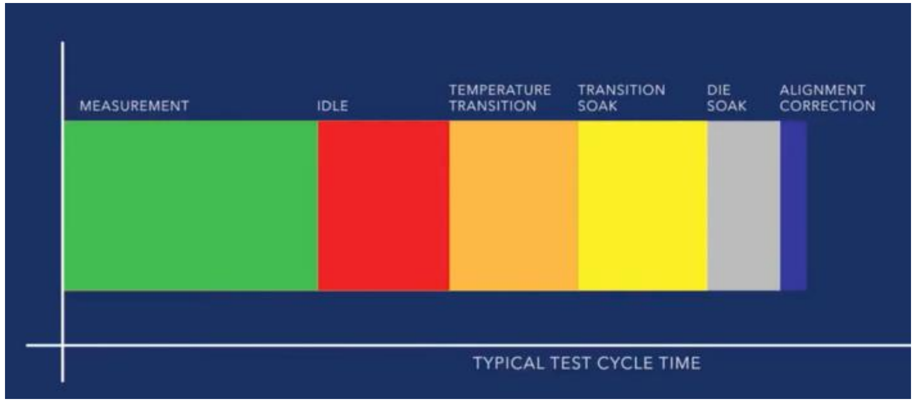
Sequence manager being used to call Python scripts

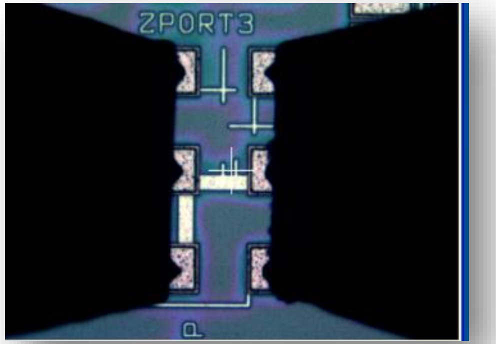


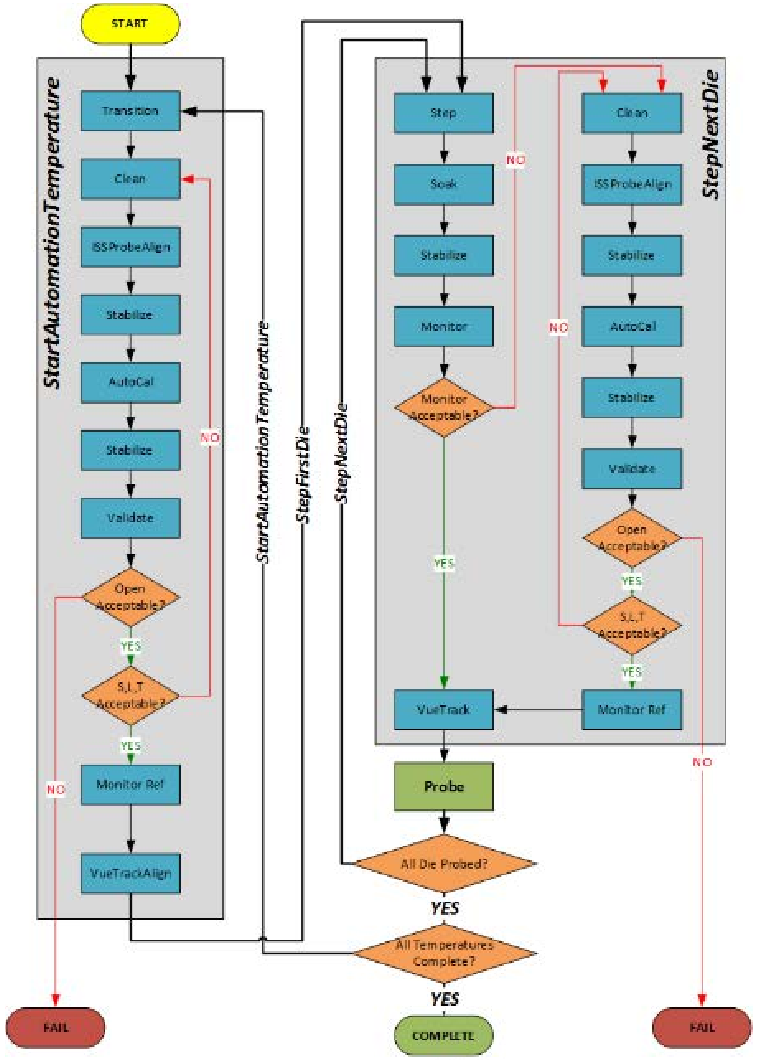
- The set of sequences is seen in the list

Problem – Device Soak Times over Temperature

- System and DUT continue to soak after temperature transition
- Requires re-alignment after transition
- Reaching thermal equilibrium can take hours and probes need realigned
- For long DUT test times realignment needed per die

