

Transmission Line Theory and Advanced Measurements in the Field

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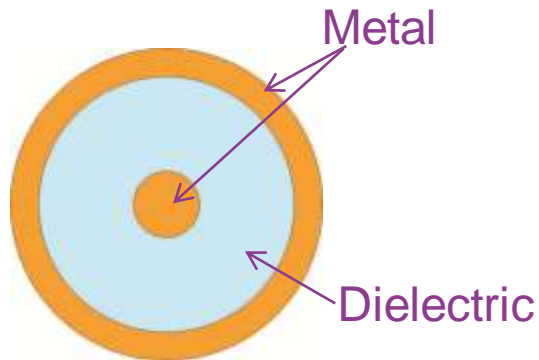
Tom Hoppin
Application Specialist
On Contract to
Component Test Division
Keysight Technologies

Agenda

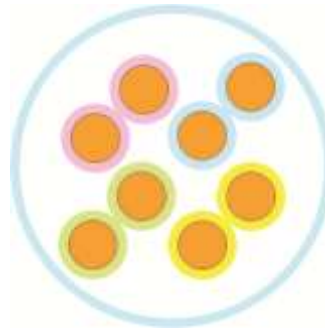
- Transmission Line Basics
- Frequency and Time Measurements
- Frequency Limitations of Connectors and Cables
- Measuring Insertion Loss
 - One-Port Techniques
 - Very Long Cables
- Troubleshooting Line Faults
 - TDR and Impulse Modes
 - Examples of Cable and Waveguide Damage
 - Velocity Factor of Coax and Waveguide
- Conclusions

Types of Common Transmission Lines

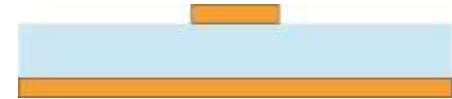
Cross Section



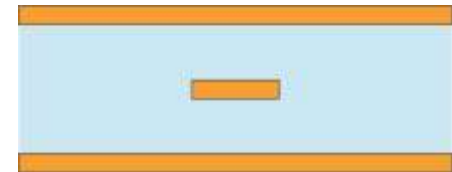
Coaxial



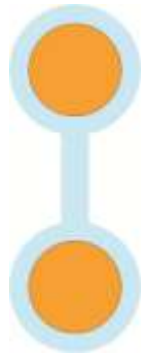
**Twisted Pair
(unshielded)**



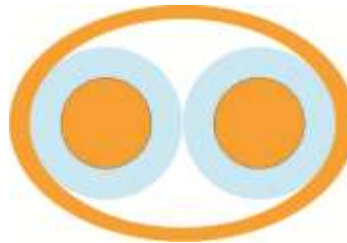
**Microstrip
(PCB)**



**Stripline
(PCB)**



Twin-lead



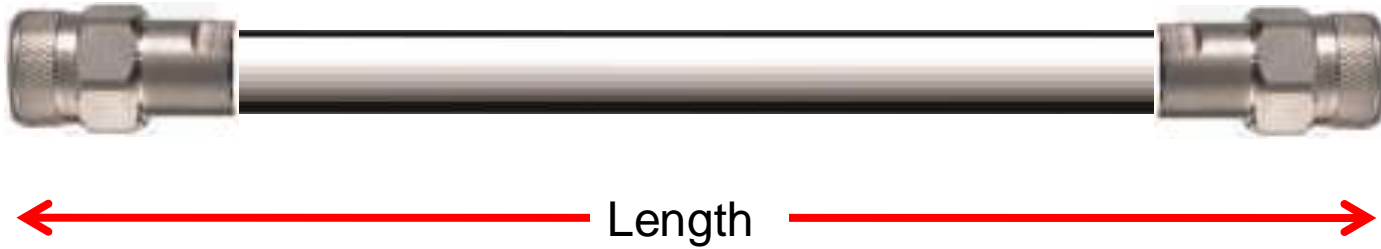
**Twinaxial
(shielded)**



Waveguide

Physical Length of a Transmission Line

When is a cable considered a “transmission line”?



Physical Length of a Transmission Line

When is a cable considered a “transmission line”?



$$\text{Length} \approx \lambda$$

Physical Length of a Transmission Line

When is a cable considered a “transmission line”?



← 1.2 meter (4 ft.) →

Example 1:

Frequency (f) = 1 kHz

$$\lambda = \frac{v_{coax}}{f} = \frac{3 \times 10^8 \text{ m/sec (VF)}}{1 \text{ kHz}} = 198 \text{ km}$$

1.2 meter cable is 0.000006λ (=0.002⁰)

Not considered a transmission line

Example 2:

Frequency (f) = 1 GHz

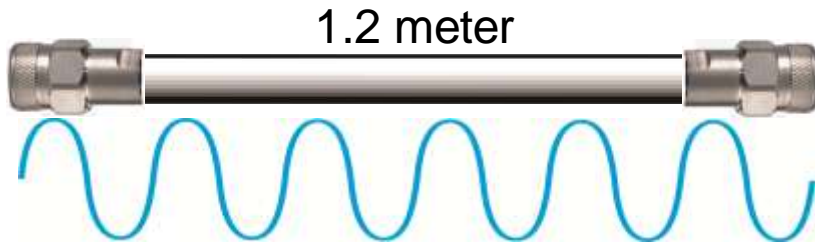
$$\lambda = \frac{v_{coax}}{f} = \frac{3 \times 10^8 \text{ m/sec (VF)}}{1 \text{ GHz}} = 0.198 \text{ m}$$

1.2 meter cable is 6.06λ (=2.2k⁰)

Yes, this is a transmission line

VF = 0.66 (cable datasheet)

