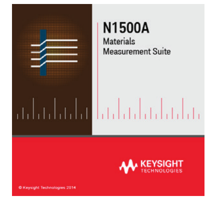
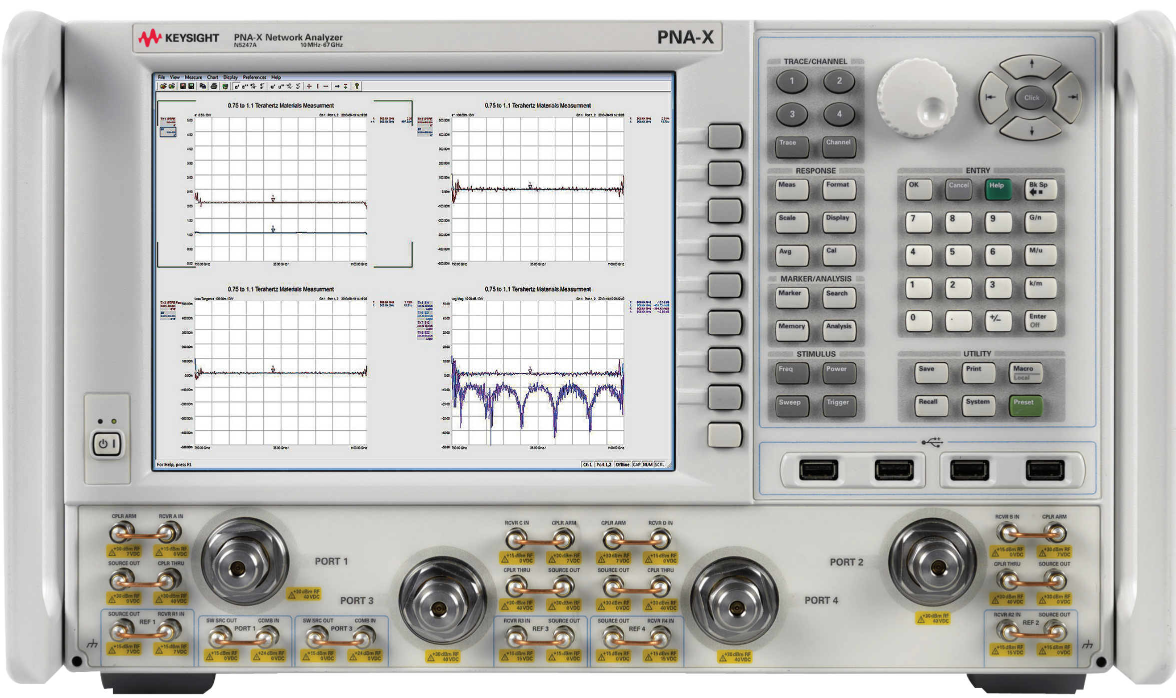
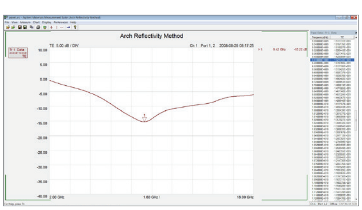
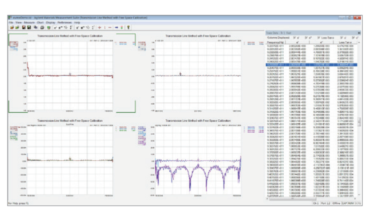
Keysight Technologies
N1500A Materials Measurement Suite

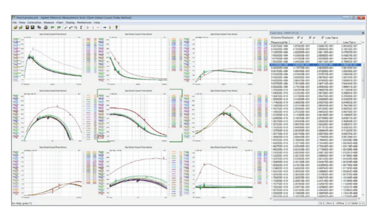


Technical Overview





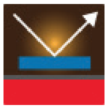


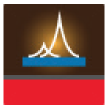


Features

- Software automates complex permittivity and permeability measurements
- Flexible option configuration allows you to choose the measurement methods you need
- One simple installation program and integrated method option loader switches seamlessly between the different measurement methods:


  - Transmission line and free space


  - Arch reflectivity


  - Resonant cavity


  - Coaxial probe

- Runs on Windows XP, Windows 7 and Windows 8
- Download a free trail from our web site: **http://na.support.keysight.com/materials/downloads.html**

Automate complex permittivity and permeability measurements with Keysight's materials measurement software suite

Measure ε_r^* and μ_r^* over a wide frequency range

With Keysight N1500A materials measurement software suite, you can determine the intrinsic electromagnetic properties of many dielectric and magnetic materials. The complete system is based on a versatile Keysight network analyzer which measures the material's response to RF or microwave energy. The N1500A software controls the network analyzer and calculates results. Depending on the Keysight network analyzer and sample holder used, frequencies can extend from the mid-MHz to the low THz.