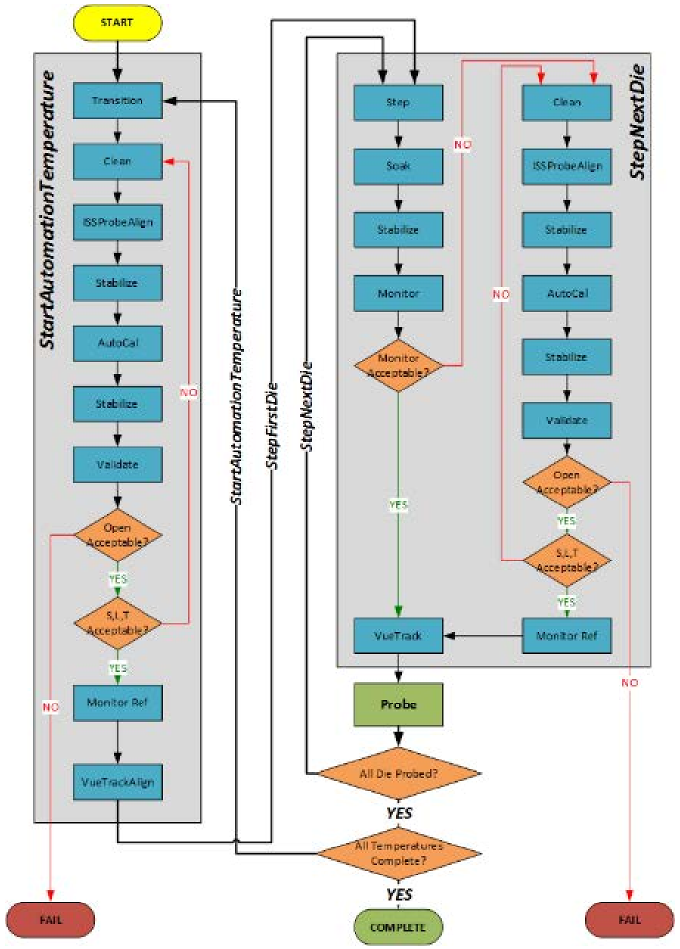






Integrating Automation assistant into test executive

- StartAutomationTemperature X does all this…
  - Changes temperature and maintains probe to probe, and probe to wafer geometry at Separate
  - Die soak at end of transition at align height always maintaining geometry
  - Checks using VNA to test for electrical stability
  - Moves bias probes out of field of view
  - Aligns probes at ISS using defined spacings
  - Re-checks stability to ensure probes didn’t cool down
  - Calibrates system
  - Verifies
  - Takes monitoring data to check system is stable later on
  - Returns probes to wafer Geometry ready for test
  - Additional options of this command performs Theta align and sizing
  - This command would already be used by Vuetrack customers although typically they typically don’t do RF



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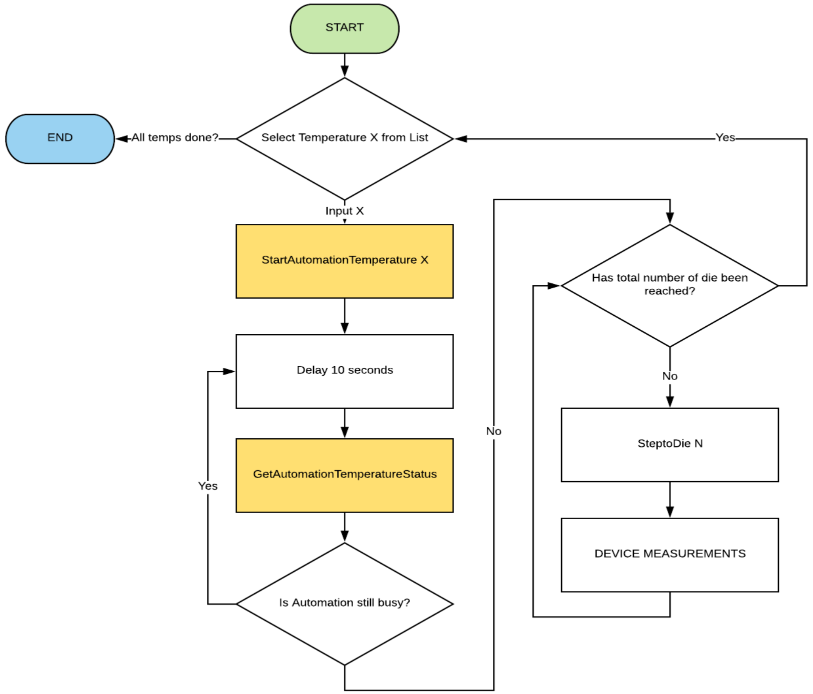
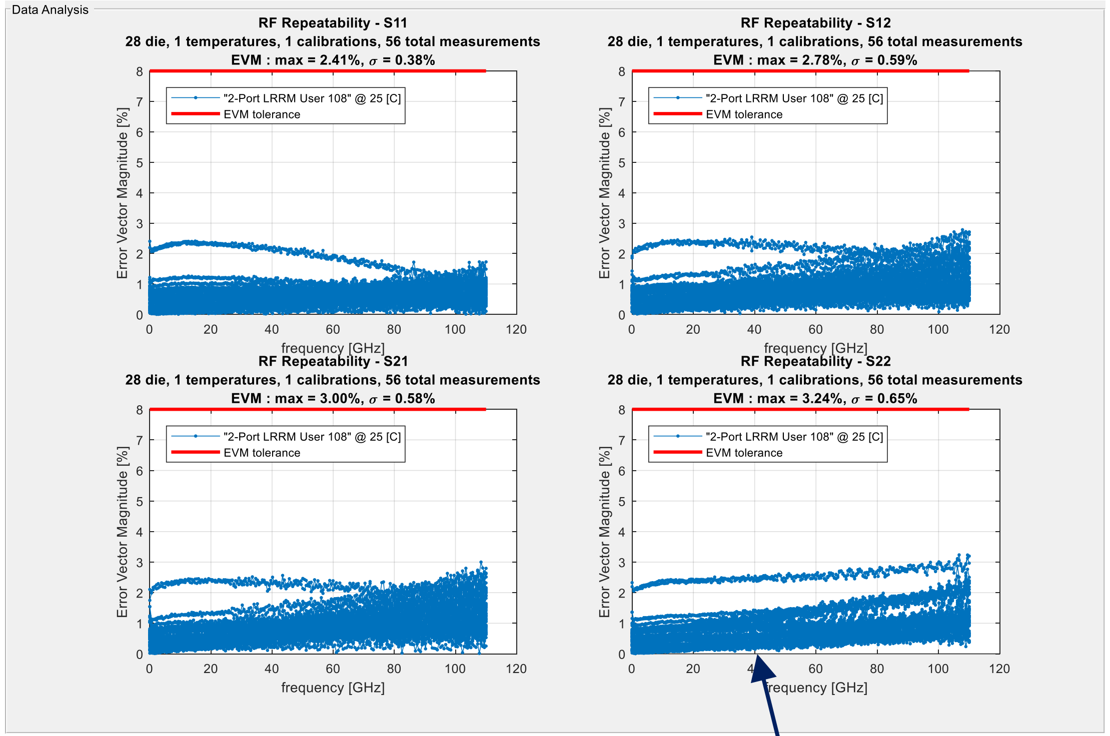
Using StartAutomationTemperature