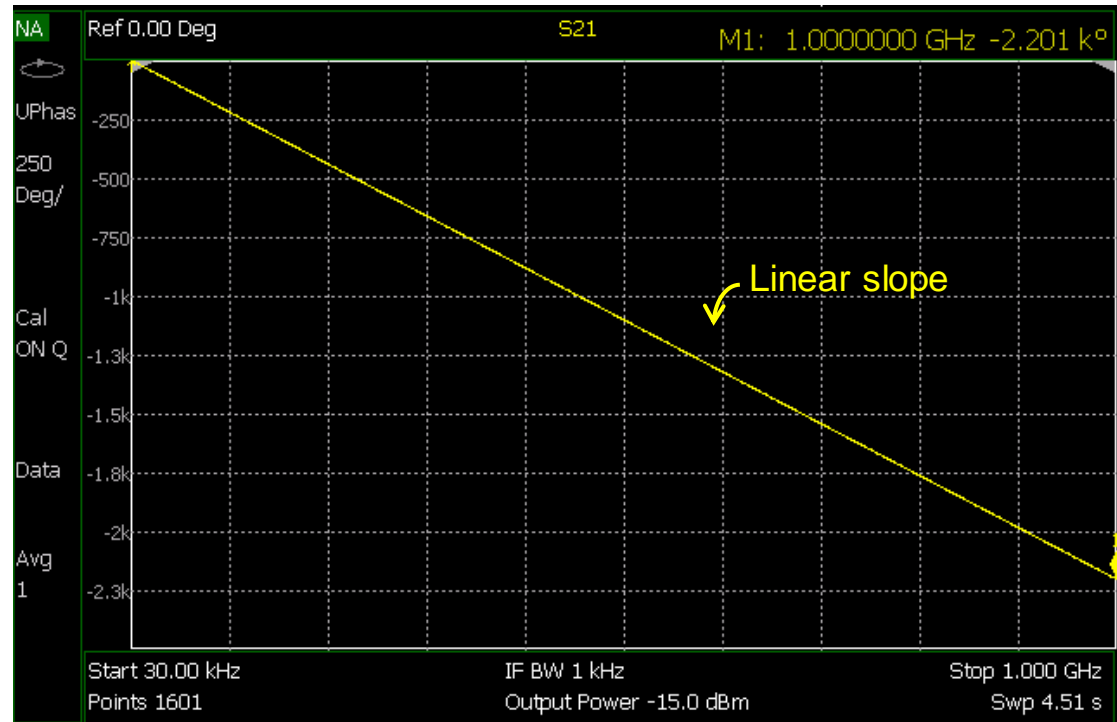
Measured S21 (Phase) vs. Frequency



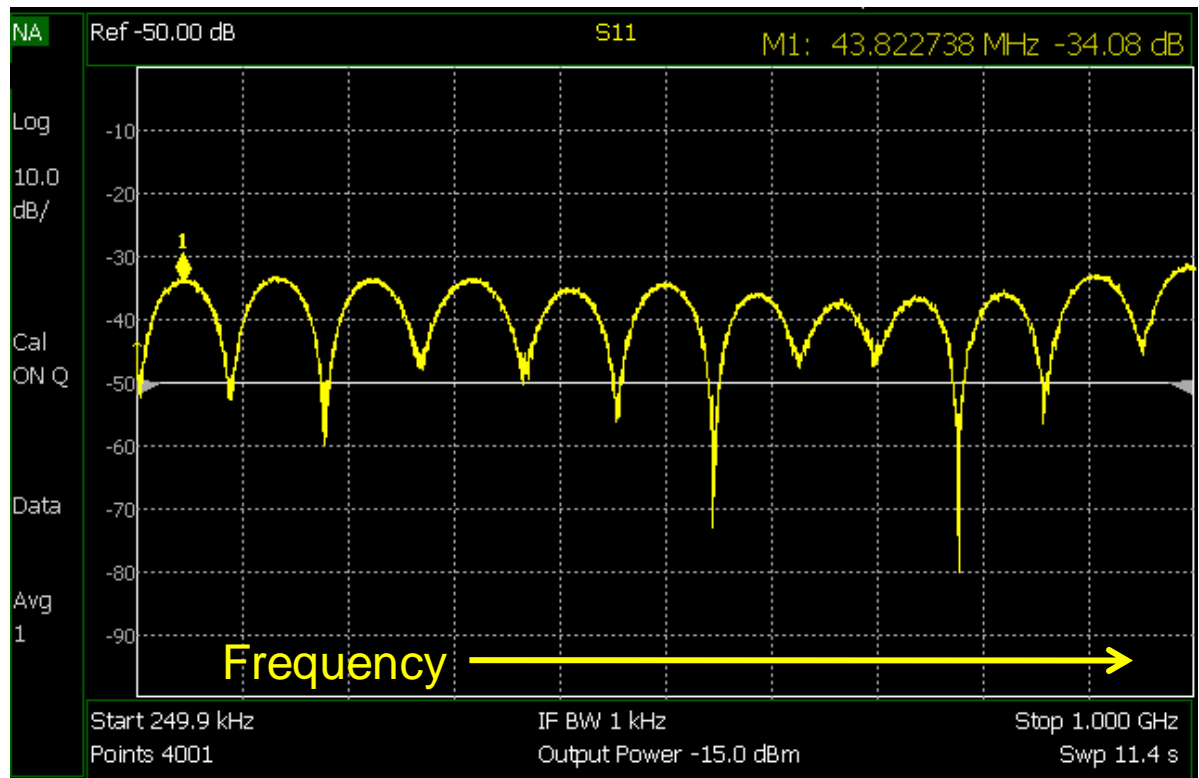
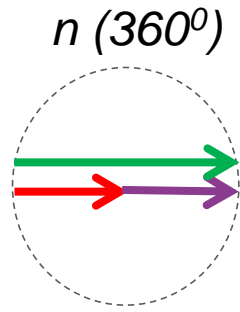
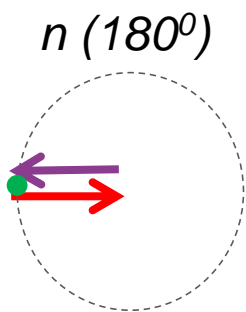
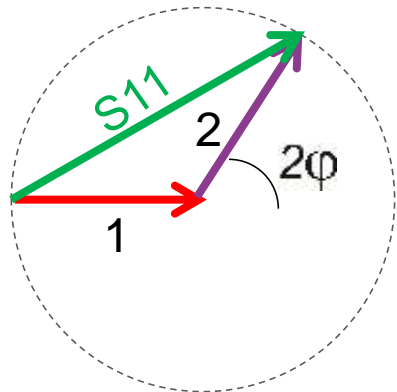
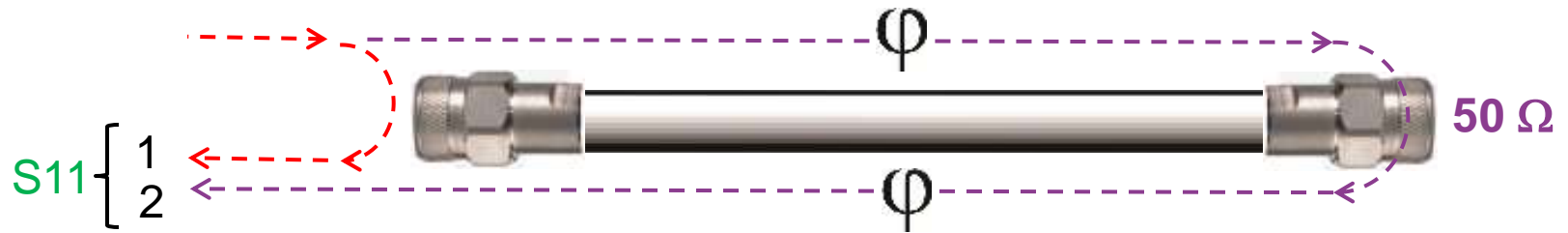
$$\text{@ 1GHz: } 6\lambda = 2.2\text{k}^\circ$$
$$(1\lambda = 360^\circ)$$

- Negative phase implies delay or lag
- Linear phase response = Non-dispersive medium
- Phase displayed in “wrapped” or “unwrapped” format.

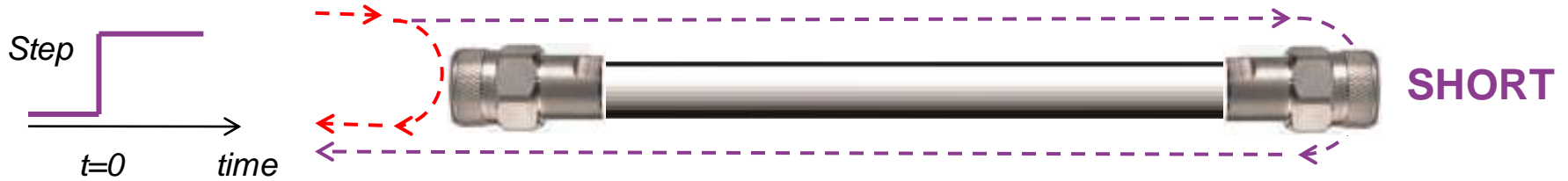
S21(unwrapped phase)



