Transmission Line Theory and Advanced Measurements in the Field

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On Contract to
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KEYSIGHT TECHNOLOGIES

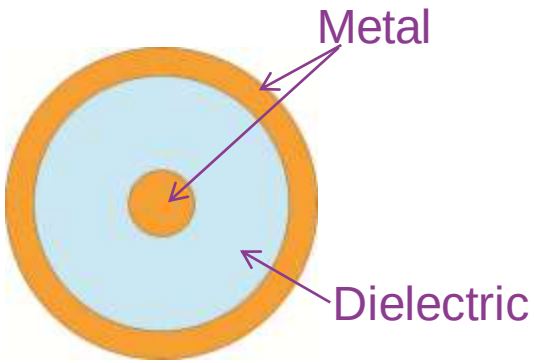
Keysight FieldFox Education Webcast Series

Agenda

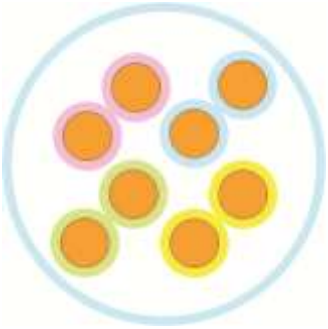
- Transmission Line Basics
- Frequency and Time Measurements
- Frequency Limitations of Connectors and Cables
- Measuring Insertion Loss
  - One-Port Techniques
  - Very Long Cables
- Troubleshooting Line Faults
  - TDR and Impulse Modes
  - Examples of Cable and Waveguide Damage
  - Velocity Factor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

Types of Common Transmission Lines

Cross Section

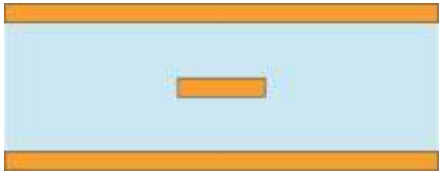


Coaxial



Twisted Pair (unshielded)

Microstrip (PCB)



Stripline (PCB)

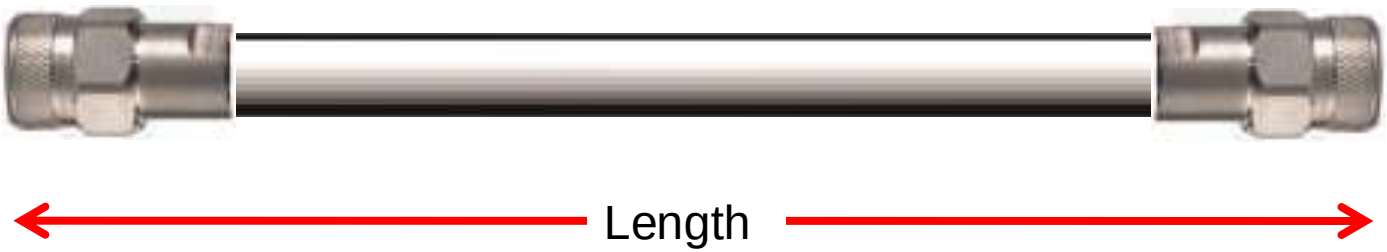
Twin-lead

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”?

$$\text{Length} \gtrsim \lambda$$

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

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

1.2 meter cable is 0.000006λ ($=0.002^0$)

Not considered a transmission line

Example 2:
Frequency (f) = 1 GHz

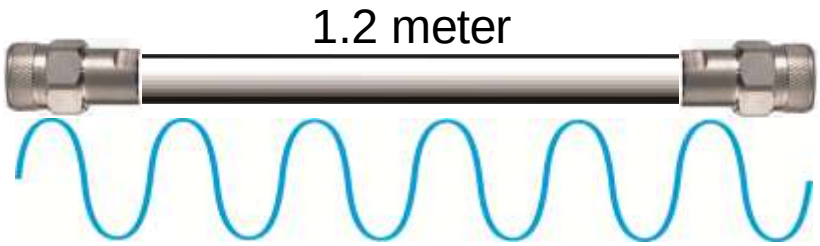
$$\lambda = \frac{v_{coax}}{f} = \frac{3\text{x}10^8\,\text{m/sec (VF)}}{1\text{GHz}} = 0.198\text{m}$$

1.2 meter cable is 6.06λ ($=2.2k^0$)

Yes, this is a transmission line

VF = 0.66 (cable datasheet)

Measured S21 (Phase) vs. Frequency

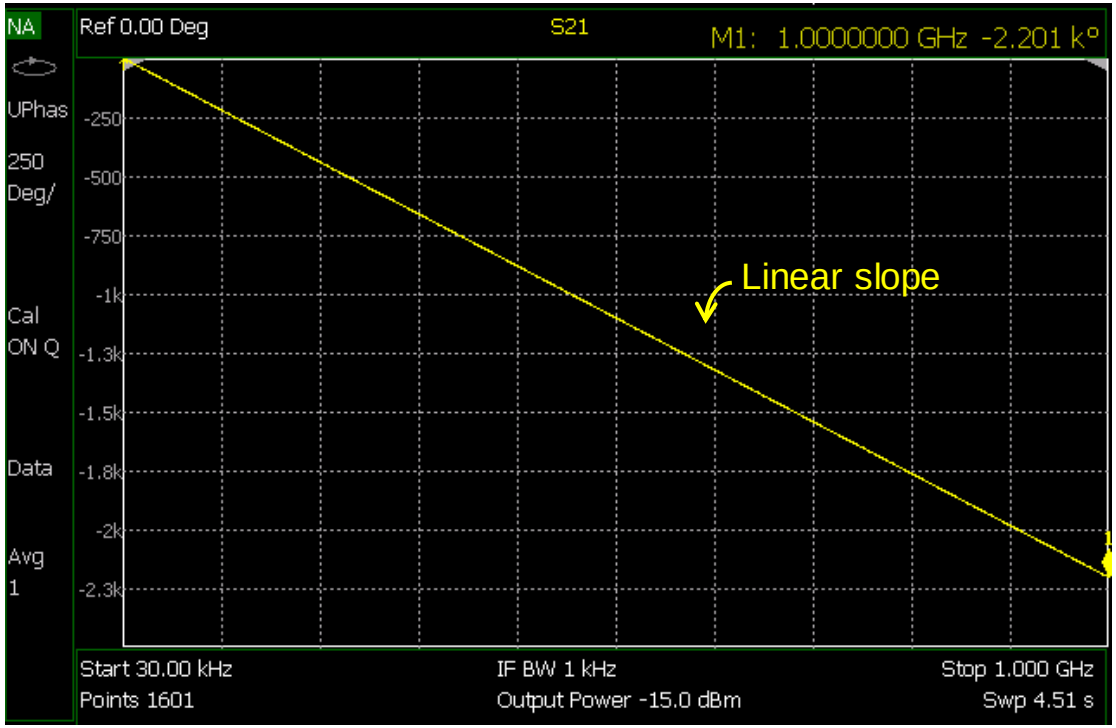


@1GHz: $6\lambda = 2.2k^0$

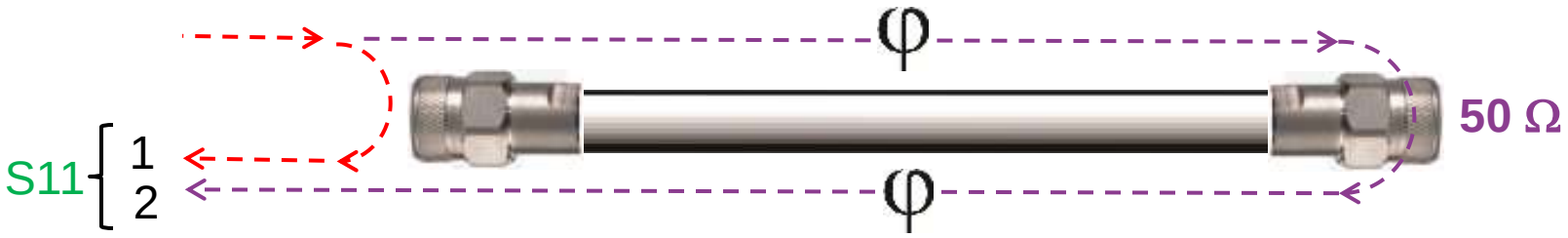
$(1\lambda = 360^0)$

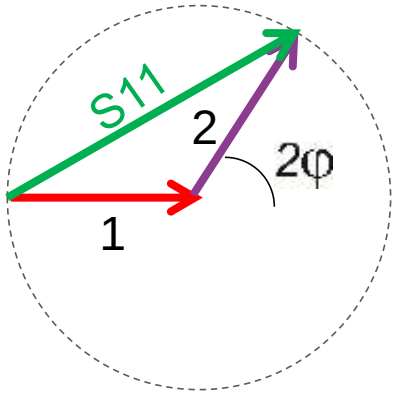
- Negative phase implies delay or lag
- Linear phase response = Non-dispersive medium
- Phase displayed in “wrapped” or “unwrapped” format.