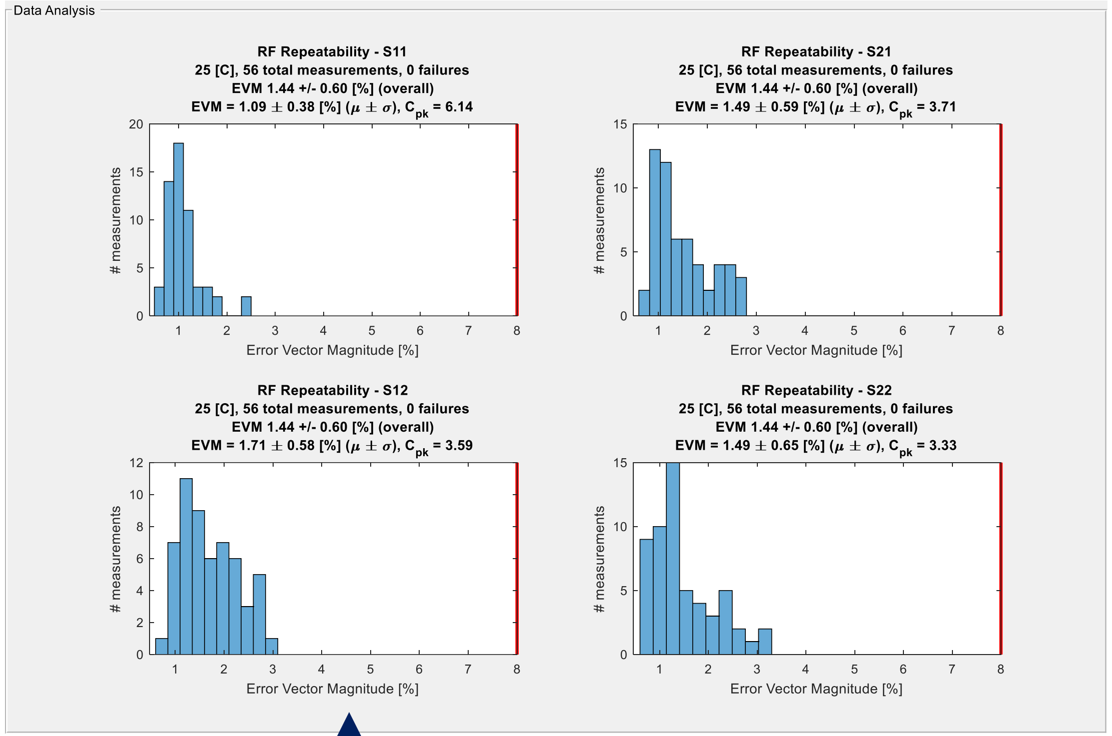


- Coloured processes are the two required commands StartAutomationTemperature GetAutomationTemperature Status
- Test exec never needs to ask system to calibrate, monitor or soak. Its all automatic
- Only needs to send temperature automation, wait till complete and then step to numbered die as normal
- Next die commands will check for drift, recalibrate if needed and automate probe on die placement
- GetAutomationTemperatureStatus typically returns Busy or Complete as the string but also a category value. A value of "2" is useful to trap error conditions and escape the test loop. The actual string may return a detailed error but preceded by @ symbol