Measured S11 (dB) as a function of Frequency



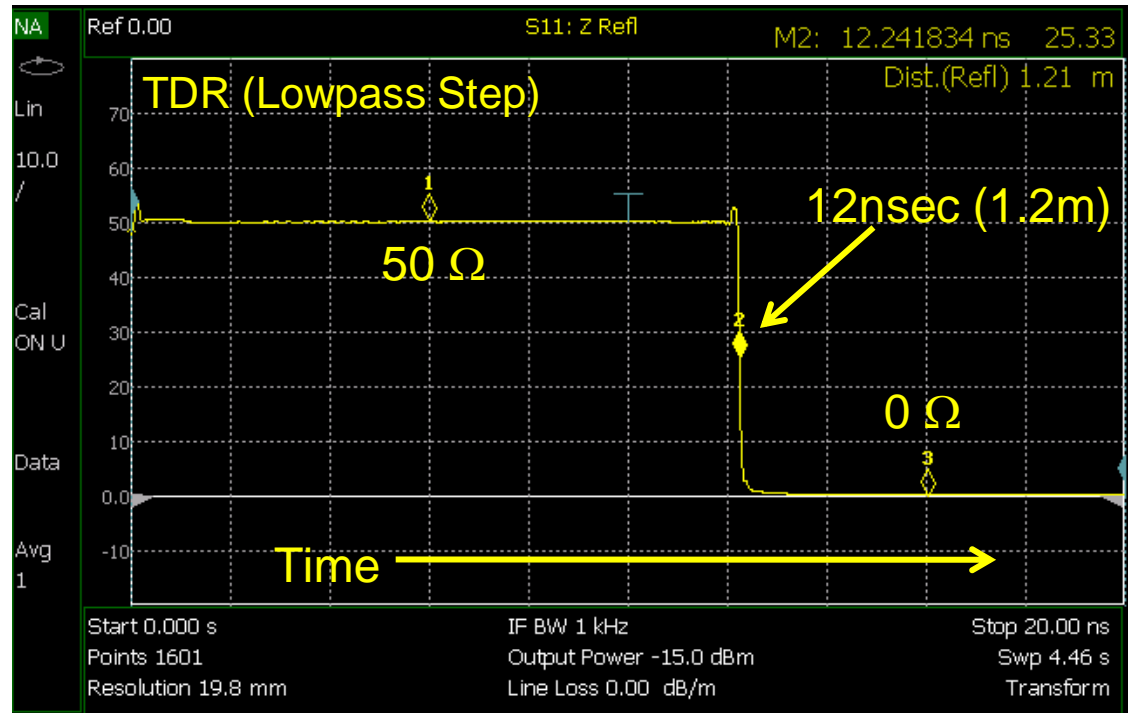
Measured S11 (Z) as a function of Time



Convert time to distance

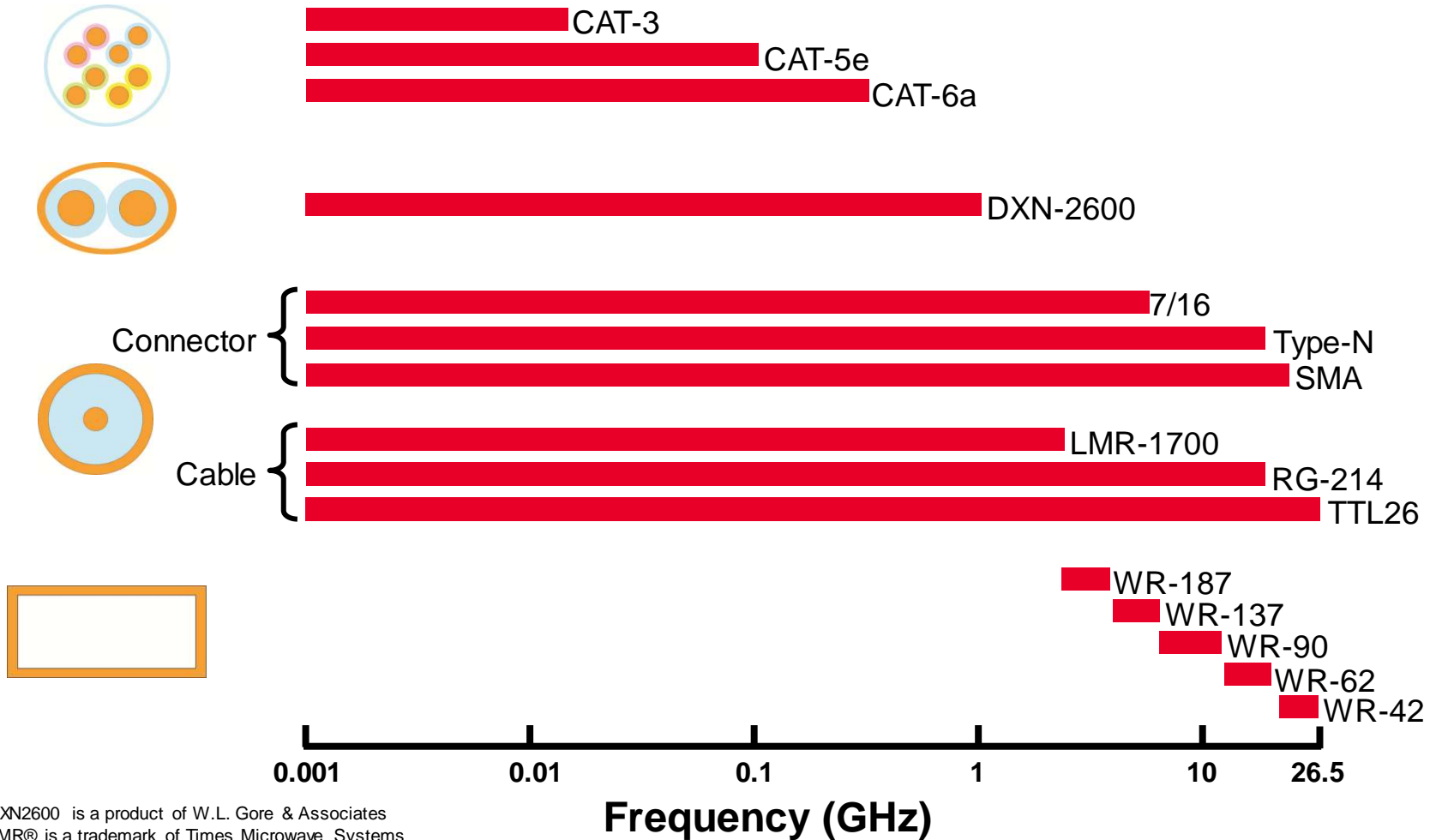
$$\text{distance} = \left(\frac{\text{time}}{2} \right) (v_{\text{coax}})$$

$$v_{\text{coax}} = (\text{VF})(c)$$



RG-214 Cable Length = 1.2 meter, Impedance = 50 ohms, Velocity Factor (VF) = 66%

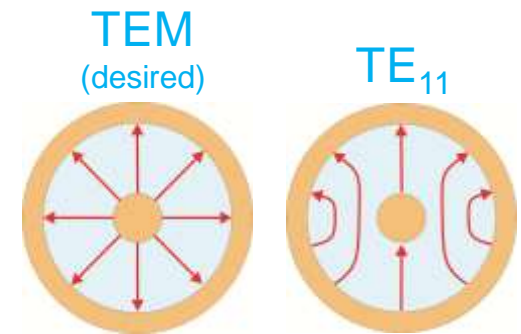
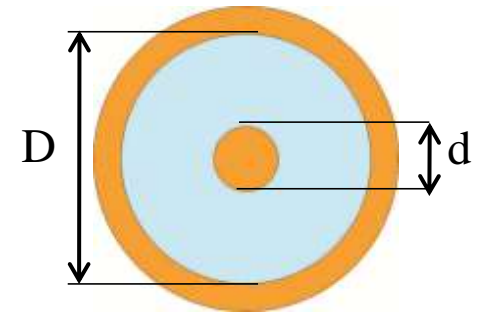
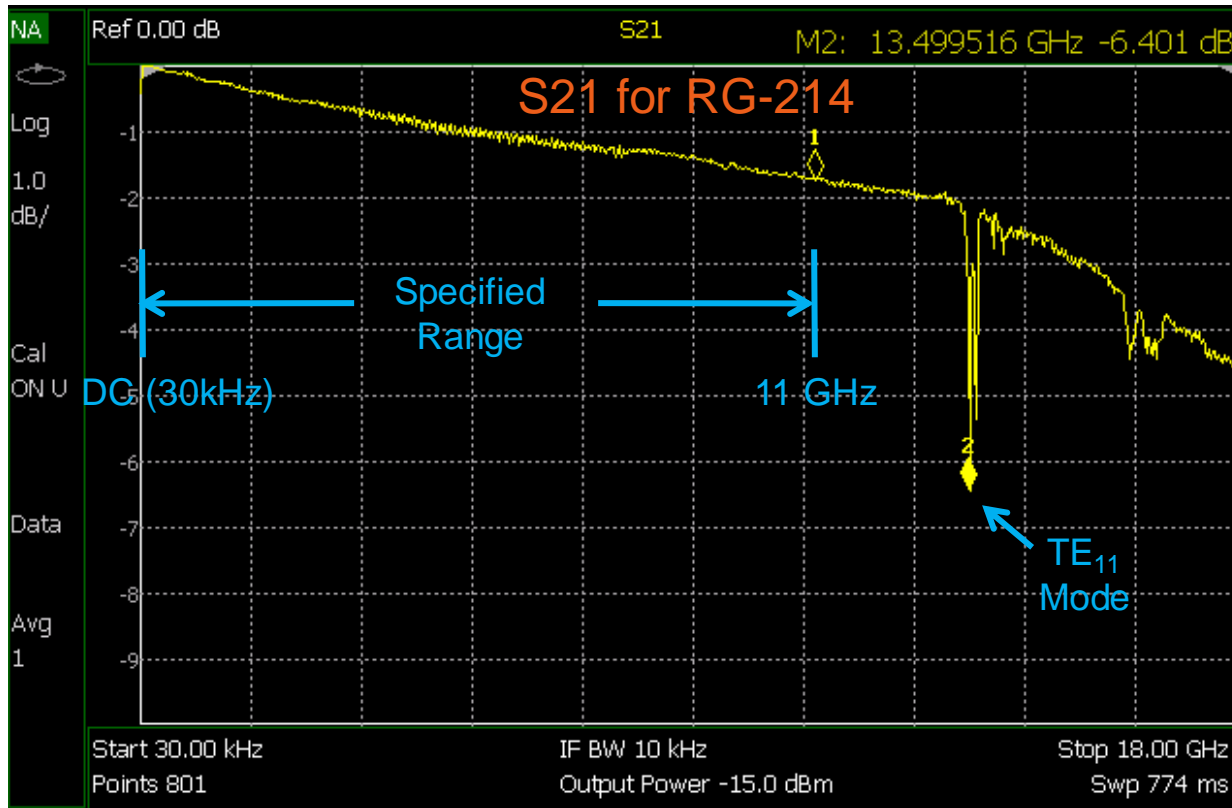
Frequency Range Specifications



DXN2600 is a product of W.L. Gore & Associates
 LMR® is a trademark of Times Microwave Systems
 TT26 is an Accuphase © cable from Carlisle Group

Frequency Limitations – Coaxial Cable

- RG-214 specified from DC to 11 GHz
- $f_{c, TE_{11}} = 13.1\text{GHz}$ (RG-214)