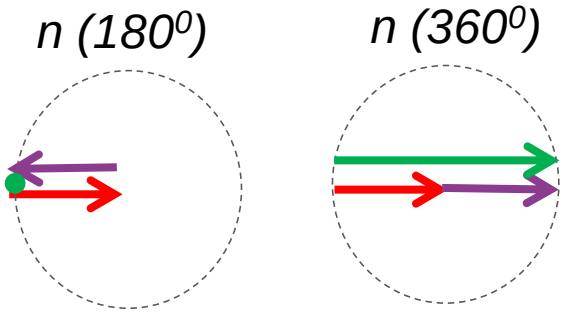
S21(unwrapped phase)

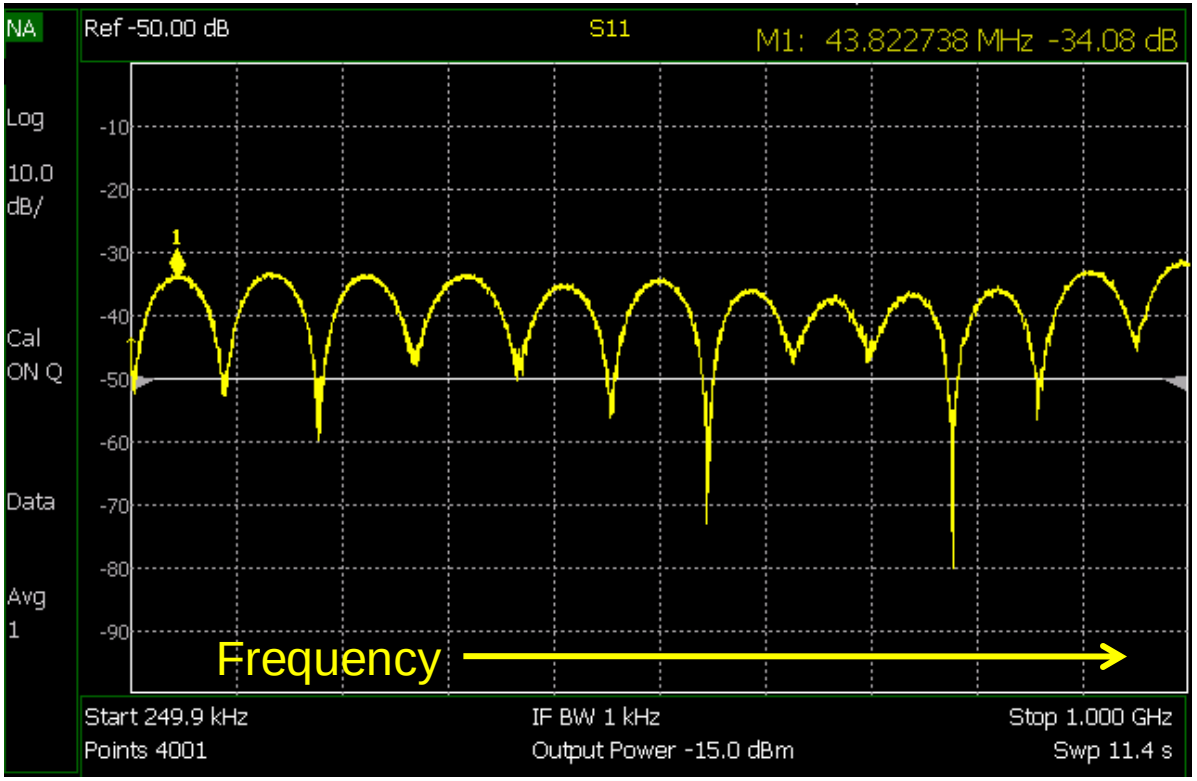


Measured S11 (dB) as a function of Frequency

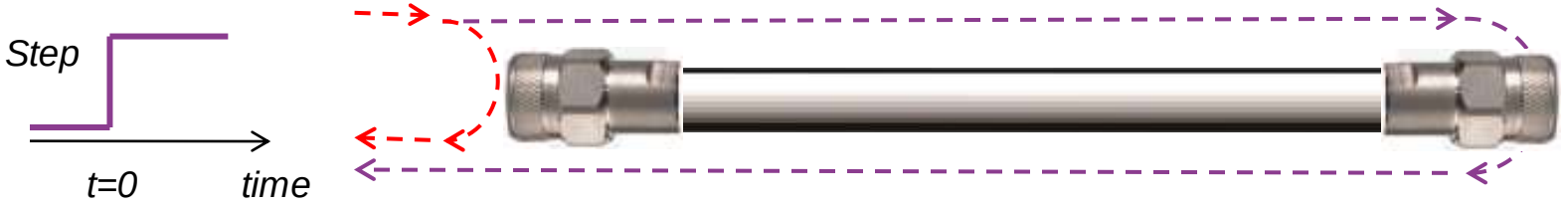


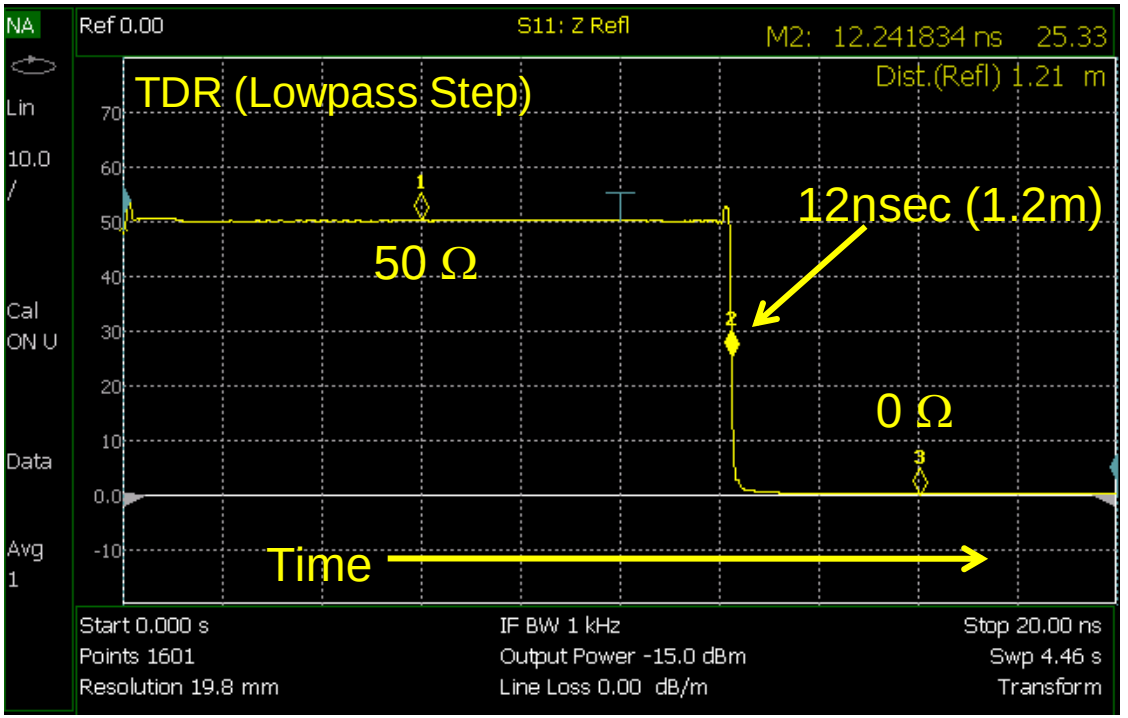






Measured S11 (Z) as a function of Time





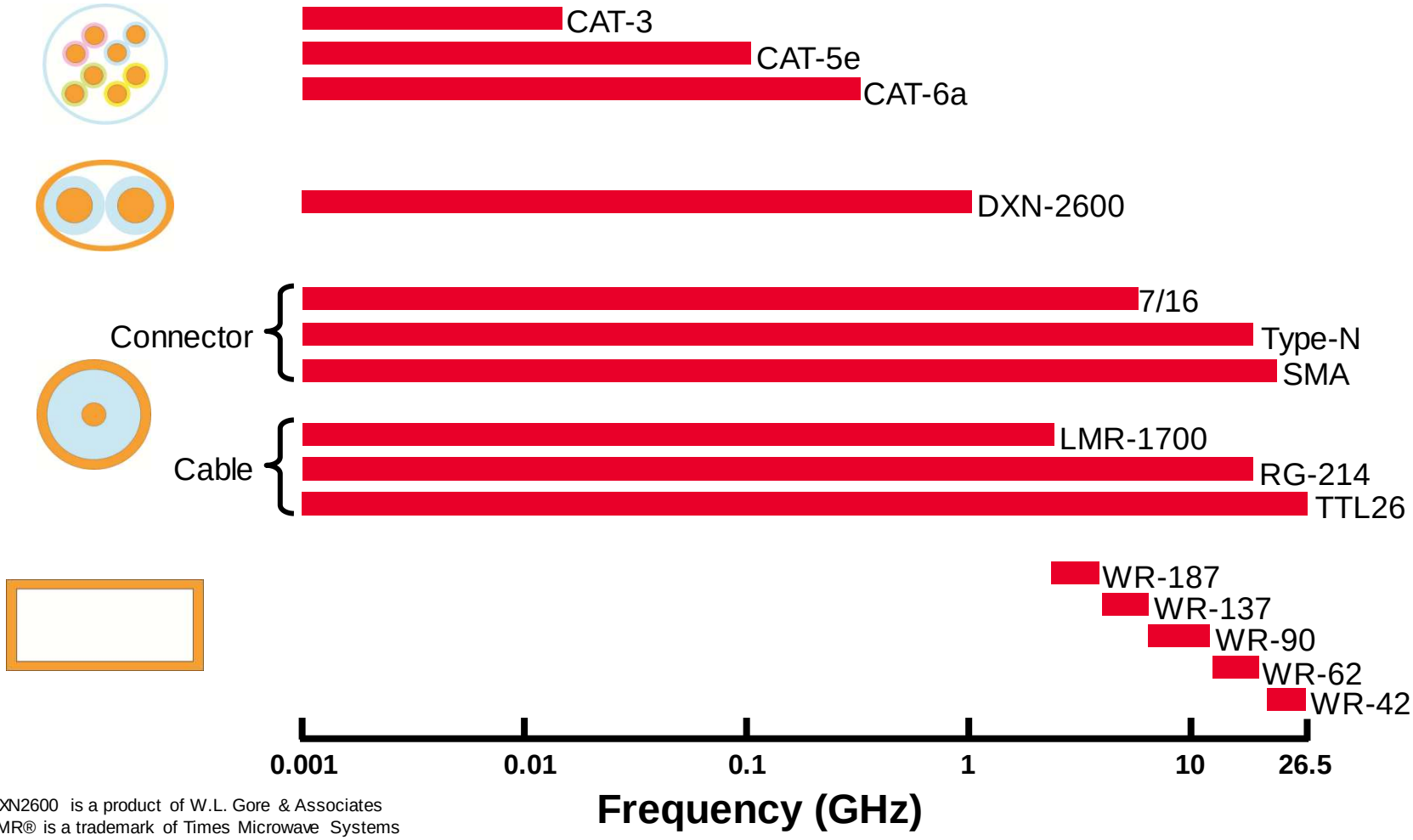
Convert time to distance

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

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