Performance analyzer - RF Measurement Repeatability



Measurement Repeatability



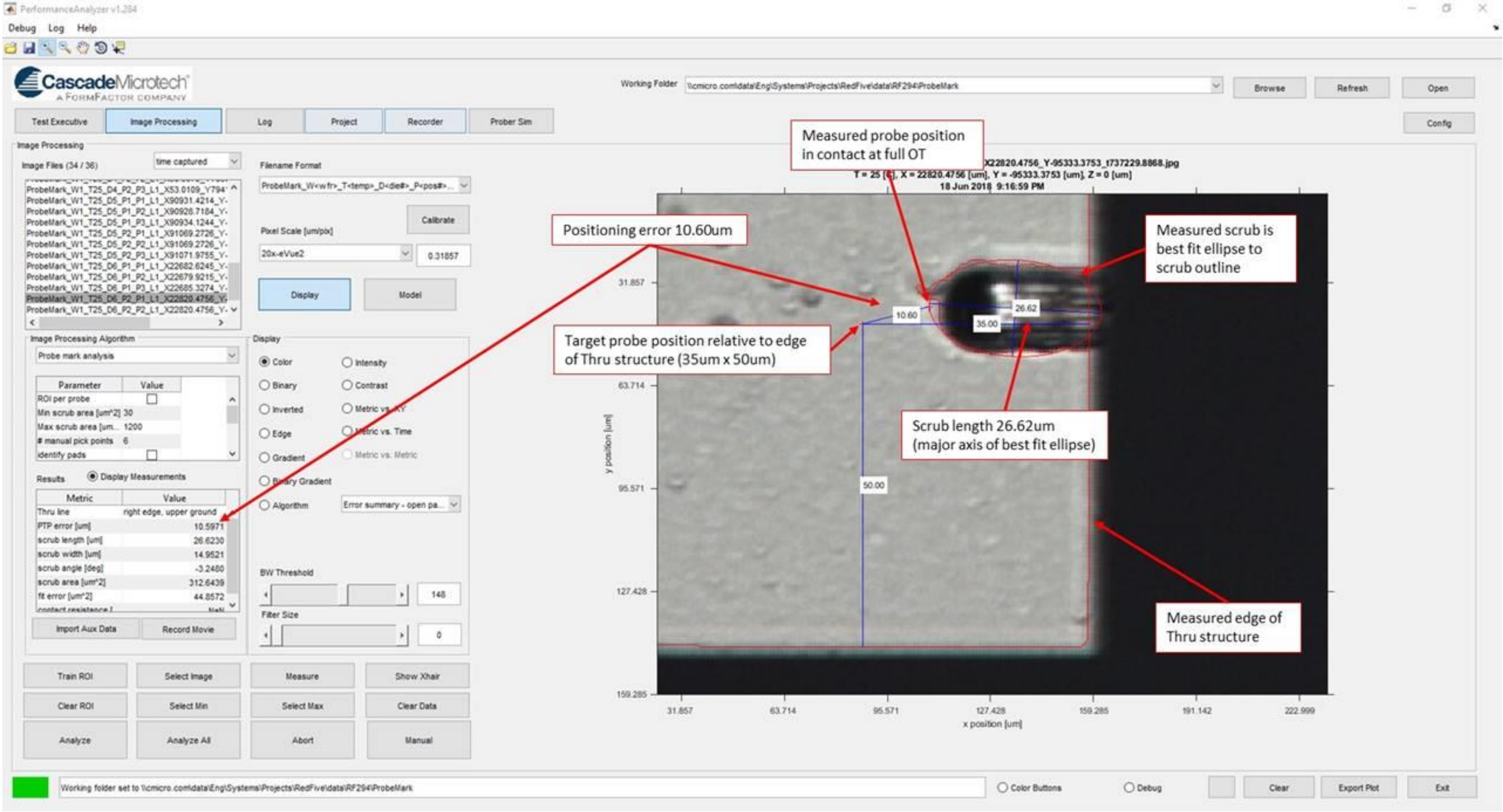
Statistical Repeatability

Measurement Repeatability illustrates EVM vs frequency relative to mean of all measurements collected during test