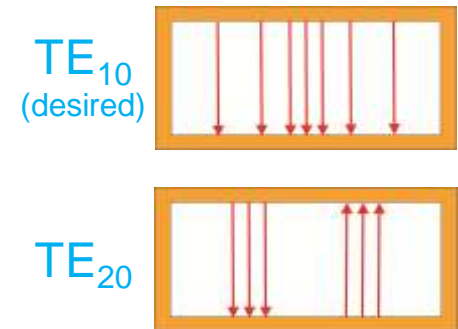
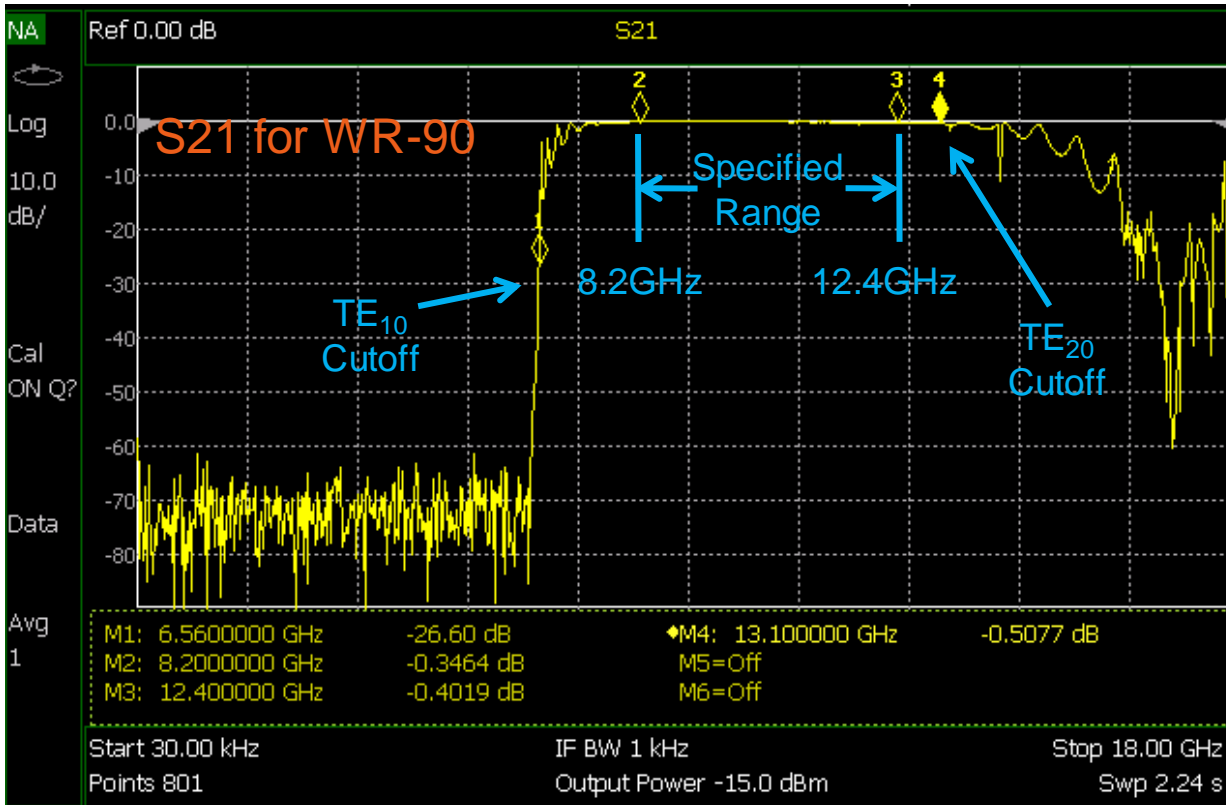
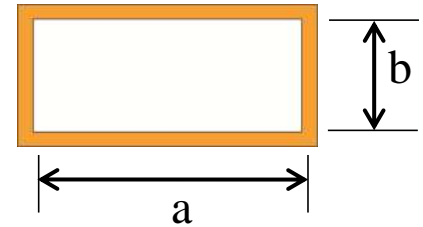
Coax TE₁₁ Mode:

$$f_{C, TE_{11}} \cong \frac{7.514}{(D + d)\sqrt{\epsilon_r}}$$

f in GHz, D & d in inches

Frequency Limitations - Waveguide

- Operates above $f_{c, TE10}$ and below $f_{c, TE20}$
- WR-90: $f_{c, TE10} = 6.56\text{GHz}$, $f_{c, TE20} = 13.1\text{GHz}$



Waveguide TE_{m0} Modes:

$$f_{c, m0} \cong \frac{m(c)}{2a\sqrt{\epsilon_r}}$$

f in GHz, D & d in inches

WR-90: a=0.9", b=0.4"

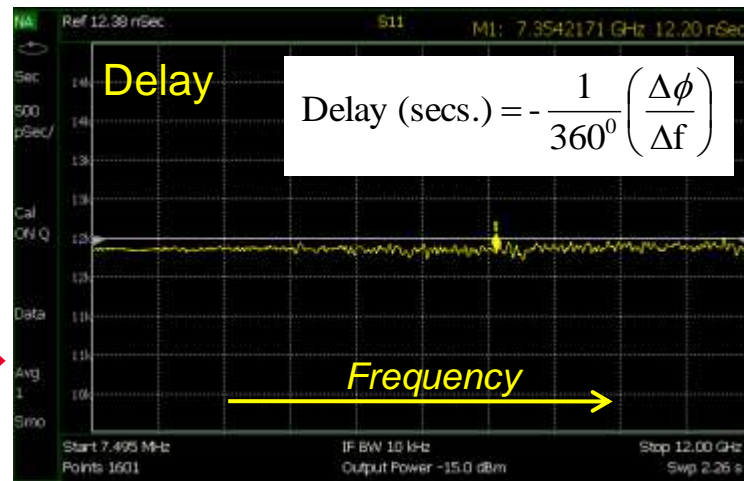
Measurement Types

- FieldFox measures s-parameters: S11, S21, S12, S22
- Calculate delay
- Calculate time domain response (step and impulse)

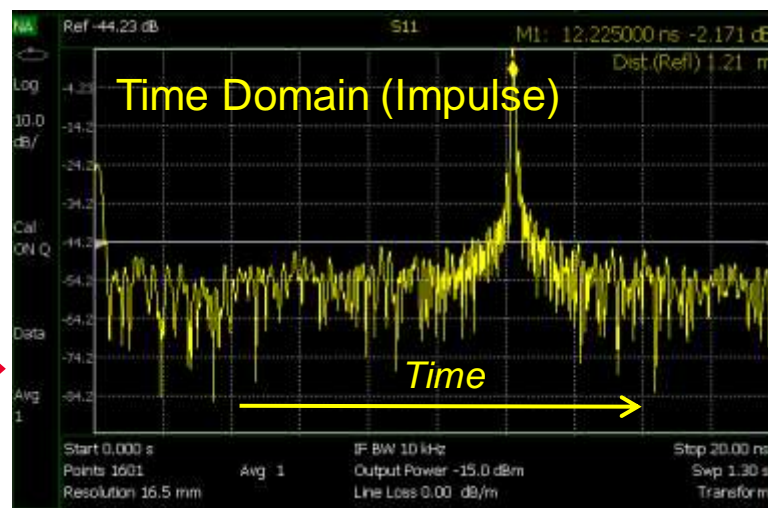
ϕ Slope 



IFFT 



Non-dispersive = "flat" response



VF required for distance calculations

$$VF = \frac{1}{\sqrt{\epsilon_r}} = \text{constant for coax}$$

Education Webcast Series

13

Insertion Loss Measurement Techniques

Traditional

- Both ends available
- Mechanical and ECal
- *CalReady* and *QuickCal*



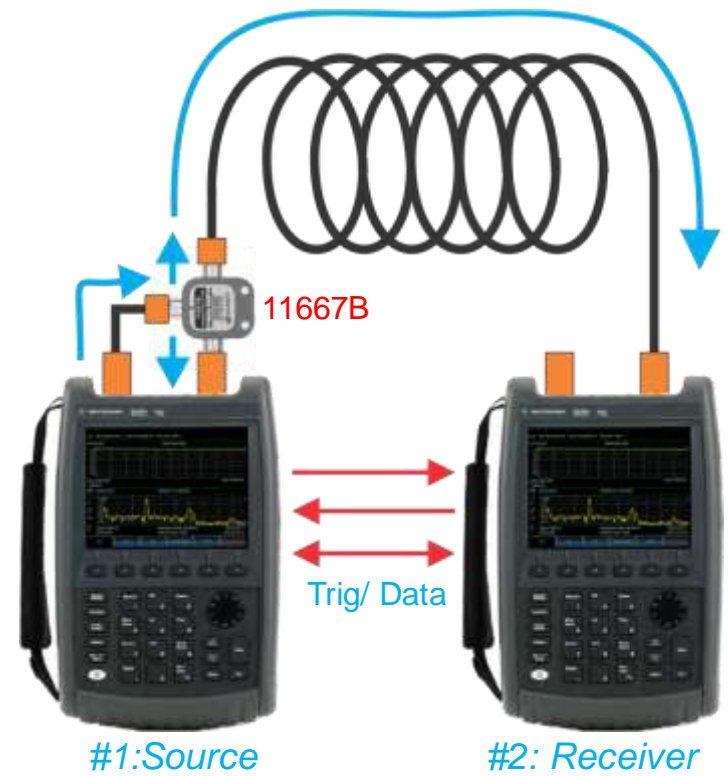
1-Port Loss

- Only one end available
- Low Loss (<30dB)



Extended Range (ERTA)