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

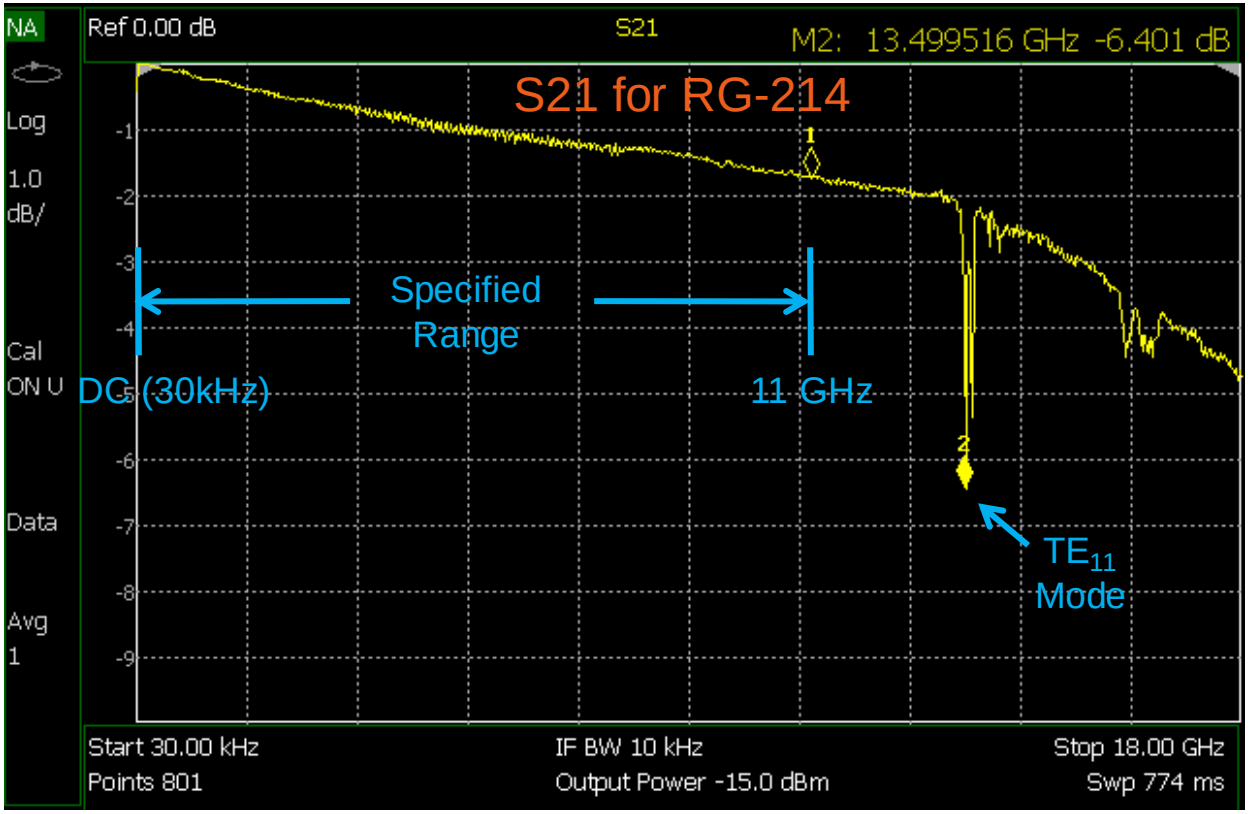
Frequency Range Specifications

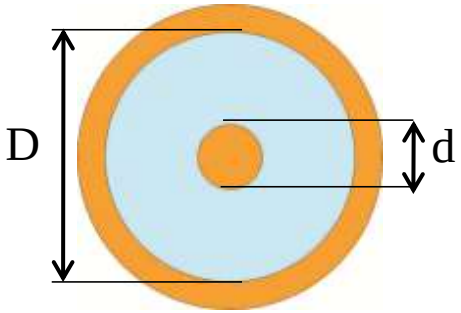


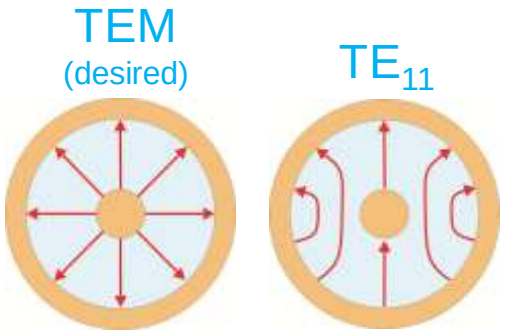
DXN2600 is a product of W.L. Gore & Associates
LMR® is a trademark of Times Microwave Systems
TT26 is an Accuphase ® cable from Carlisle Group

Frequency Limitations – Coaxial Cable

- RG-214 specified from DC to 11 GHz
- $f_{c,\ TE11}$ = 13.1GHz (RG-214)