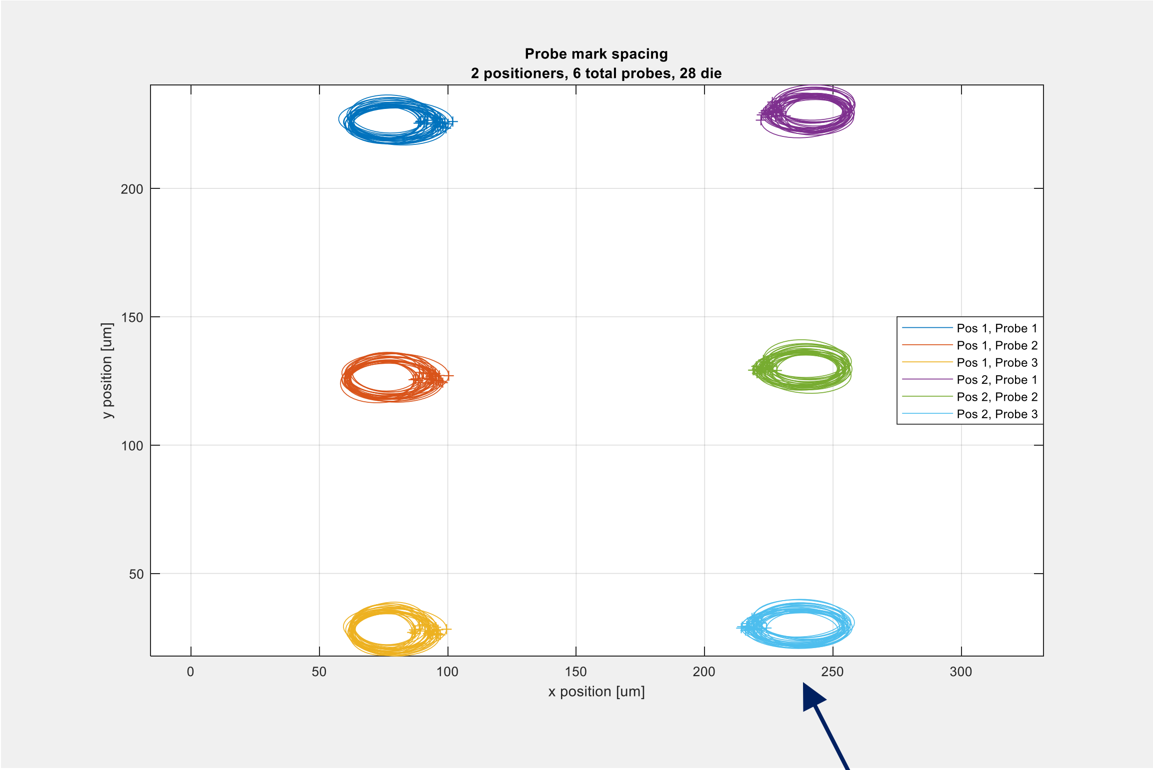
Statistical Repeatability illustrates EVM distribution relative to mean of all measurements collected during test

Error: None
EVM Result: 1.44 ± 0.60 %
PTTE Result: 5.21 ± 2.67 um

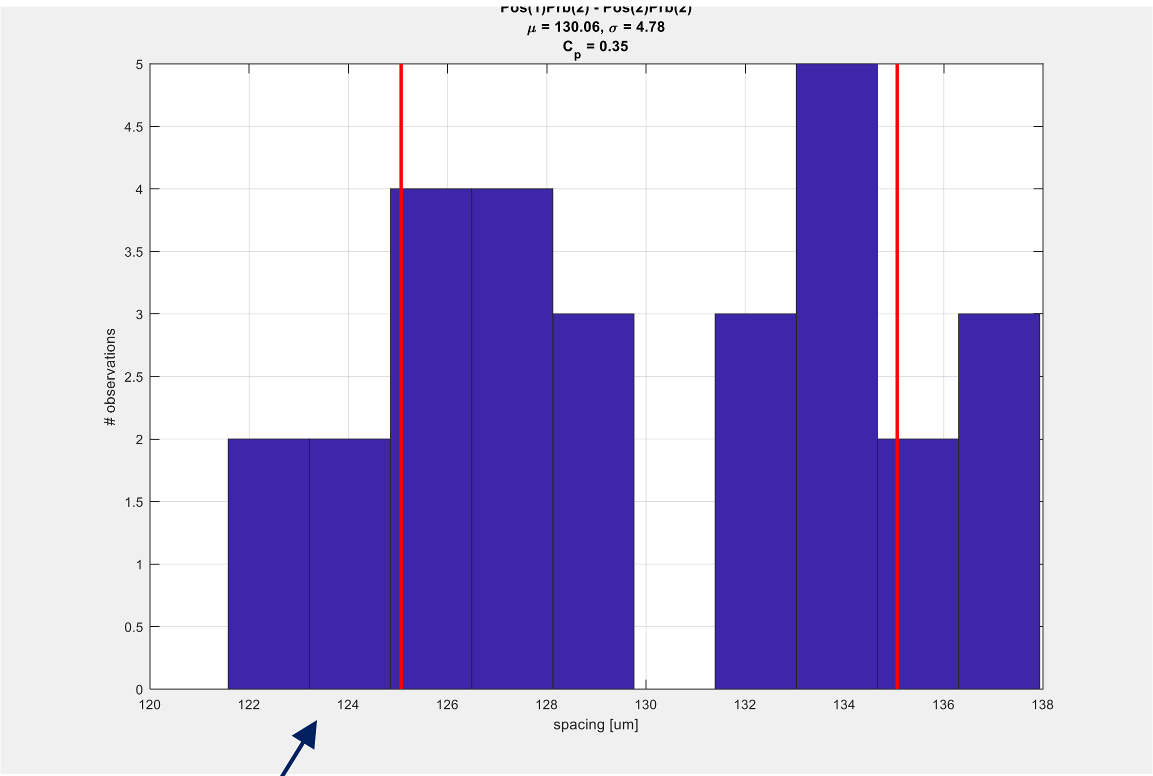
Performance analyzer – mark analysis



Performance analyzer - Probe-to-Probe Spacing



Probing Layout



Probe-to-Probe Spacing Distribution
130.06 ± 4.78 [um] (μ±σ)

Probing Layout illustrates relative positions of probes on wafer during test, including chuck offsets for multiple-temperature test runs

Probe-to-Probe Spacing Distribution illustrates variability of relative scrub mark positions for all touchdowns during test