- High Dynamic Range
- No calibration or warm-up time
- Frequency Offset Capable

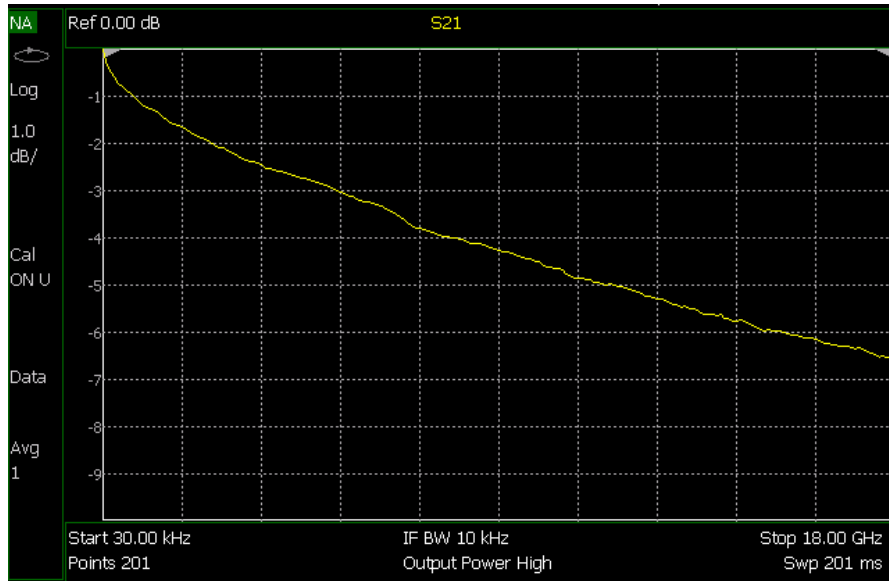


Low-Loss Cable Measurement

2-Port VNA



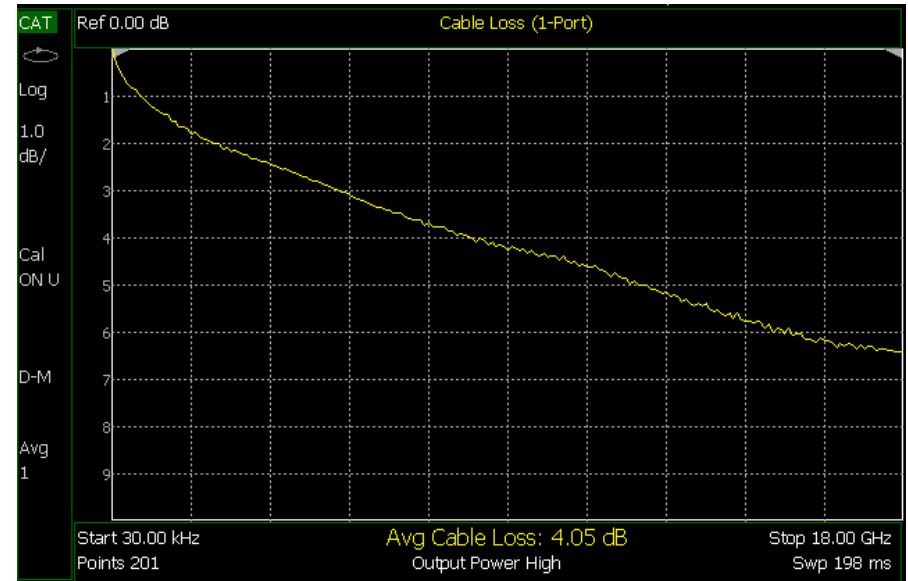
CableLoss (S21)



1-Port CAT



Cable Loss

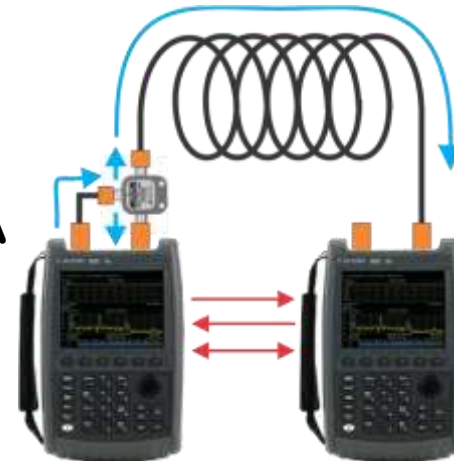


Long Cable Measurement

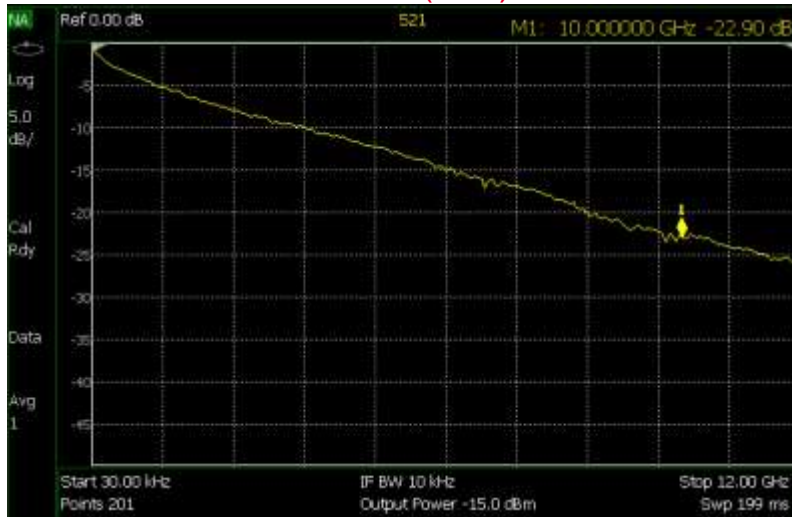
2-Port VNA



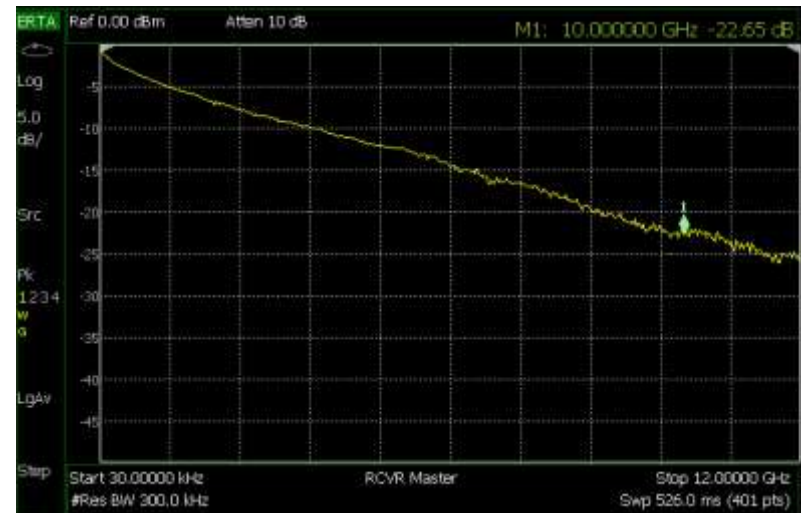
ERTA



Cable Loss (S21)



Cable Loss



100-foot Coaxial Cable, Type-N

Other Transmission Line Configurations

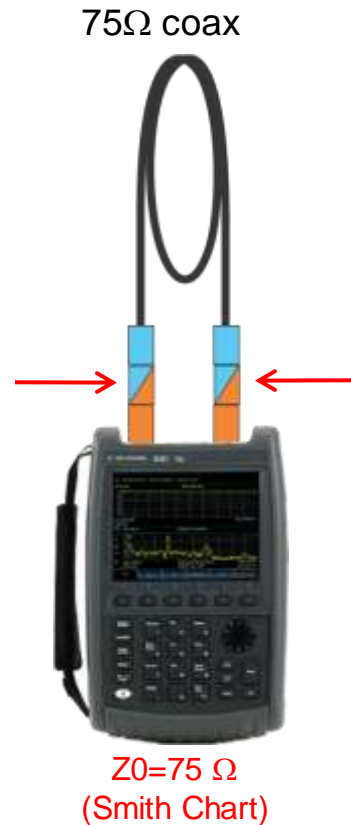
50Ω Cable

Direct
Connection



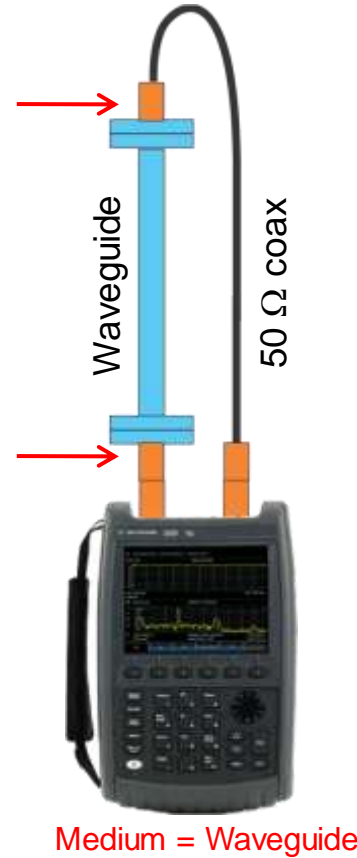
75Ω Cable

N9910X-846
50-75Ω adapter



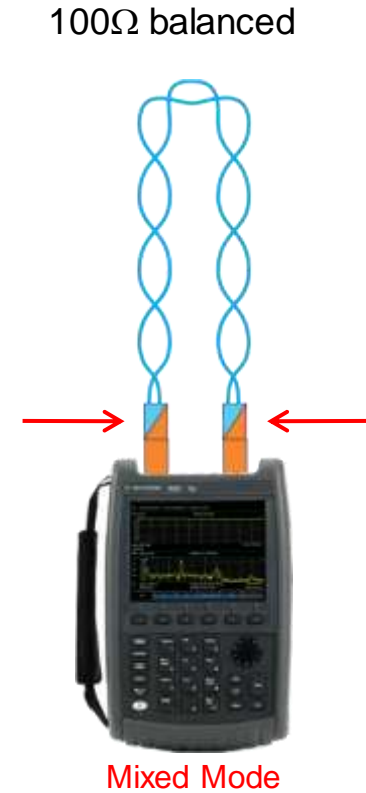
Waveguide

Coax-to-WG
Adapter



Twisted Pair

RJ45-to-SMA
Adapter or Balun



Troubleshooting Transmission Lines

CAT and VNA Modes

- Verify transmission line performance (line sweeping)
- Determine the location of damage (DTF)
- Determine the type of failure