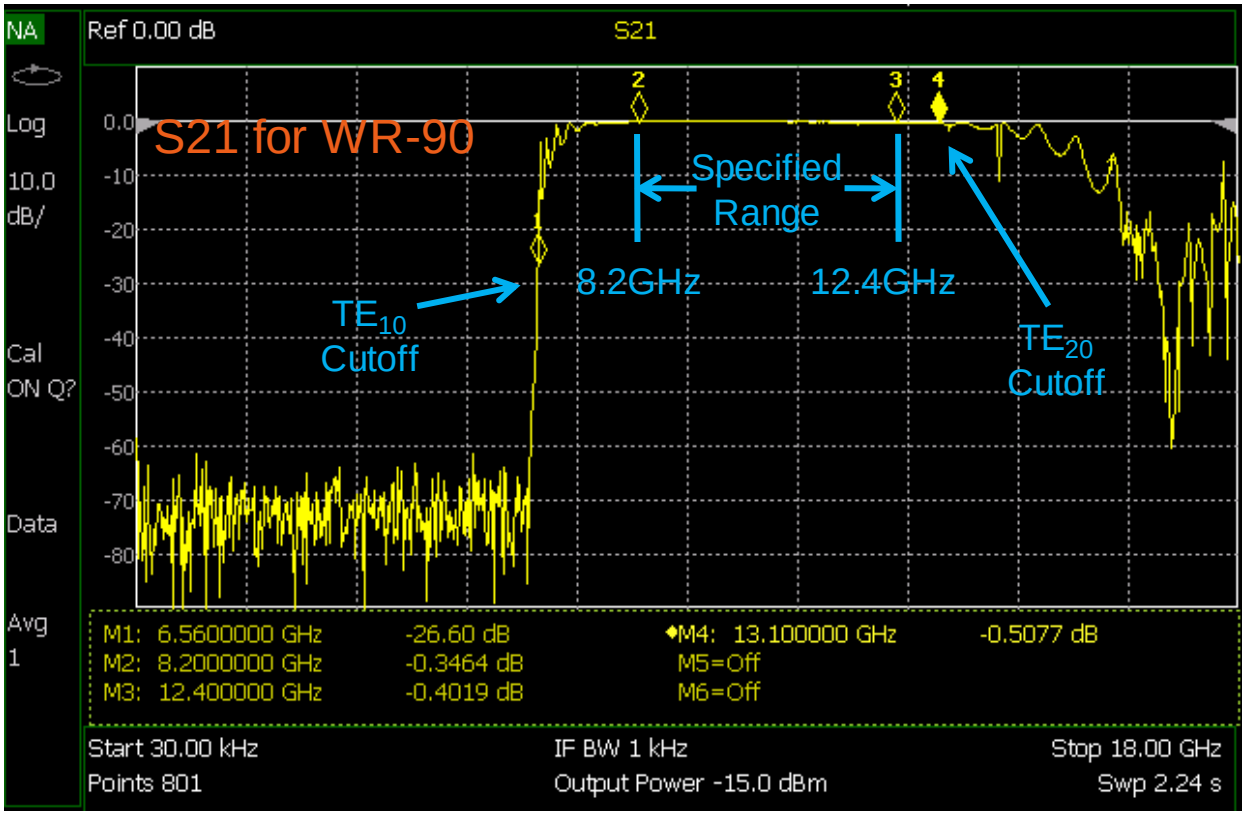
Coax TE_{11} Mode:

$$f_{C,\mathrm{TE}_{11}} \cong \frac{7.514}{(\mathrm{D}+\mathrm{d})\sqrt{\varepsilon_r}}$$

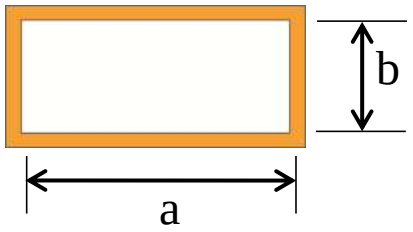
f in GHz, D & d in inches

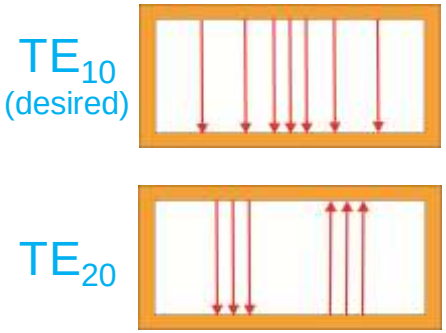
Frequency Limitations - Waveguide

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



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





Waveguide TE_{m0} Modes:

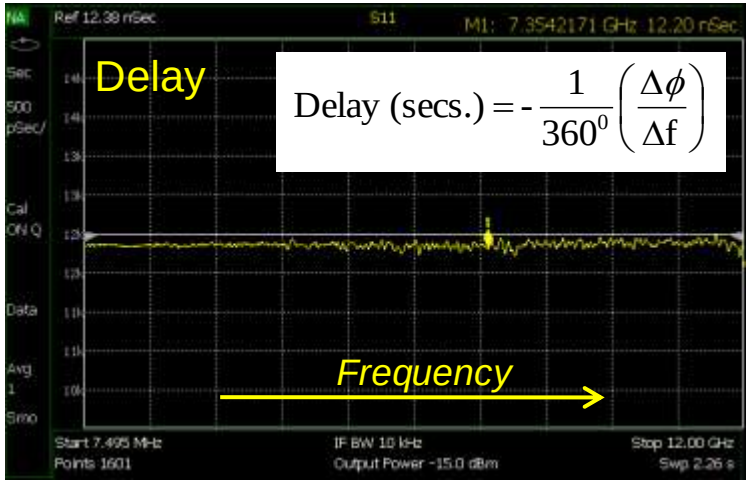
$$f_{C,\mathrm{m0}} \cong \frac{m(c)}{2a\sqrt{\varepsilon_r}}$$

f in GHz, D &d in inches

Measurement Types

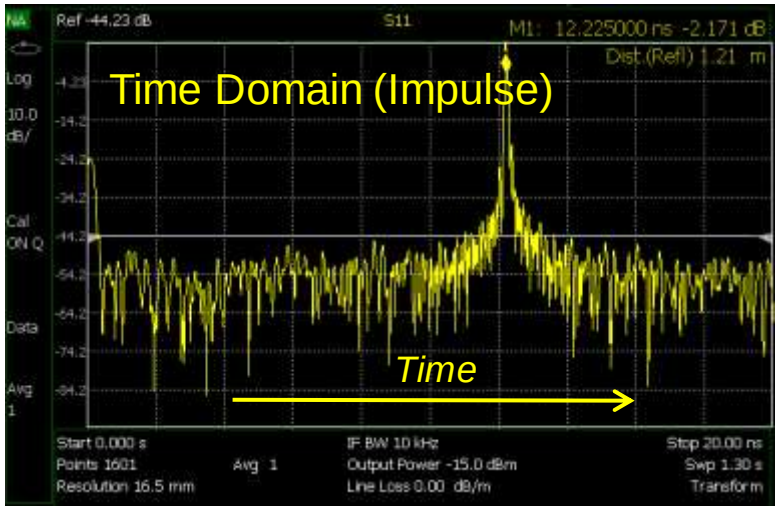
- FieldFox measures s-parameters: S11, S21, S12, S22
- Calculate delay
- Calculate time domain response (step and impulse)

ϕ Slope



Non-dispersive = "flat" response

IFFT



VF required for distance calculations

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

Insertion Loss Measurement Techniques

Traditional

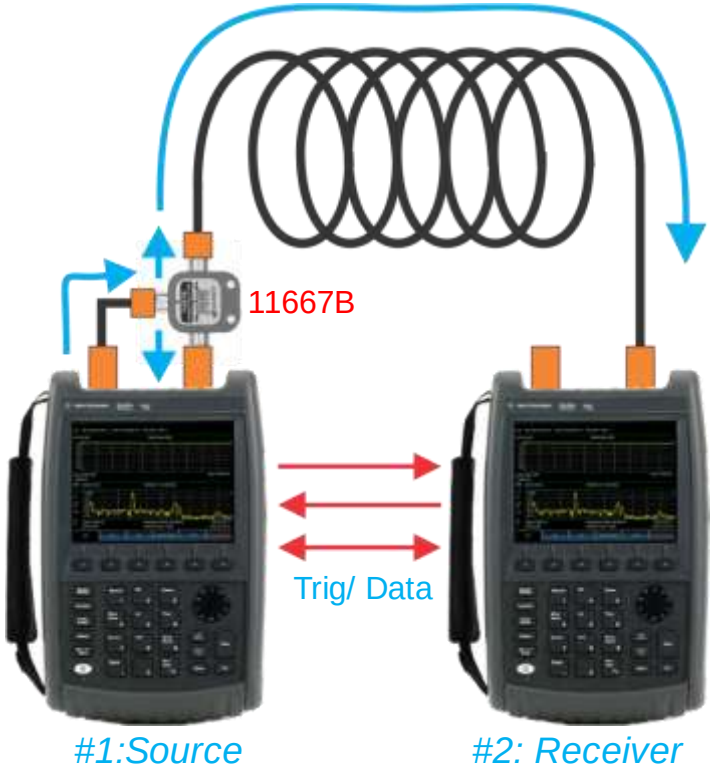
- Both ends available
- Mechanical and ECal
- *CalReady* and *QuickCal*