Powerful features

- Multiple channel and port selections provide maximum flexibility when setting up network analyzers with up to four ports.
- Multiple charts and traces aid in data analysis. Depending on method option selected, data can be displayed in a variety of formats:
  - Permittivity: $\varepsilon_{r'}$, $\varepsilon_{r''}$, tan δ, Cole Cole
  - Permeability: $\mu_{r'}$, $\mu_{r''}$, tan δ_μ
  - S-parameters: log mag, linear mag, phase, unwrapped phase, group delay, smith chart, polar chart, real, imaginary, and SWR
  - Trace math functions: +, -, *, /, mean and standard deviation
  - Trace data pane: displays the active data trace in tabular format

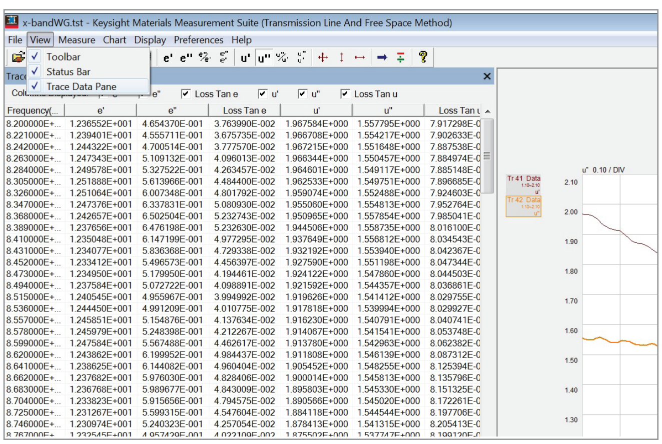


Figure 1. Configurable trace data pane allows you to choose if and where it is displayed and which data columns to include.

- Markers with reference and delta functions and rubberband zoom scaling allow close inspection of critical data.
- Off line mode allows software to run on a PC without being connected to an instrument. Free up shared network analyzer resources by taking your data analysis back to your desk, or wherever you want!
- S-parameter import and save
- Measurement report captures trace and tabular data, equipment used, sample description, user name, date and more in a professionally formatted document ready to print, save, or send electronically in an Adobe Acrobat (.pdf) file.

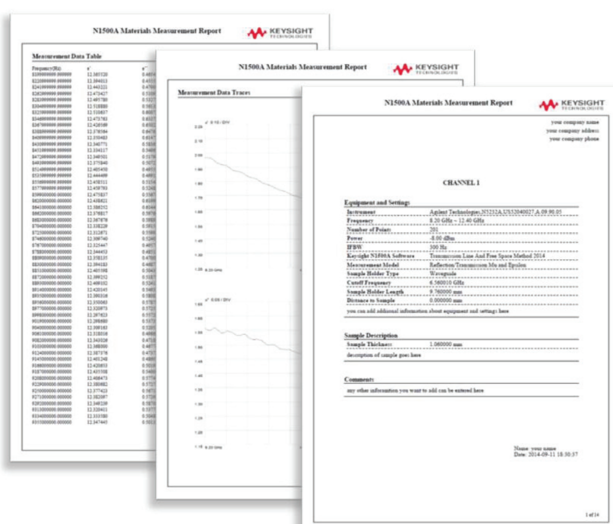


Figure 2. Measurement reports

Connect to other programs

Data can also be saved in a variety of formats to bring into other programs for reporting or further data analysis. An application programmable interface (API) allows the measurements to be set up, triggered and read from a user written program.