Types of Faults

- Loose connector, flange screws
- Failed seal at a cable splice or flange (water ingress)
- Failed solder joint at connector interface
- Cut, crushed and/or weather-induced cracks
- Minimum bend radius exceeded
- Breakdown, and arcing effects

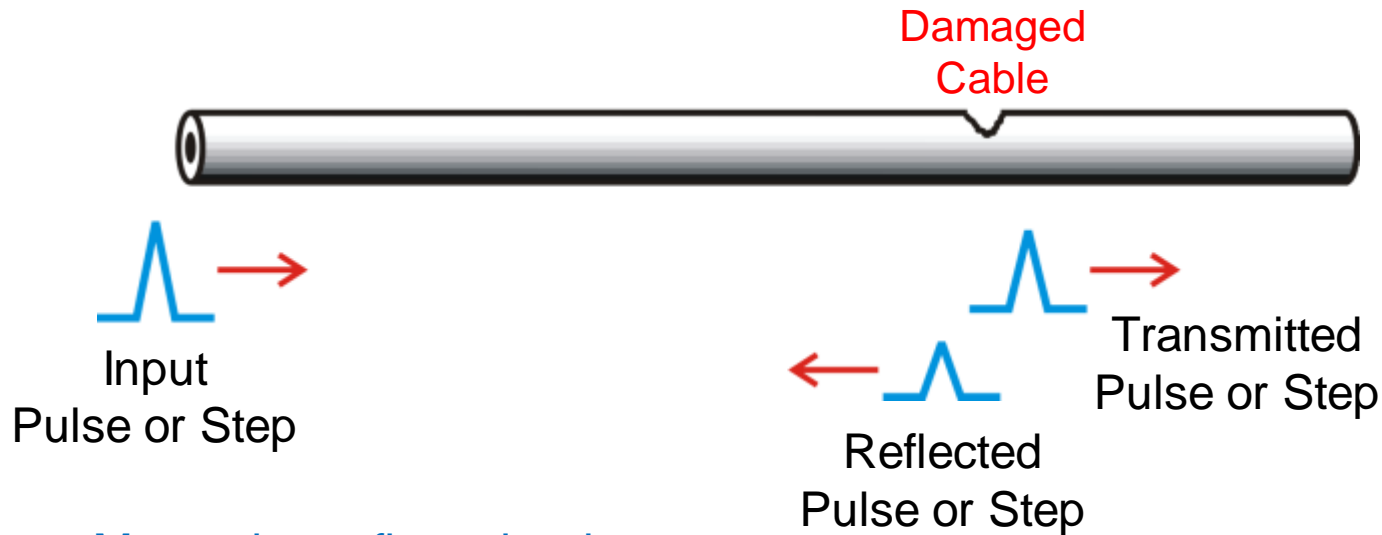
DTF = Distance to Fault



Images courtesy of John Arthur, Wireless EDGE

Distance to Fault (DTF) Measurements

Technique to determine the location of problems along a transmission line

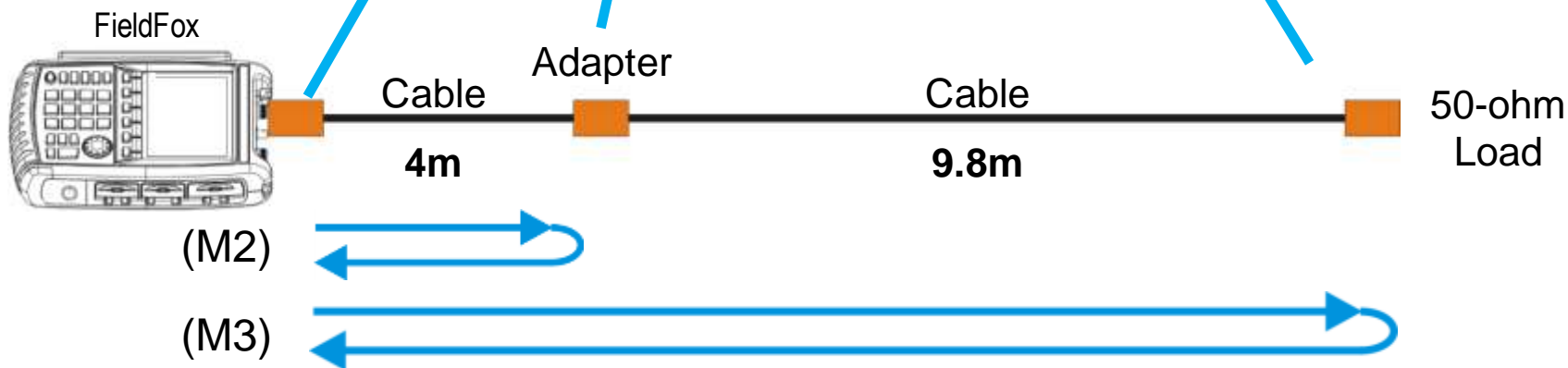
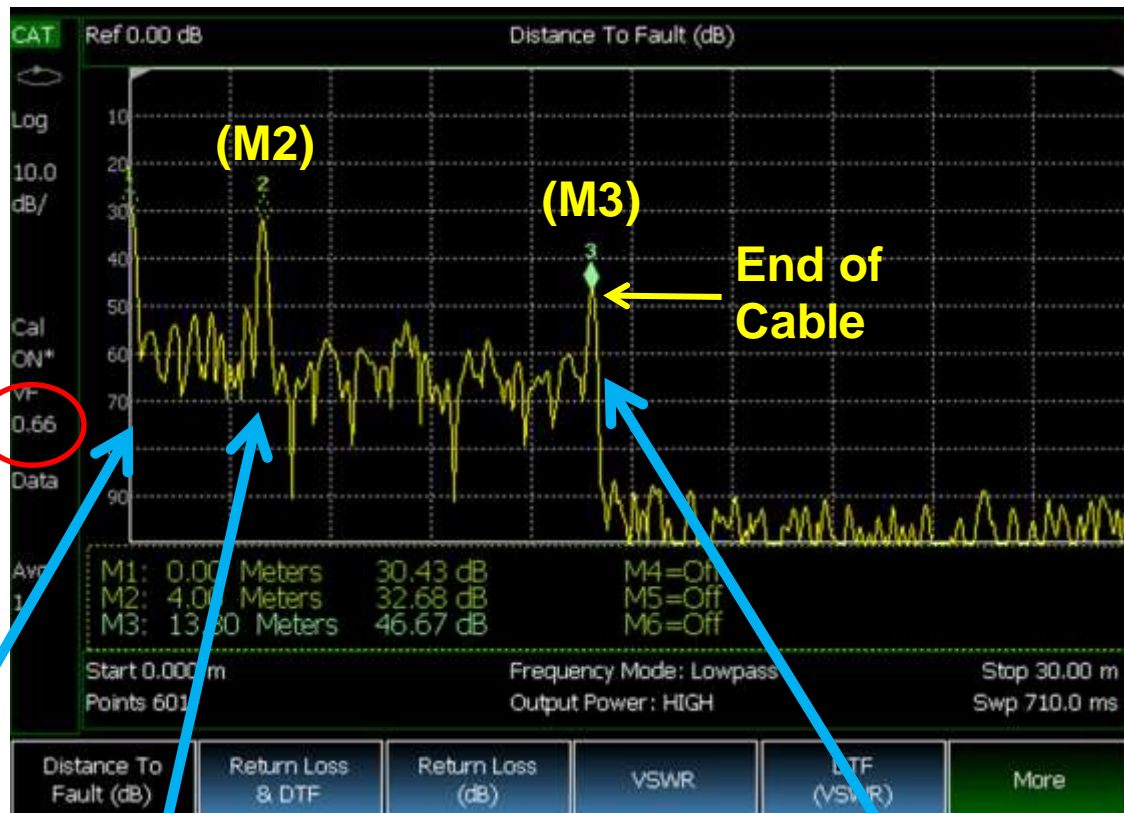