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



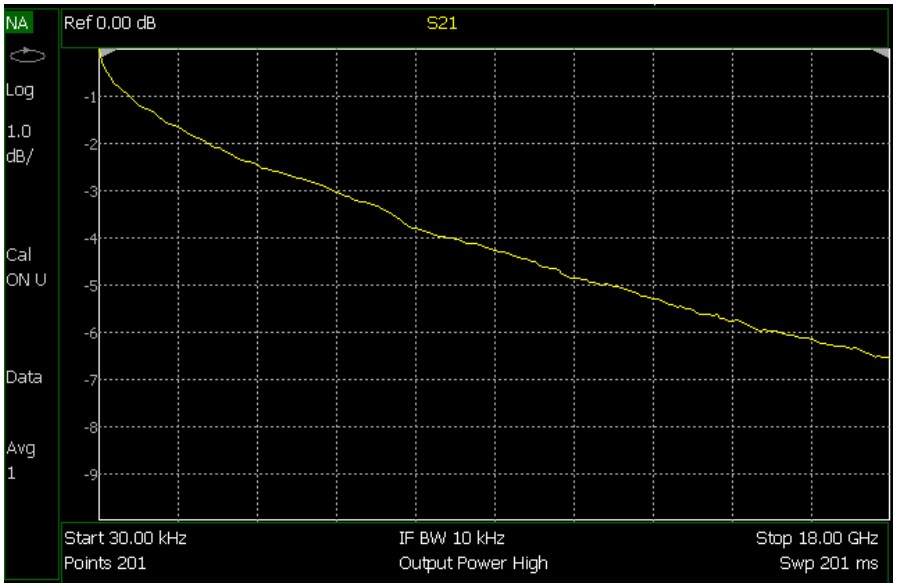
KEYSIGHT TECHNOLOGIES

Low-Loss Cable Measurement

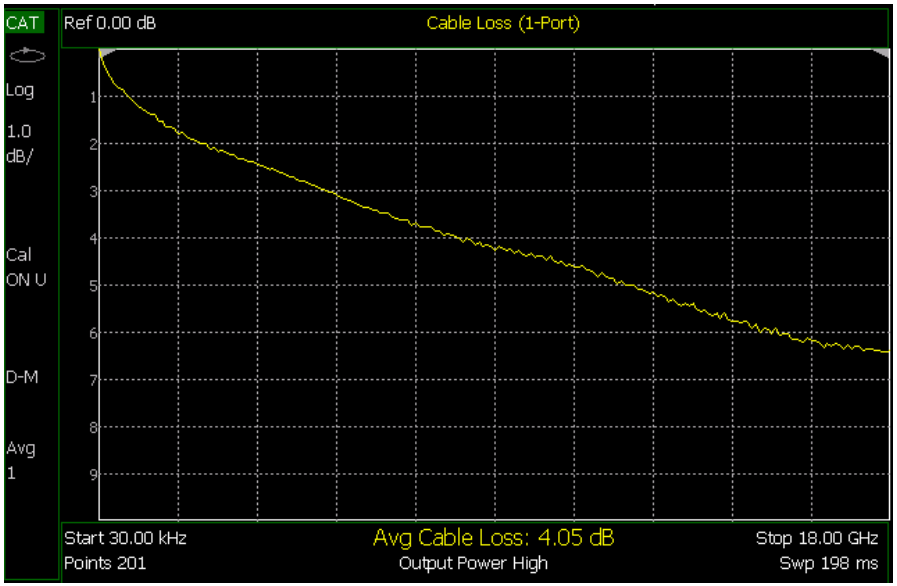
2-Port VNA

1-Port CAT

CableLoss (S21)



Cable Loss

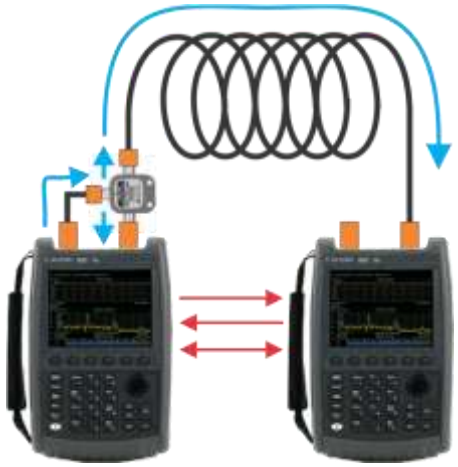


10-foot Coaxial Cable, SMA

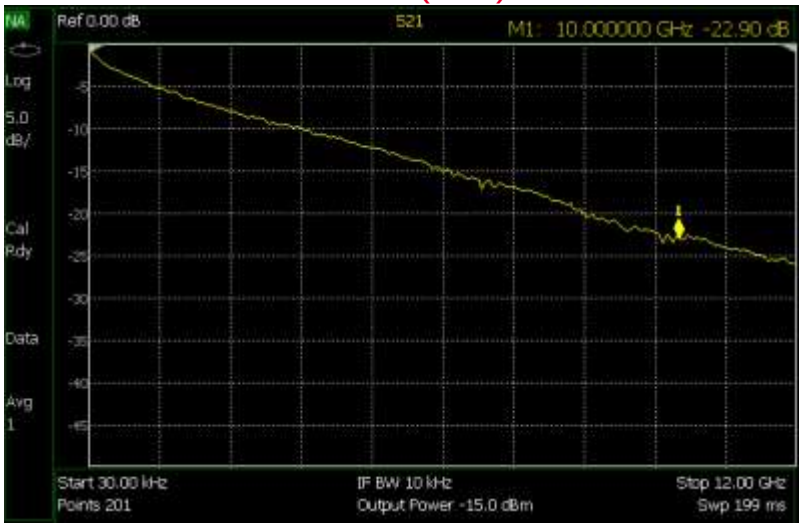
Long Cable Measurement

2-Port VNA

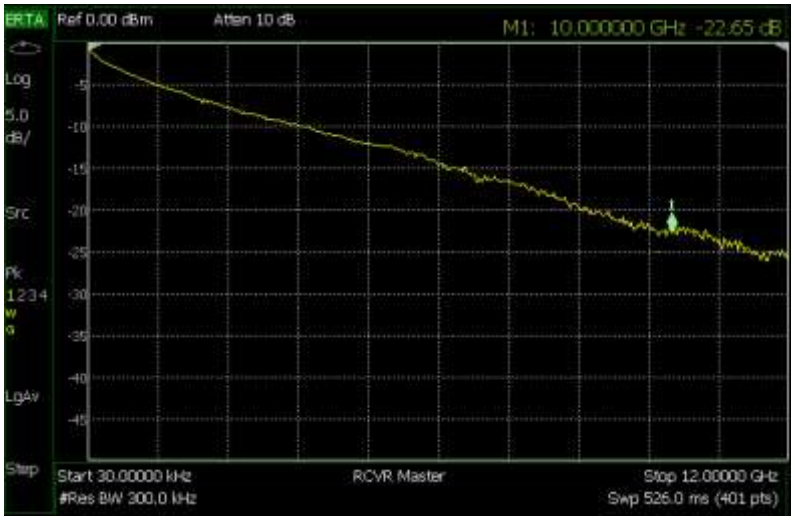
ERTA



Cable Loss (S21)



Cable Loss



100-foot Coaxial Cable, Type-N

Other Transmission Line Configurations

50Ω Cable

Direct Connection

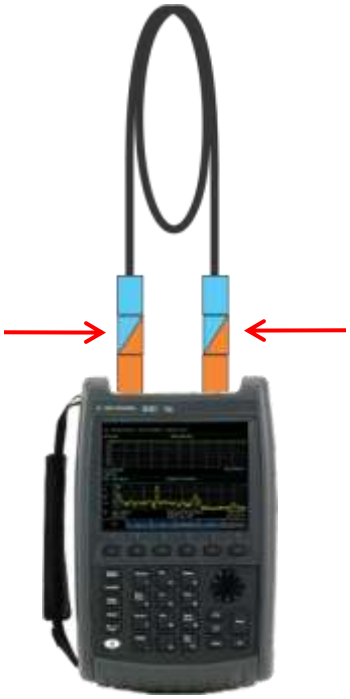
50 Ω coax

Type N or 3.5mm

75Ω Cable

N9910X-846 50-75Ω adapter

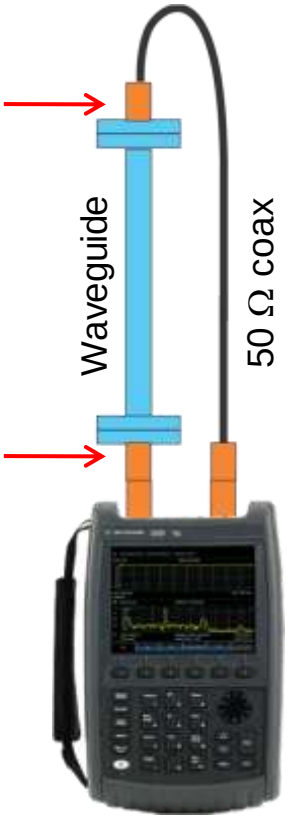
75Ω coax



Z0=75 Ω (Smith Chart)