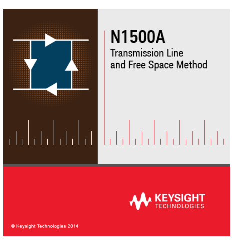
Software Update Service (SUS)

Materials measurement suite has an annual update called "SUS" that stands for "Software Update Service". Each new license comes with 12 months of SUS. After 12 months, a 1 year extension can be purchased to allow continued software updates and technical support.

Measurement method options

Keysight offers a variety of measurement methods to meet the needs of most materials under test. Each method has its own strengths and limitations that make it more or less useful for a particular application. Flexible option configuration allows you to choose one or more methods to meet your specific needs.

Transmission line and free space method – Option 001



The sample is placed in a guided transmission line such as a coaxial airline or waveguide straight section, or suspended in free space between two antennae. Several algorithms to calculate permittivity and permeability from S-parameter measurements are available to choose from.

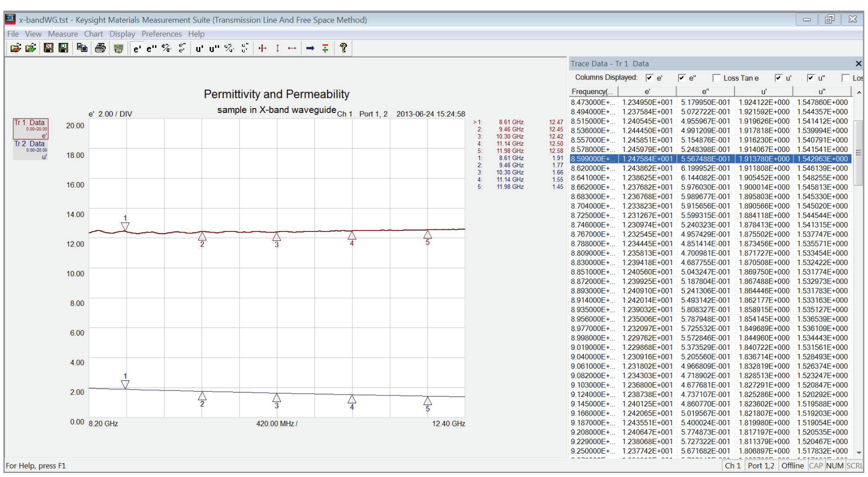


Figure 3. Example of transmission line measurement results.

Transmission Line

Coaxial airlines or rectangular waveguide transmission lines are used as sample holders. The transmission line method works best for materials that can be precisely machined to fit inside the sample holder. The N1500A Option 001 includes an algorithm that corrects for the effects of air gap between the sample and holder, reducing the largest source of error with the transmission line technique.

Typical transmission line system configuration

- *Keysight network analyzer*
- Waveguide or coaxial transmission line for sample holder
- Waveguide or coaxial calibration kit to match sample holder connectors
- A pair of test port cables
- Adapters as required to connect cables to network analyzer and sample holder

Free space

In this method, materials are placed between two antennae for a non-contacting measurement. The free space method works best for large flat solid materials, but granular and powdered materials can also be measured in a fixture. It is very useful for many applications such as non-destructive testing, measuring materials that must be heated to very high temperatures, or measuring a large area of material that is non-uniform such as honeycomb or a composite.

Typical free space system configuration

- *Keysight network analyzers*
- Free space fixture consisting of a pair of horn antennae, sample holder and metal plate for calibration. Antenna should be placed approximately $2d^2/\lambda$ from the sample, where d is the larger antenna aperture dimension.
- Waveguide or coaxial calibration kit to match horn antennae input connector
- A pair of test port cables to reach from network analyzer ports to free space fixture (not required for millimeter-wave systems where horns are usually connected to millimeter-wave frequency extender modules).
- Adapters as required to connect cables to network analyzer and sample holder

Powerful free space calibration and gating techniques

Gated isolation/ response calibration reduces errors from diffraction effects at the sample edges, and multiple residual reflections between the antennas. Gated reflect line (GRL) calibration makes accurately calibrating in free space fast and easy. A software wizard automatically sets up all the free space calibration definitions and network analyzer parameters, saving engineering time. It reduces costs associated with TRM and TRL calibration methods by eliminating the need for micro antennae positioners or direct receiver access.