Error: None
EVM Result: 1.44 ± 0.60 %
PTTE Result: 5.21 ± 2.67 um

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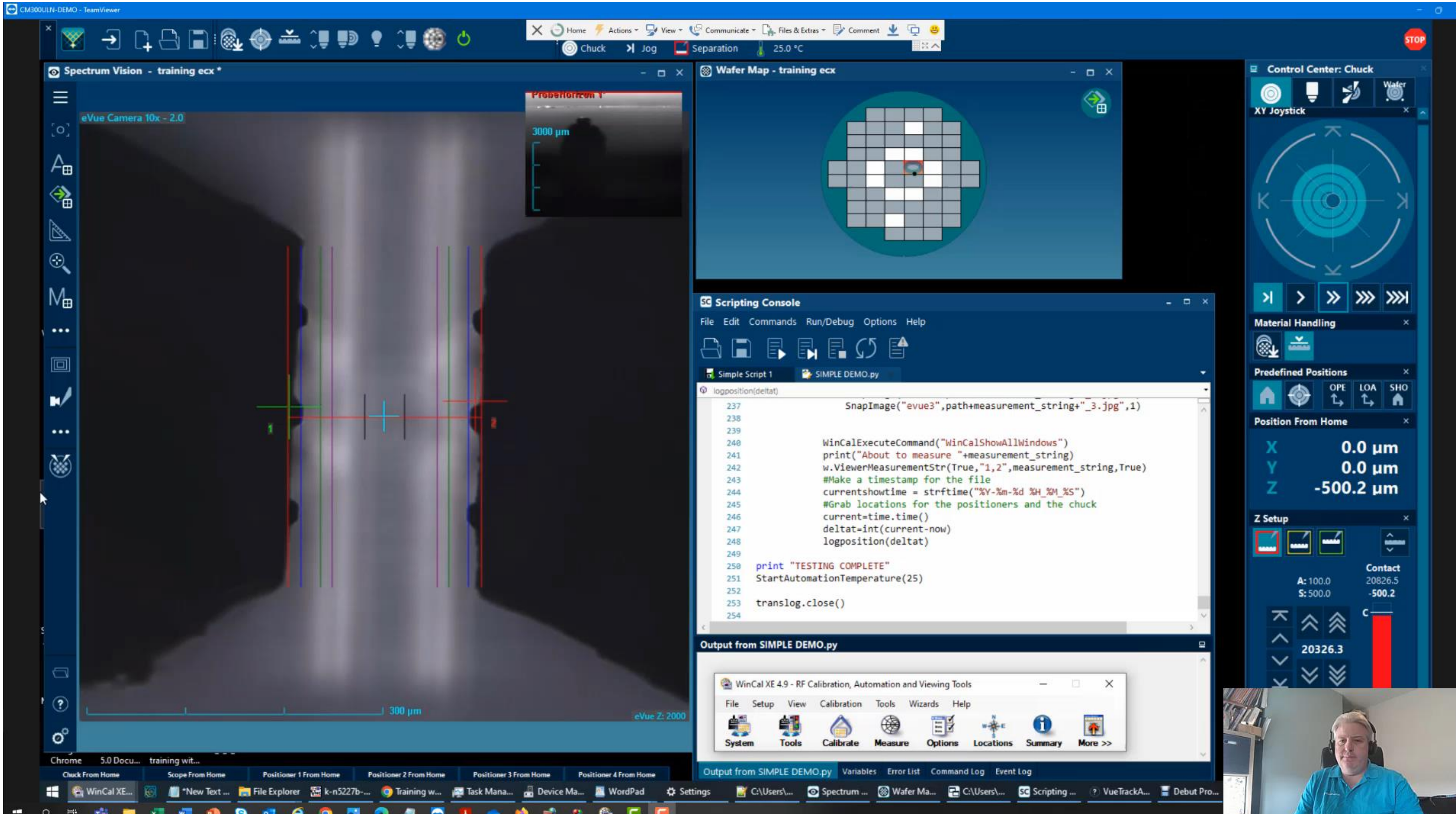
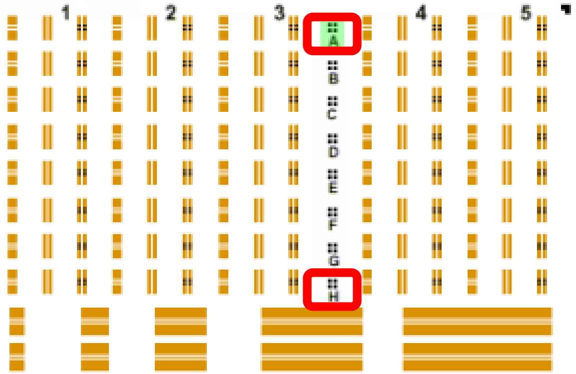
Practical Example2 – Using Python to carry our multi die, multi subsite autonomous testing with multi device geometry