Waveguide

Coax-to-WG Adapter

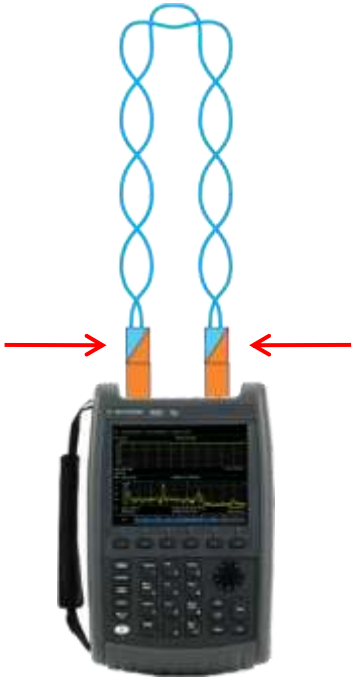


Medium = Waveguide

Twisted Pair

RJ45-to-SMA Adapter or Balun

100Ω balanced



Mixed Mode

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

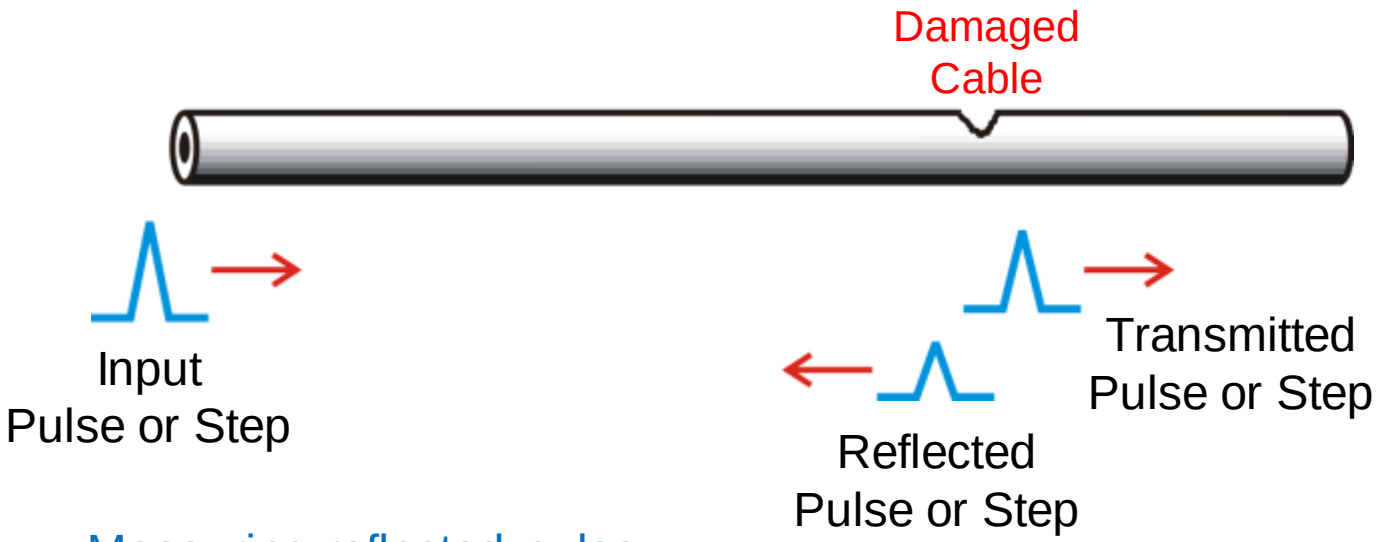
- Loose connector, flange screws
- Failed seal at a cable splice or flange (water ingress)
- Failed solder joint at connector interface
- Cut, crushed and/or weather-induced cracks
- Minimum bend radius exceeded
- Breakdown, and arcing effects

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

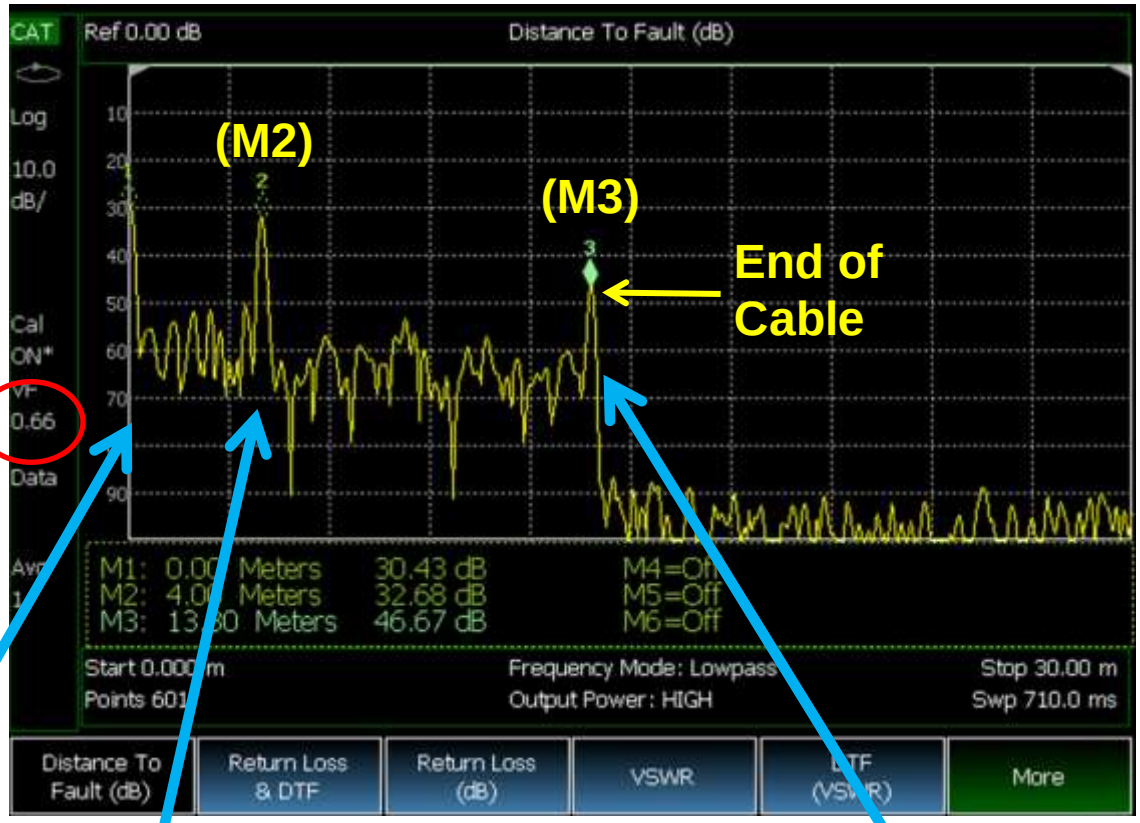


Measuring reflected pulse:

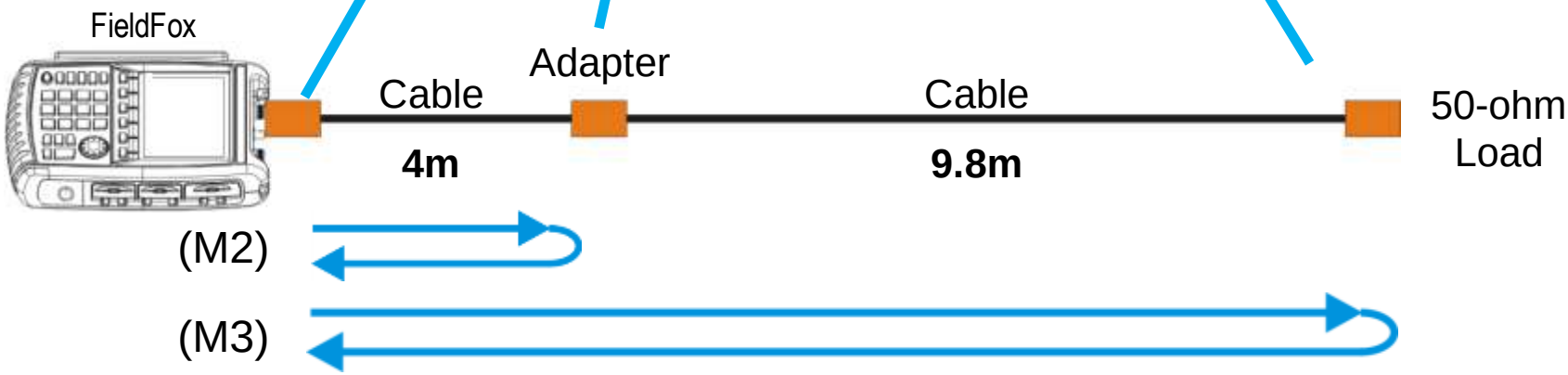
$$\mathrm{DTF(meters)} = \left[\frac{time_{\mathrm{roundtrip}}}{2}\right]\left[v_{\mathrm{cable}}\right]$$

$$= \left[\frac{time_{\mathrm{roundtrip}}}{2}\right]\left[(\mathrm{VF})(c)\right]$$

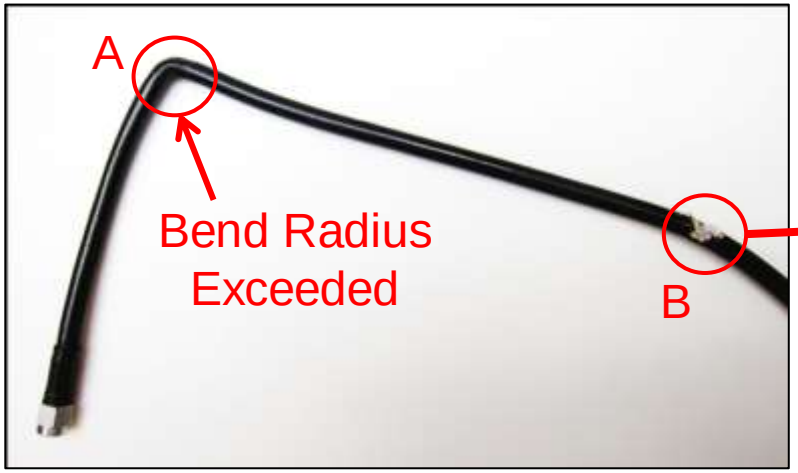
DTF For Coax

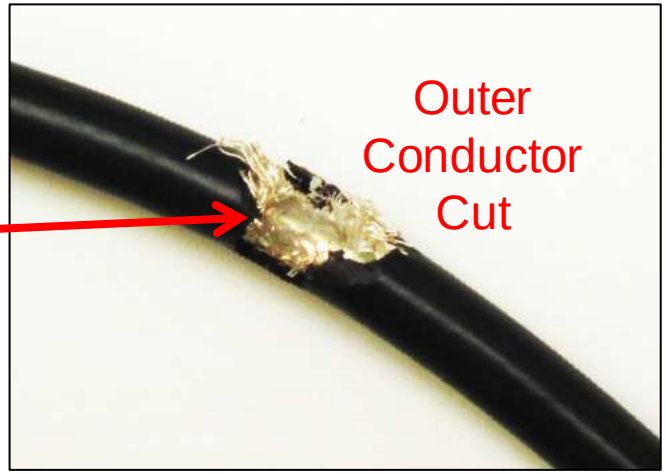


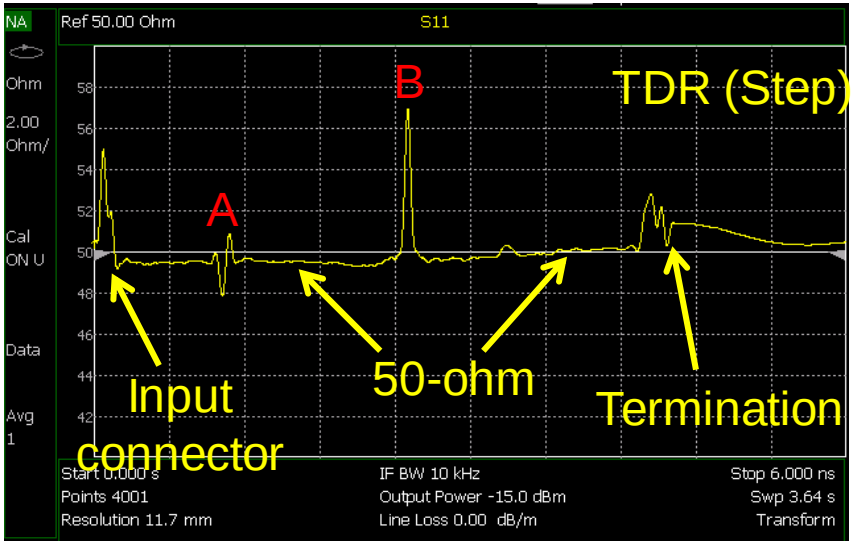
"Velocity Factor" (VF)

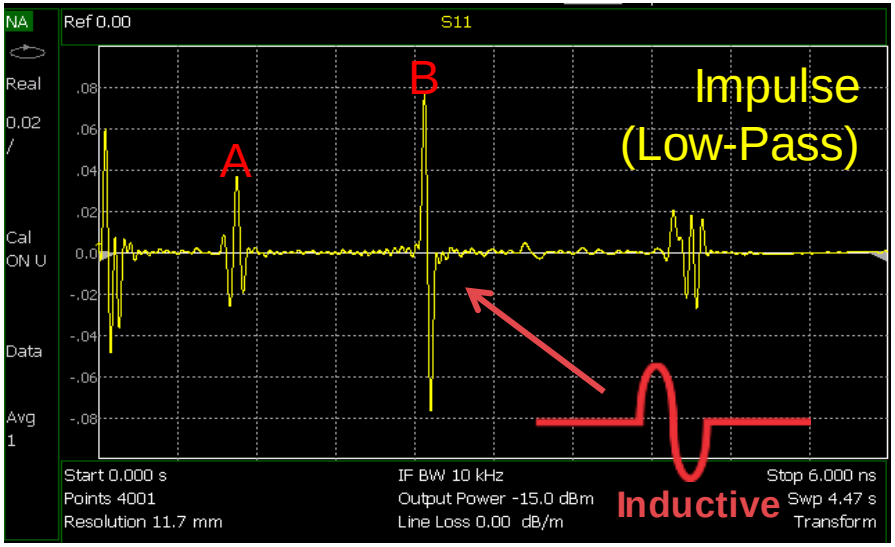


TDR and Impulse Response









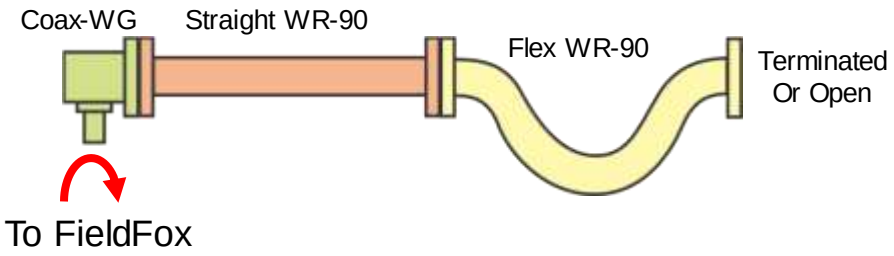
Types of Discontinuities

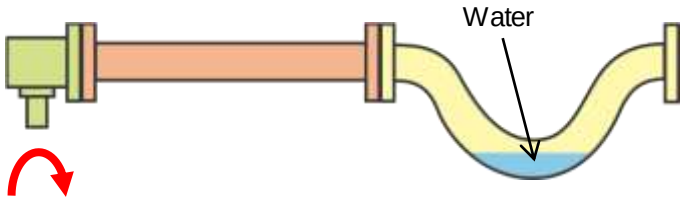
	TDR (Step)	Impulse (Low-Pass)
$R > Z_0$		
$R < Z_0$		
Inductor		
Capacitor		