There are now two ways to perform GRL calibration. The original 2 tier GRL calibration technique converts a previously saved full 2-port coaxial or waveguide calibration into a full 2-port free space calibration by measuring two additional standards, the empty free space fixture and a metal plate. With 1 tier GRL cal, a waveguide or coaxial cal is not required before the metal plate and empty fixture measurements. Because 1 tier GRL cal requires a longer alias free time domain span, it is best suited for set ups that don't have long cables, when the frequency span is not extremely wide, or a large number of points is not desired. GRL calibration requires a network analyzer with full S-parameter (S11, S21, S12, S22) capability and time domain option. An appropriate free space fixture with metal calibration plate is also needed.

Mathematical models

Option 001 has nine different algorithms to choose from, each with benefits for different materials and applications. The reflection transmission model described by Nicolson and Ross, is best for magnetic materials such as ferrites and absorbers. It calculates both [ε_r* and μ_r* (including loss) from a two-port measurement of a single sample. There are two additional two-port algorithms for non-magnetic materials (μ_r*=1). These models do not suffer from discontinuities at frequencies where the sample length is a multiple of half-wavelengths like the Nicholson Ross model and are best for long, low-loss materials. The two polynomial fit models can smooth out the effects of measurement error due to noise and mismatch, but are not suitable for materials that have sharp narrow band responses.

While the two-port algorithms are best for most solid materials, one-port algorithms provide a simple calibration and measurement, and can be better suited to measurements of liquids and powders. For example, a shorted waveguide can be turned on end vertically and filled with a material for a one-port measurement. One-port fixtures are also better suited for high-temperature measurements where one end of the fixture can be heated, while cooling mechanisms at the other end protect the network analyzer. Although one-port fixtures are usually terminated with a short circuit, the N1500A-001 also accommodates an arbitrary termination which produces more reliable results for thin samples.

N1500A	Alternate	S-parameters measured	Result	Description	References
Reflection / Transmission Mu and Epsilon	Nicholson-Ross -Weir, NRW	S11, S21, S12, S22	ε_r, μ_r	Originally developed by Nicholson and Ross, and later adapted to automatic network analyzers by Weir to calculate permittivity and permeability from transmission and reflection coefficients. Can have discontinuities for low loss samples with thickness of > ½ wavelength. Best for magnetic materials such as ferrites and absorbers.	AM. Nicolson and G. F. Ross, "Measurement of the intrinsic properties of materials by time domain techniques," IEEE Trans. Instrum. Meas., IM-19(4), pp. 377-382, 1970. W.W. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," *Proc.IEEE* vol. 62 pp.33-36, Jan 1974
Reflection / Transmission Epsilon Precision	NIST Precision	S11, S21, S22	ε_r	Developed by NIST to calculate permittivity from transmission and reflection coefficients. Best for longer samples of low-loss dielectric materials.	Improved Technique for Determining Complex Permittivity with the Transmission/Reflection Method, James Baker-Jarvis et al, IEEE transactions on microwave Theory and Techniques vol 38, No. 8 August 1990.
Transmission Epsilon Fast	Fast Transmission	S21, S12	ε_r	An iterative technique that estimates permittivity and then minimizes the difference between the S-parameter value calculated from that permittivity and the measured values until the error is less than the expected system performance. Uses only transmission parameters S21, S12, or the average of S21 and S12. Best for longer samples of low-loss dielectric materials or for systems with significant reflection error.	Not Published