Measuring reflected pulse:

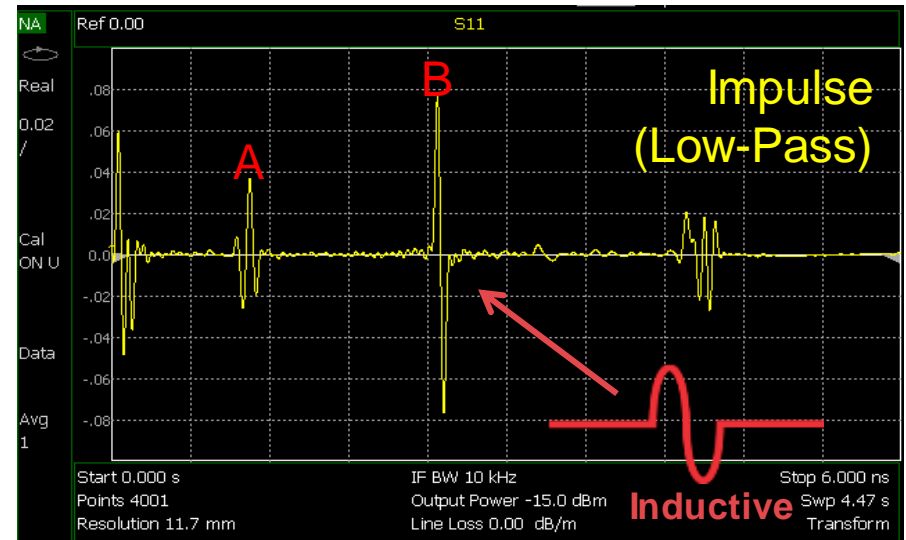
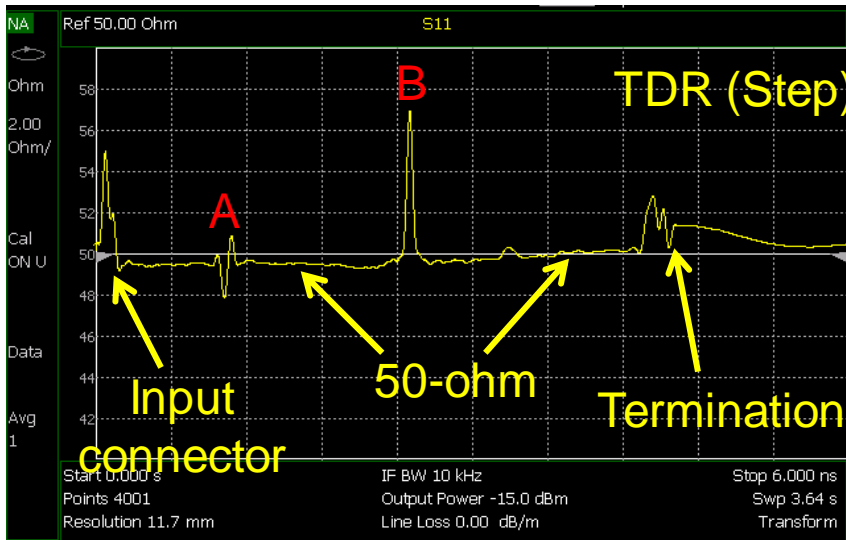
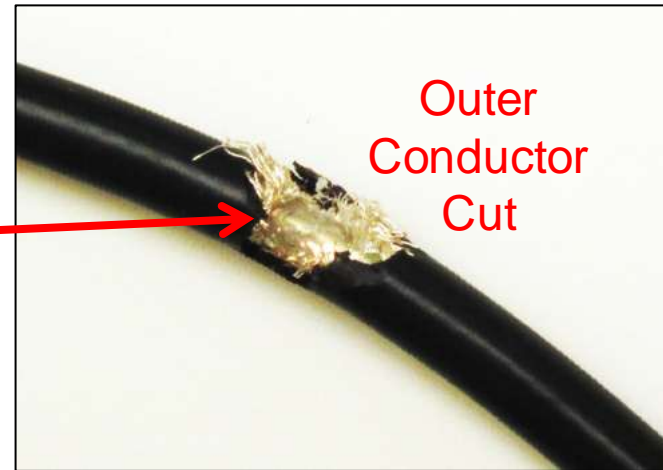
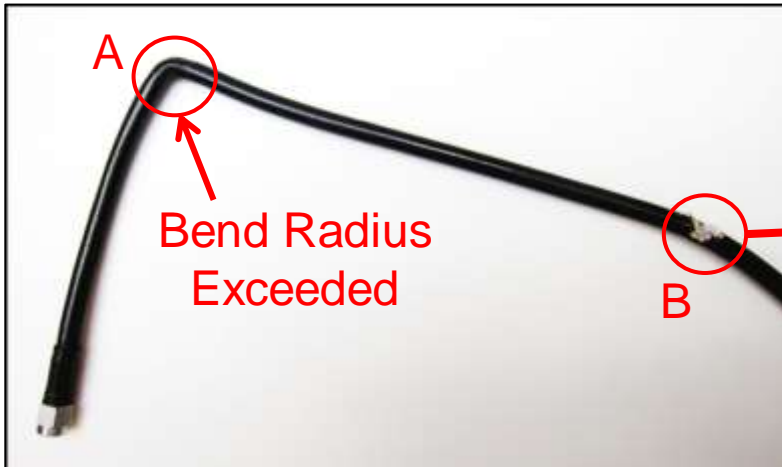
$$\begin{aligned} \text{DTF(meters)} &= \left[\frac{\text{time}_{\text{roundtrip}}}{2} \right] [v_{\text{cable}}] \\ &= \left[\frac{\text{time}_{\text{roundtrip}}}{2} \right] [(\text{VF})(c)] \end{aligned}$$

DTF For Coax









“Velocity Factor” (VF)



TDR and Impulse Response



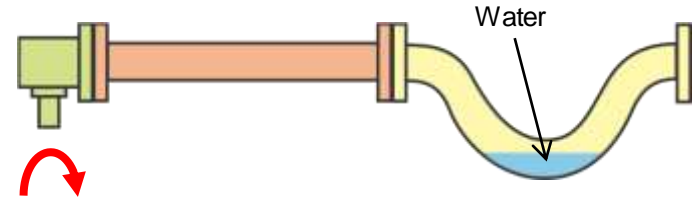
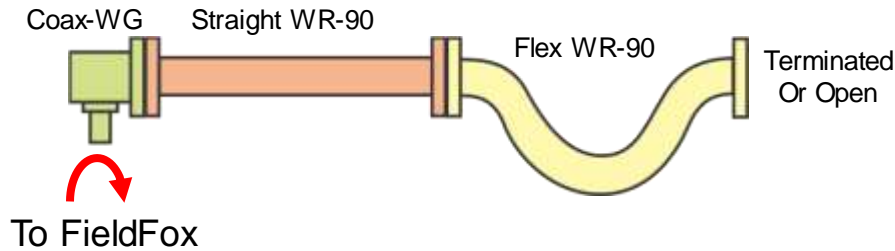
Types of Discontinuities