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

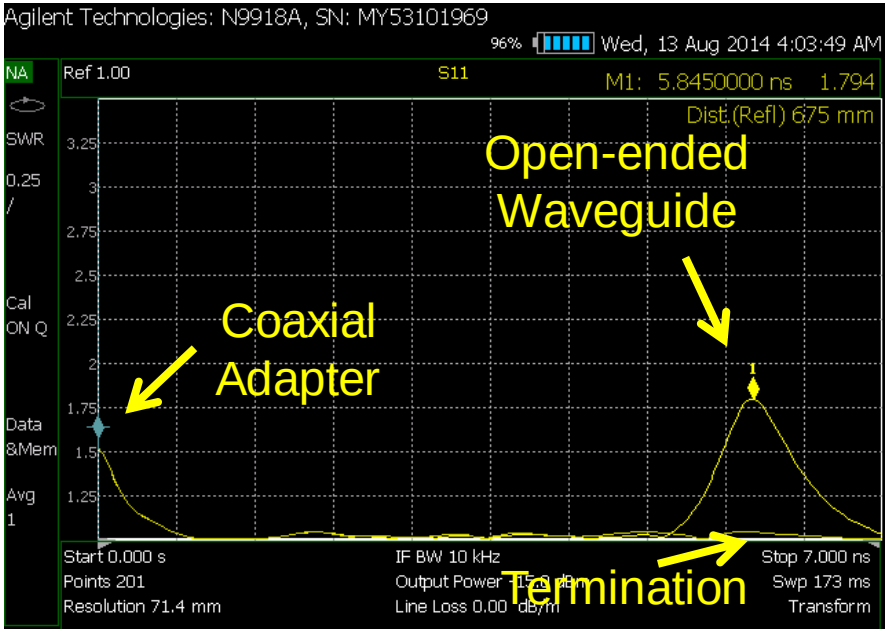
- Cable and Antenna Test Option includes TDR (Step)
- VNA option includes Step, Low-Pass Impulse, Band-Pass Impulse

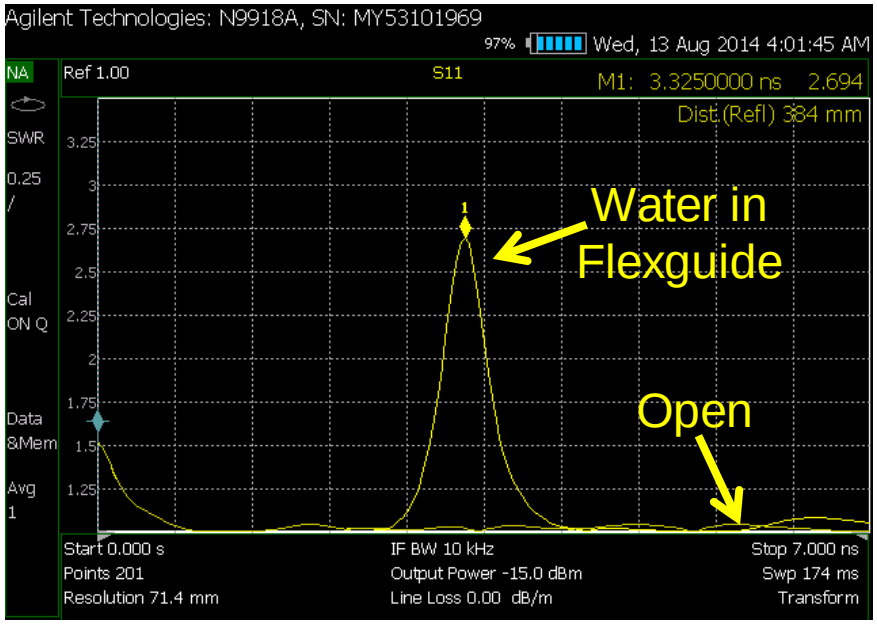
DTF For Waveguide





Bandpass Mode Required

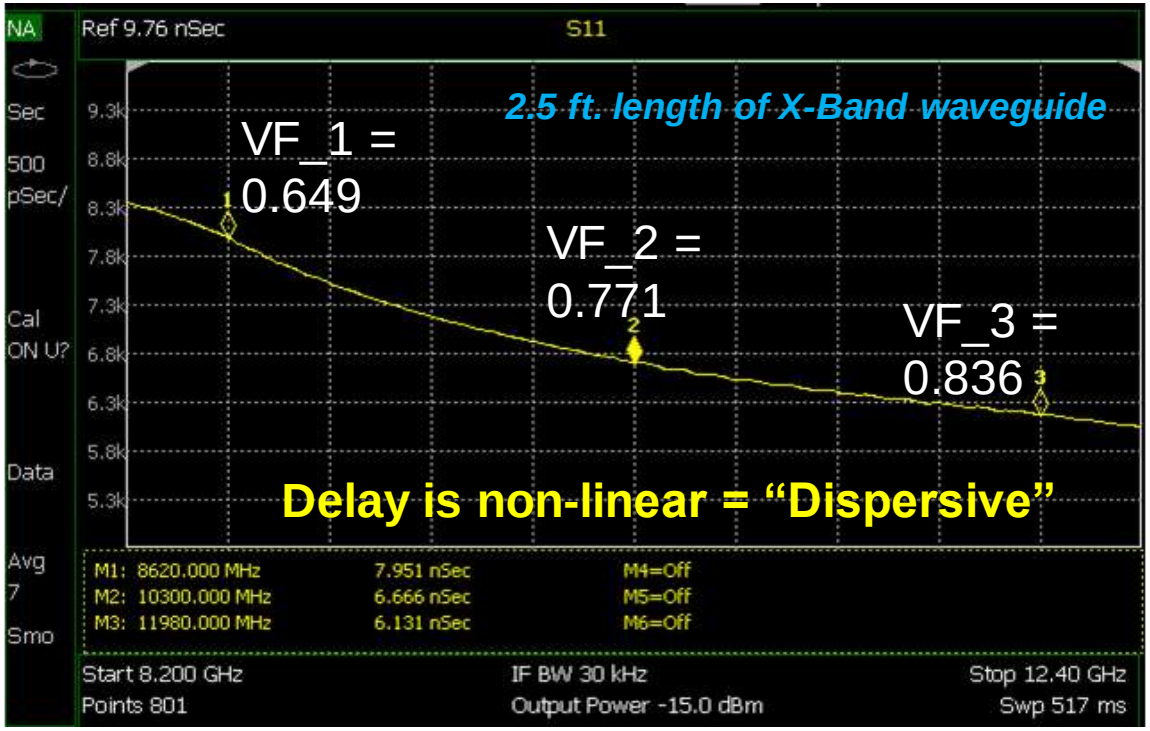




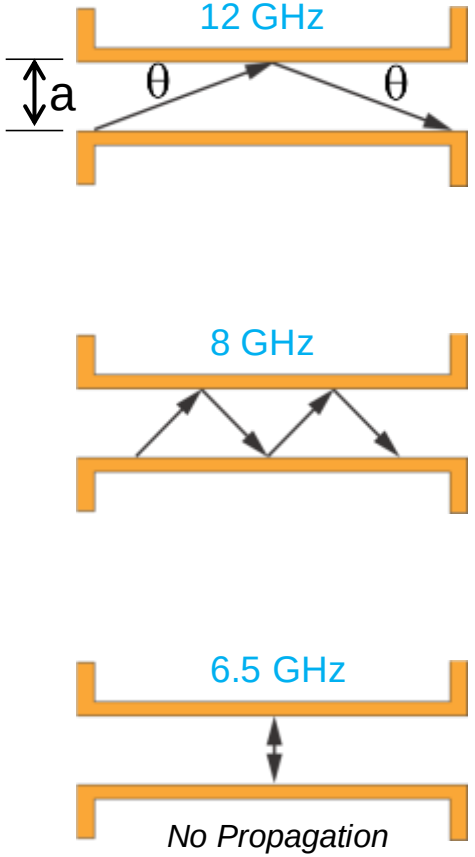
What about the *VF* for Waveguide?

Velocity Factor For Waveguide

Velocity Factor is a function of frequency



Cross section of Waveguide

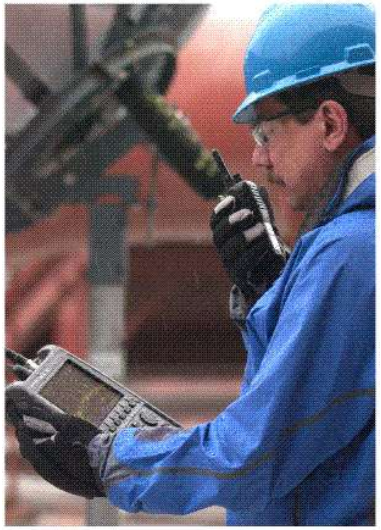


Time Domain Corrected for Non-linear VF

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

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
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