N1500A	Alternate	S-parameters measured	Result	Description	References
Polynomial Fit Reflection / Transmission Mu and Epsilon	Poly Fit, Bartley	S11, S21, S12, S22	ε_r, μ_r	Uses an iterative technique to fit measured S-parameters to a polynomial, incrementing the order of the polynomial until the error is less than the expected system performance. Best for magnetic samples. Not recommended for meta or left handed materials.	P. G. Bartley, and S. B. Begley, "A New Technique for the Determination of the Complex Permittivity and Permeability of Materials Proc. *IEEE Instrument Meas. Technol. Conf.*, pp. 54-57, 2010.
Polynomial Fit Transmission Epsilon	Poly Fit, Bartley	S21, S12	ε_r	Uses an iterative technique to fit measured S-parameters to a polynomial, incrementing the order of the polynomial until the error is less than the expected system performance. Best for magnetic samples. Not recommended for meta or left handed materials.	P. G. Bartley, and S. B. Begley, "A New Technique for the Determination of the Complex Permittivity and Permeability of Materials Proc. IEEE Instrument Meas. Technol. Conf., pp. 54-57, 2010.
Stack Transmission Mu and Epsilon	Stack Two Transmission	S21, S12 (2 samples)	ε_r, μ_r	An iterative technique that uses two transmission measurements. One measurement is of the sample which optionally may be backed by a known dielectric. The second is of the sample, backing and another known dielectric. The model is useful for free space measurements. It requires a full 2-port or a two-port transmission resp/isol cal.	Not Published
Reflection Only Epsilon Short-Backed	Short Backed	S11	ε_r	An iterative technique that minimizes the difference between the measured and calculated reflection coefficient of a material backed by a short. The idea of measuring a material backed by a short was published by Von Hippel. Although, Von Hippel uses tables to determine the value of permittivity instead of iteration.	A. R. Von Hippel, Ed. *Dielectric Materials and Applications*, John Wiley and Sons, New York, 1954)
Reflection Only Epsilon Arbitrary- Backed	Arbitrary Backed	S11	ε_r	An iterative technique that minimizes the difference between the measured and calculated reflection coefficient of a material backed by a separately measured backing. This model is an extension of method proposed by Von Hippel. It is useful when the material is electrically short such that the voltage across the material is effectively zero when backed by a short.	A. R. Von Hippel, Ed. *Dielectric Materials and Applications*, John Wiley and Sons, New York, 1954)
Reflection Only Mu and Epsilon Single/Double Thickness	Single/Double Thickness	S11 (2 samples)	ε_r, μ_r	Uses two reflection coefficient measurements to calculate S11 and S21 of the material. The measurements are a sample and a sample that is twice the length as the original. After doing so the Nicolson Ross model is used to determine the material properties.	Not Published

De-embedding

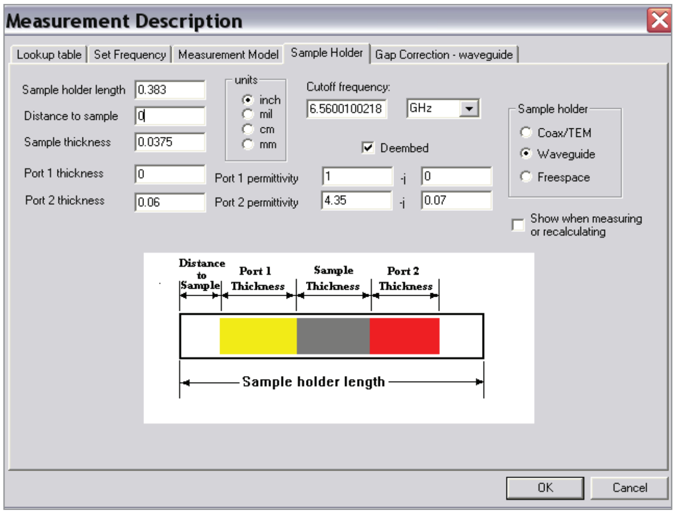


Figure 4. Sample holder definition screen with de-embedding

De-embedding allows a sample to be backed with a dielectric backing on one or both sides. It mathematically removes the effects of the backing, so the electromagnetic properties of just the sample are reported. This is useful when a sample is not stiff or thick enough to stand up by itself, or it cannot be removed from a substrate. The backing must have a known permittivity and thickness. If the permittivity of the backing is not known, it can be measured separately first. The backing material cannot be magnetic and it must allow the microwave signal to transmit through it so that S21 and S12 can be measured.