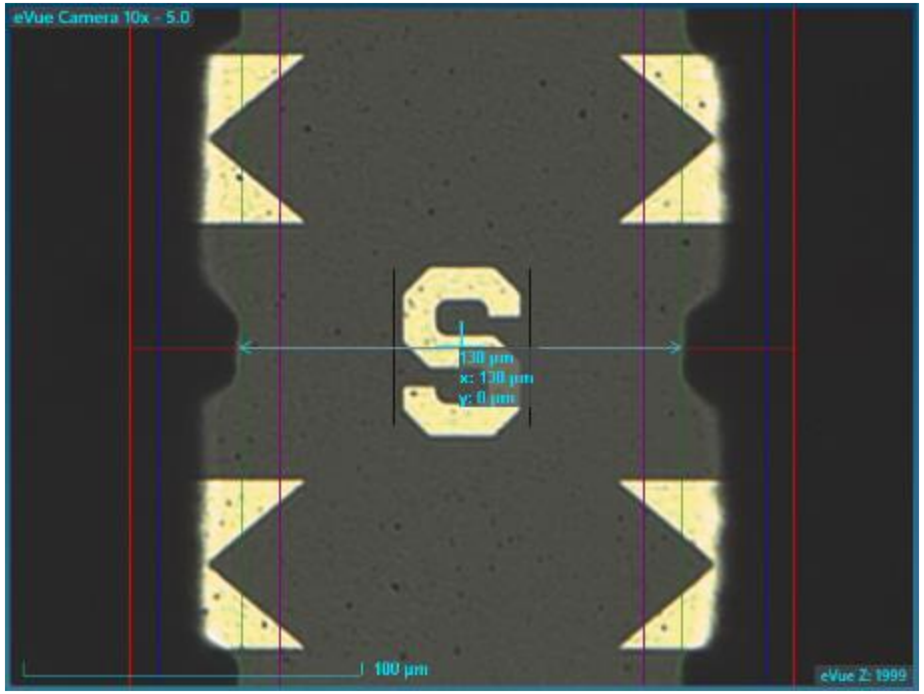


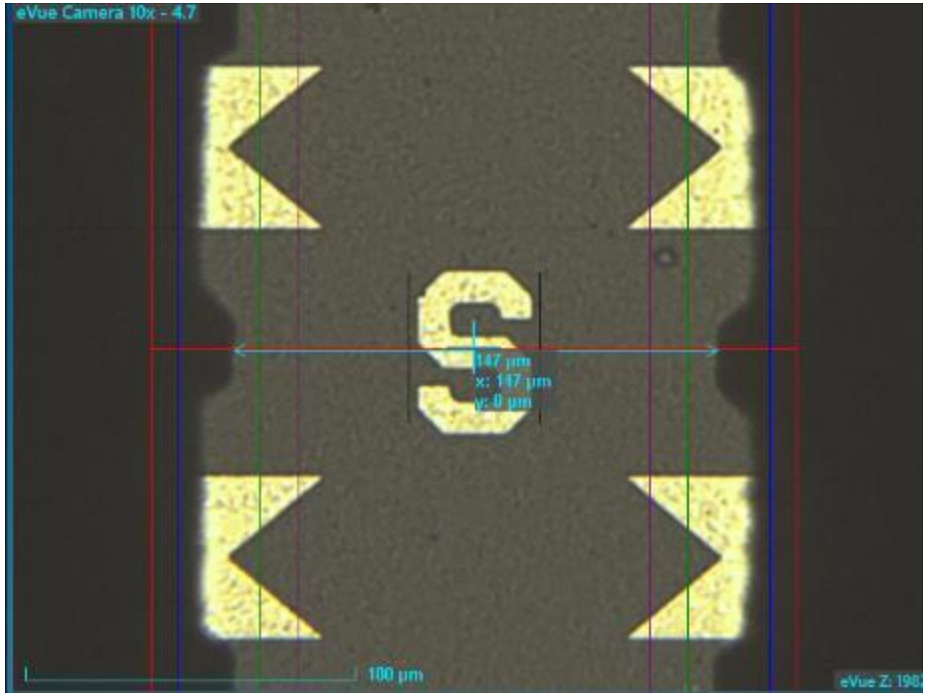
CM300ULN-DEMO - TeamViewer
Home
Actions
View
Communicate
Files & Extras
Comment
Chuck
Jog
Separation
25.0 °C
STOP
Spectrum Vision - training ecx *
eVue Camera 10x - 2.0
ProbeHorizon 1
3000 µm
300 µm
eVue Z: 2000
Wafer Map - training ecx
Control Center: Chuck
XY Joystick
Material Handling
Predefined Positions
OPE
LOA
SHO
Position From Home
X 0.0 µm
Y 0.0 µm
Z -500.2 µm
Z Setup
Contact
A: 100.0
S: 500.0
20826.5
-500.2
20326.3
Scripting Console
File Edit Commands Run/Debug Options Help
Simple Script 1
SIMPLE DEMO.py
logposition(deltat)
SnapImage("evue3",path+measurement_string+"_3.jpg",1)
WinCalExecuteCommand("WinCalShowAllWindows")
print("About to measure "+measurement_string)
w.ViewerMeasurementStr(True,"1,2",measurement_string,True)
#Make a timestamp for the file
currentshowtime = strftime("%Y-%m-%d %H_%M_%S")
#Grab locations for the positioners and the chuck
current=time.time()
deltat=int(current-now)
logposition(deltat)
print "TESTING COMPLETE"
StartAutomationTemperature(25)
translog.close()
Output from SIMPLE DEMO.py
WinCal XE 4.9 - RF Calibration, Automation and Viewing Tools
File Setup View Calibration Tools Wizards Help
System Tools Calibrate Measure Options Locations Summary More >>
Output from SIMPLE DEMO.py
Variables
Error List
Command Log
Event Log
Chuck From Home
Scope From Home
Positioner 1 From Home
Positioner 2 From Home
Positioner 3 From Home
Positioner 4 From Home