	TDR (Step)	Impulse (Low-Pass)
$R > Z_0$		
$R < Z_0$		
Inductor		
Capacitor		

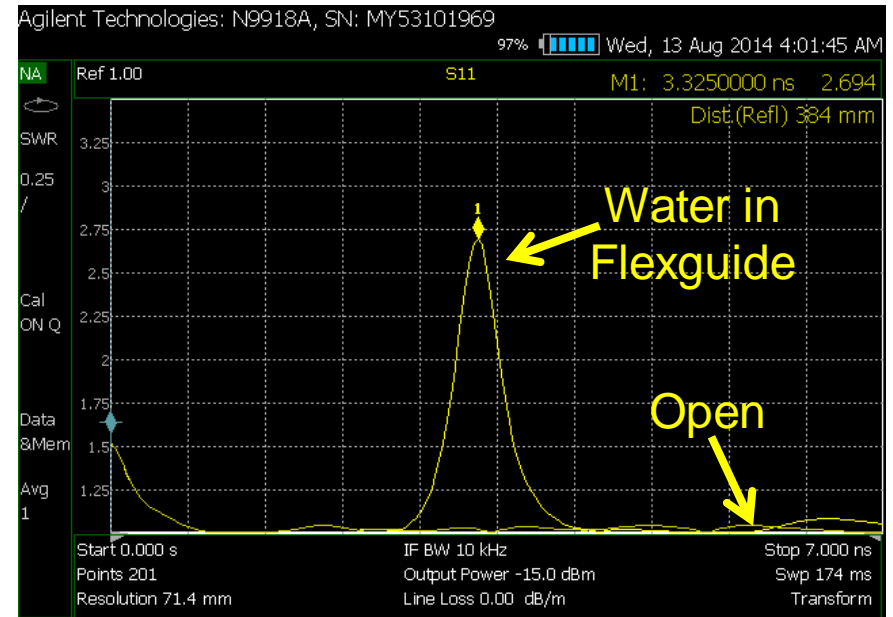
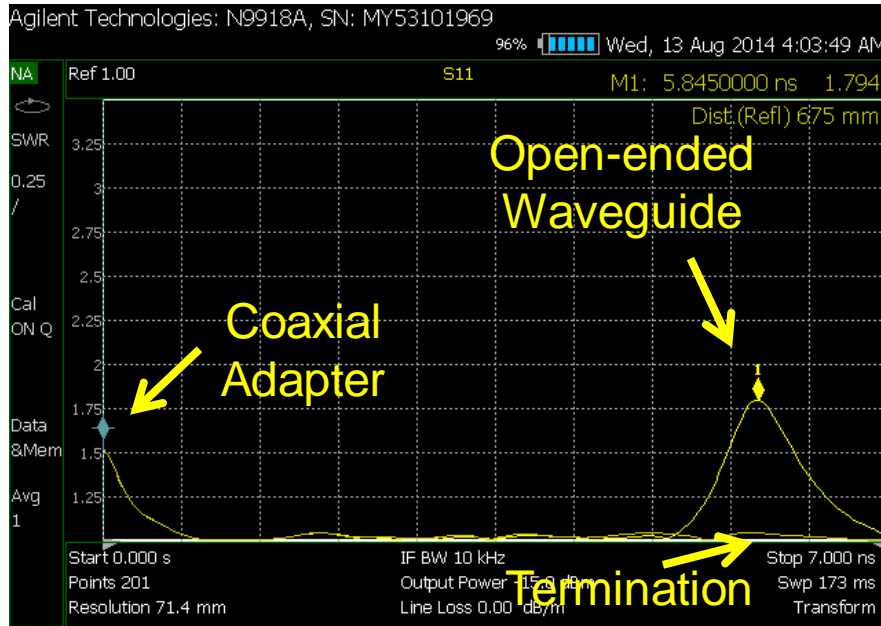
Step and Low-pass mode requires transmission line operation to DC

- Cable and Antenna Test Option includes TDR (Step)
- VNA option includes Step, Low-Pass Impulse, Band-Pass Impulse

DTF For Waveguide



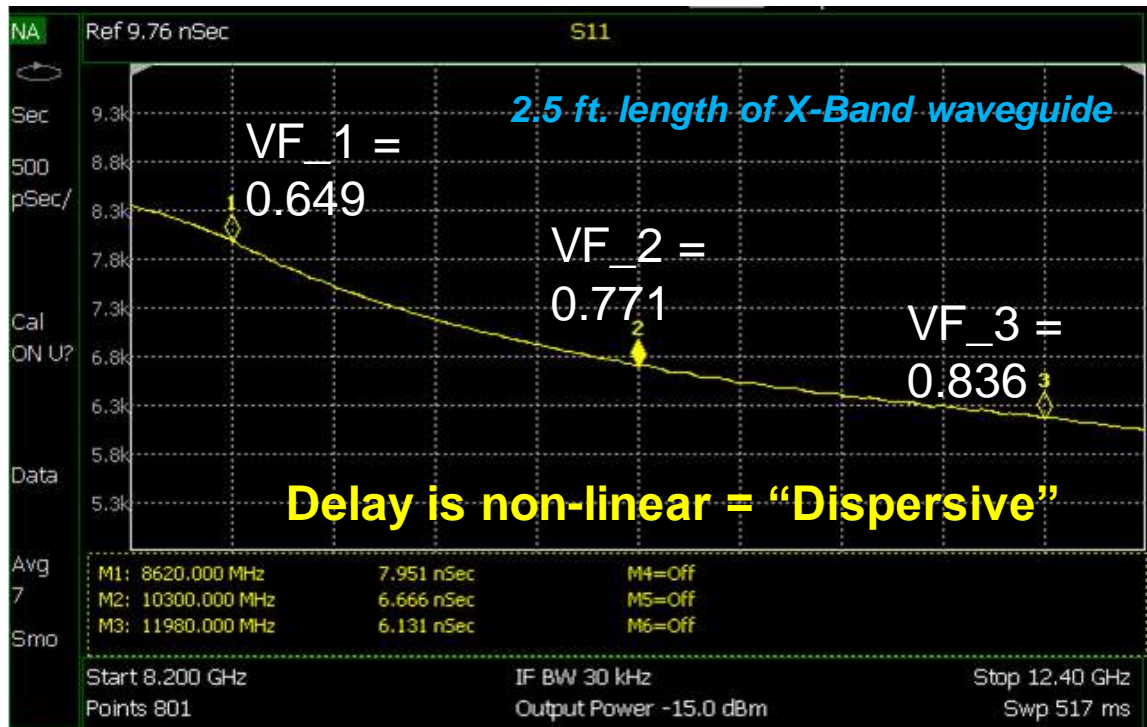
Bandpass Mode Required



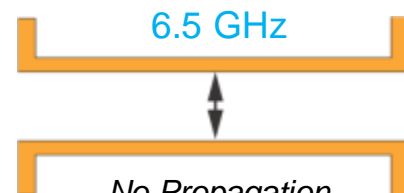
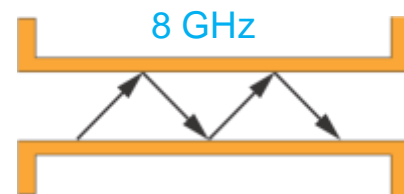
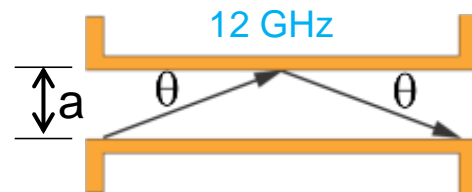
What about the VF for Waveguide?

Velocity Factor For Waveguide

Velocity Factor is a function of frequency



Cross section of Waveguide

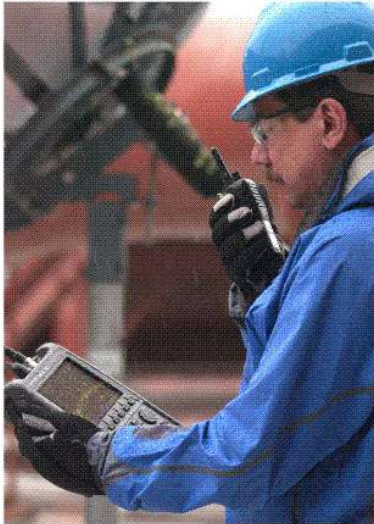


Time Domain Corrected for Non-linear VF

$$VF(f) = \sqrt{1 - \left(\frac{f_{cutoff}}{f}\right)^2}$$

Select "Waveguide" media on FieldFox

FieldFox Rugged to MIL-PRF-2880F Class 2



MIL-Spec durability

Meets MIL-PRF-28800F Class 2 requirements

Type tested and meets MIL-STD-810G, Method 511.5 Procedure 1 requirements for operation in explosive environments

Field-proof

Type tested to IP53: completely sealed instrument enclosure provides measurement stability in dusty and wet environments

3-year warranty ensures field confidence (standard on all FieldFox analyzers)

Low emissions, meets CISPR Pub 11, class B

Water-resistant chassis, keypad, and case withstand wide temperature ranges, and salty, humid environments

- Case withstands shock and vibrations
- Wide operating temperature -10 to +55 °C (+14 to +131 °F)
- Wide storage temperature -51 to +71 °C (-60 to +160 °F)



Keysight FieldFox Combination Analyzers

Combination Analyzers can be configured with the following capabilities

- Vector Network Analyzer (VNA)
- Cable and Antenna Test (CAT)
- Spectrum Analyzer
- Vector Voltmeter (VVM)
- Power Meter
- Independent Source

Models include frequencies up to **26.5 GHz**

- 6.6 pounds (3 kg)
- Built-in GPS
- 3.5 hour battery life



Carry precision with you - Keysight-quality measurements

Conclusions

- Transmission lines have lengths on the order of a wavelength
- Phase affects the magnitude response
- Operating frequency is limited by geometry
 - Two-conductor lines operate down to DC
 - Waveguide is narrowband
- Insertion loss can be measured several ways
- Troubleshooting faults requires a time domain response
- Non-dispersive lines have a linear phase slope
 - Coaxial lines are non-dispersive
 - Waveguide is dispersive
- With industry's best transmission line measurement capability, FieldFox is the ideal tool for testing in the field

For More Information

Web: www.keysight.com/find/FieldFox

Literature:

- *Techniques for Precise Interference Measurements in the Field*, Application Note, Literature Number 5991-0418EN
- *Techniques for Precise Cable and Antenna Measurements in the Field*, Application Note, Literature Number 5991-0419EN
- *Correlating Microwave Measurements between Handheld and Benchtop Analyzers*, Application Note, Literature Number 5991-0422EN
- *Techniques for Precise Measurement Calibrations in the Field*, Application Note, Literature Number 5991-0421EN
- *Techniques for Precision Validation of Radar System Performance in the Field*, Application Note, Literature Number 5991-4107EN

FieldFox handheld education application webcast series

Registration: www.keysight.com/find/FieldFoxWebcasts

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Thank you for your time. Questions?