De-embedding feature works with the following transmission models:

- Reflection/Transmission Mu and Epsilon
- Transmission Epsilon Fast
- Polynomial Fit

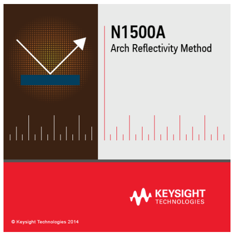
Typical frequency range	100 MHz[1] to 1.1 THz
Material properties	Dielectric and magnetic Material under test is assumed to be homogeneous (uniform composition) with no layers[2] Anisotropic materials can be measured in waveguide
Sample form	Most often used for solid materials Sample is assumed to have flat parallel sides
Typical accuracy	1 to 2%
Data formats	Permittivity: ε_r', ε_r'', tan δ, Cole Cole Permeability: μ_r', μ_r'', tan δ_μ S-parameters: log mag, linear mag, phase, unwrapped phase, group delay, smith chart, polar chart, real, imaginary, and SWR Trace math functions: +, -, *, /, mean and standard deviation Data pane: view displays trace data in tabular format
File formats	Data and Setup: .tst Data: .prn, .csv Measurement report: .pdf S-parameters: .s2p, .ts
Sample holders and fixtures	For a list of recommended sample holders and fixtures, please see; http://na.support.keysight.com/materials/docs/SampleHolders.pdf

1. Minimum frequency is set by the maximum practical sample length (L): f (in GHz) >

$$\frac{1}{\sqrt{\varepsilon_r'\mu_r'}} \quad \frac{30\text{ cm}}{\text{L(in cm}} \quad \frac{20}{360}$$

2. If the material is not homogeneous through the length of the sample (i.e., layers), the reflection from the front (S11) and back (S22) face will be different and will lead to a potentially erroneous result. If the material is not homogeneous across the face of the sample, the result is an average value over the cross section that is exposed to the EM field (weighted by the intensity).

Arch reflectivity method – Option 002



First developed by the U.S. Naval Research Lab, the NRL arch measurement method is a useful technique to test angular dependent absorptive characteristics of a material. The typical setup involves a network analyzer connected to two horn antennas fixed to an arch armature above (or below) a flat piece of the material under test. One antenna operates as the transmitting antenna while the second one receives the reflected signal to complete a one-port measurement. Sample should be in “far field”.

Typical arch reflectivity system configuration

- *Keysight network analyzer*
- NRL arch fixture
- Cables and adapters as needed

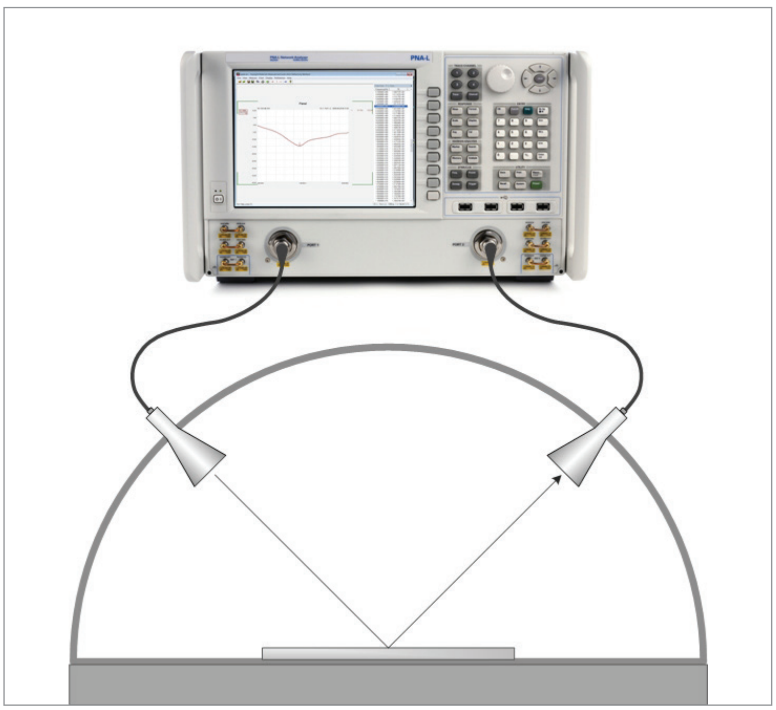


Figure 5. In the NRL arch method, one antenna transmits energy onto the MUT and the second antenna receives the reflected portion.

Option 002 automates NRL arch measurements. The program guides you through the complete process of setup, calibration and measurement of material reflectivity.