Contact sensing – Contaminants can affect planarity



- In WinCal XE the probe geometry is set at a single reference location in terms of XYZ
- During calibration, the system steps using iss co-ordinates assuming the planarity is perfect
- Contaminants under the substrate can cause planarity to change, and results in more or less overtravel affecting probe final position at the standards away from the reference





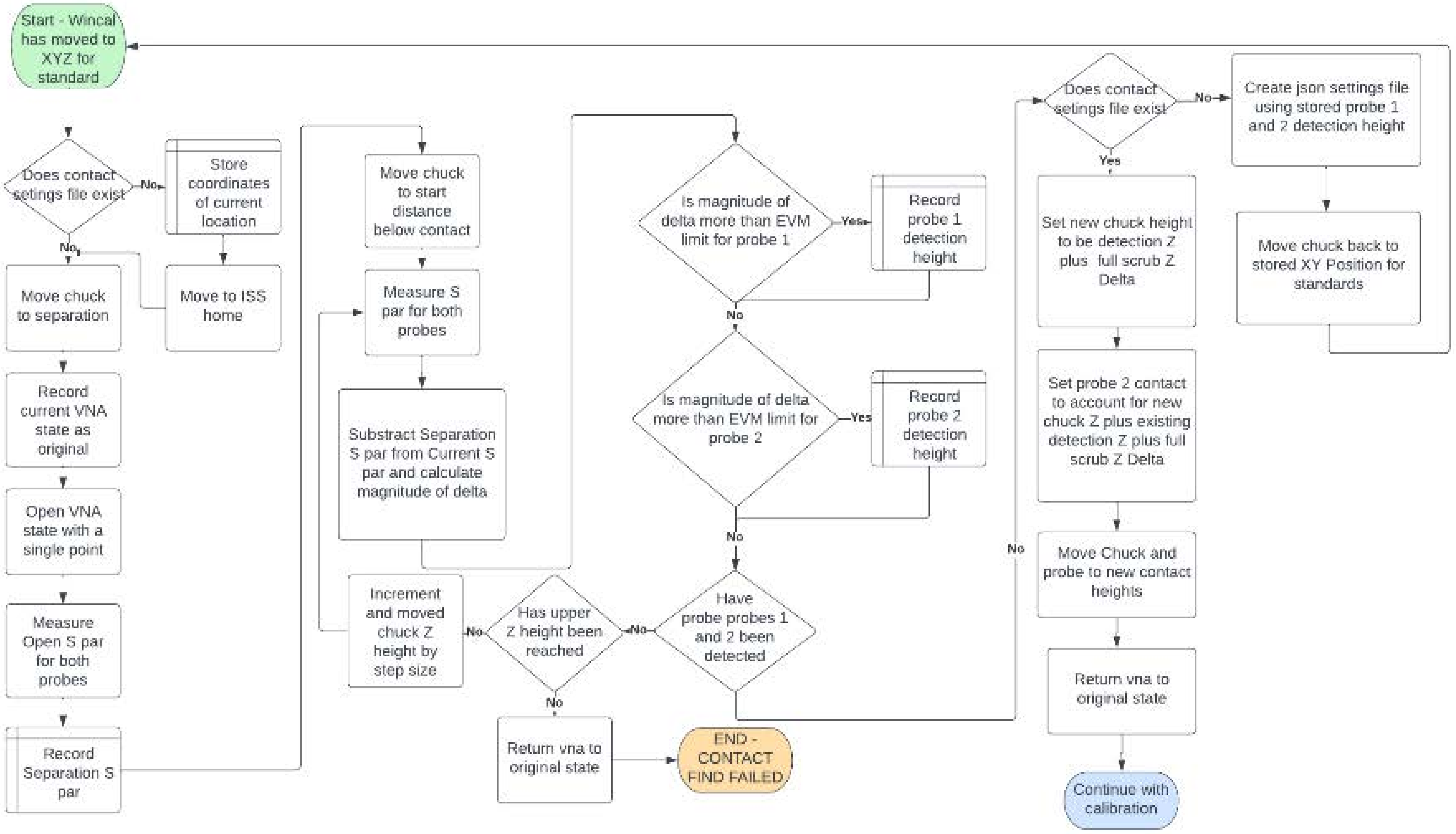
- Augmented alignment Green lines set to be 130 um – probe geometry set to this spacing at alignment Mark A
- Stage move to location H – Less skate and probes now spaced to 140 um

FormFactor™

Contact sensing

- Very repeatable and uses the measurement system itself
- Is dynamic and reflects the height of the probe at the actual time of calibration (as probes cool the height can change)
- Can be very quick when communicating directly with the vna via tcp (as we did)
- Drawback of direct approach is a driver is needed per instrument type additional to Wincal’s own
- Can be compatible with Autonomous RF setups
- Is simple – probes need setup for the iss anyway....
- Delta Magnitude = ((Real_current – Real_Open)^2+(Imag_current – Imag_Open)^2)^0.5

How does it work in general inside Python script?



This is a flowchart of the general contact sense python script logic

This script is run during the calibration process

Questions