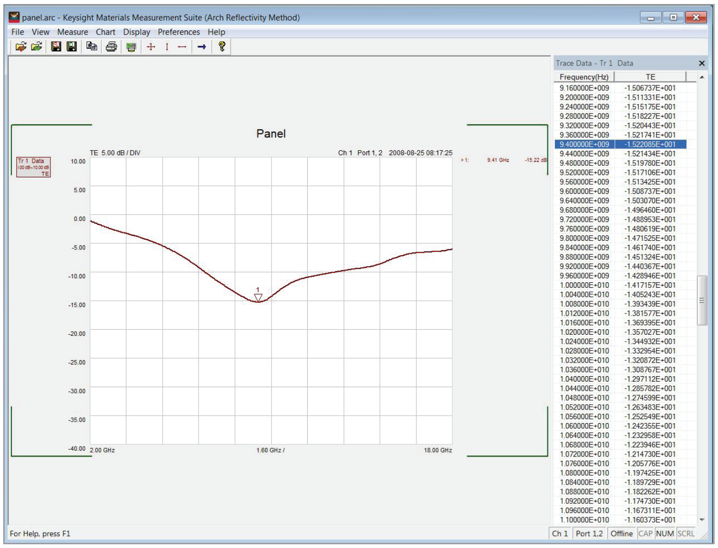
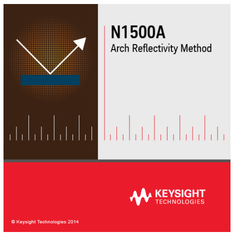


Figure 6. Example of arch reflectivity measurement results.

Typical frequency range	100 MHz to 1.1 THz
Material properties	Dielectric and magnetic
Sample form	Most often used for solid materials Sample is assumed to have flat parallel sides
Typical accuracy	1 to 2%
Data formats	Bi-static reflection (S21) in dB Data pane view displays trace data in tabular format
File formats	Data and Setup: .arc Data: .prn, .csv Measurement report: .pdf S-parameters: .s2p, .ts

Resonant cavity method – Option 003



Choose the resonant cavity method for thin films, substrate materials, and other low loss dielectric materials. The resonant cavity method uses a network analyzer to measure resonant frequency and Q of a resonant cavity fixture, first empty and then loaded with the sample under test. Permittivity can then be calculated from these measurements, knowing the volume of the sample, and some other parameters about the resonant cavity. Because it is a resonant method, only one frequency point is reported. However, it is much more sensitive and has better resolution than the other techniques. Typical resolution for this method is 10^{-4} where the broadband method is 10^{-2}.

A least squares circle fitting technique is used to calculate Q, which uses both magnitude and phase information and is more repeatable than other Q calculation methods. The software then calculates ε_r', ε_r'' and loss tangent and displays them in its easy to use interface.

Typical resonant cavity system configuration

- *Keysight network analyzer*

One or more resonant cavity fixtures:

- Split post dielectric resonators (SPDR) from QWED. These resonators are high quality and are available in frequencies from 1 GHz to 15 GHz. For more information, please **email info@qwed.com.pl** or visit **http://www.qwed.com.pl/hardware.html**
- ASTM D2520 standard waveguide resonators
- Keysight 85072A split cylinder resonator

A pair of test port cables
Adapters as required to connect cables to network analyzer and resonant cavity

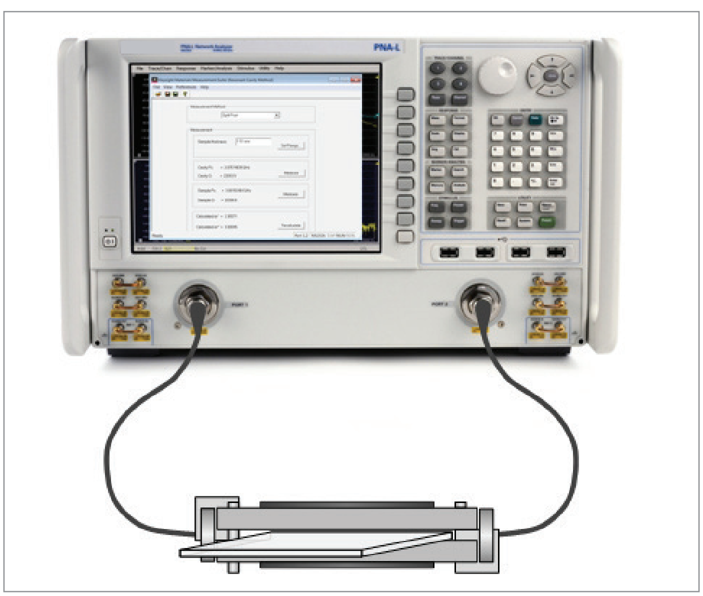


Figure 7. Resonant cavity system

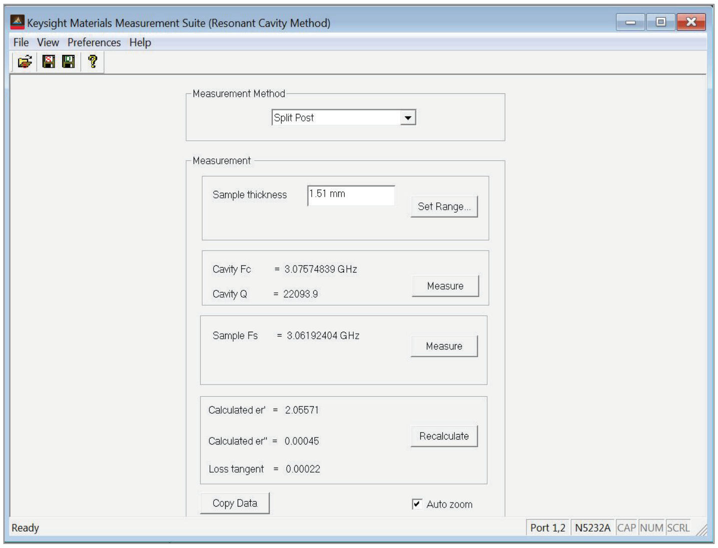
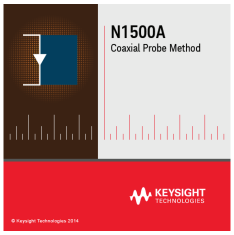


Figure 8. Resonant cavity method user interface

Typical frequency range	1 to 15 GHz
Material properties	1 to 15 GHz
Sample form	For split post and split cylinder resonator's, sample is thin sheet with flat parallel sides. For ASTM D2520 method, sample is a cylindrical rod shape.
Typical accuracy	1%, loss tangent resolution $1x10^{-4}$
Data formats	Permittivity: $\varepsilon_{r'}$, $\varepsilon_{r''}$, tan δ
File formats	Data and Setup: .cav Data: .prn

Coaxial probe method – Option 004



The coaxial probe method works with Keysight 85070 series dielectric probe kit hardware. Measurements are conveniently made by immersing the probe into liquids or semi-solids – no special fixtures or containers are required. Measurements are non-destructive and can be made in real time. These important features allow the dielectric probe kit to be used in process analytic technologies.

Typical coaxial probe system configuration

- *Keysight network analyzer*
- Keysight N1501A or 85070E dielectric probe kit with cable and probe stand.
- Optional Keysight Ecal module for electronic calibration refresh. Electronic calibration refresh with ECal is not compatible with FieldFox network analyzers. ECal module requires USB connection to PC or PNA and ENA series network analyzers.
  - 8509xC Series
  - N469x Series
  - N443x Series (ports a and b only)

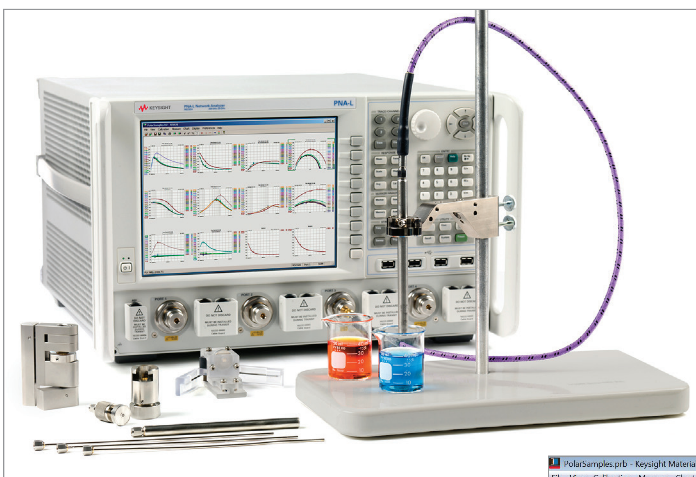


Figure 9. Coaxial probe system

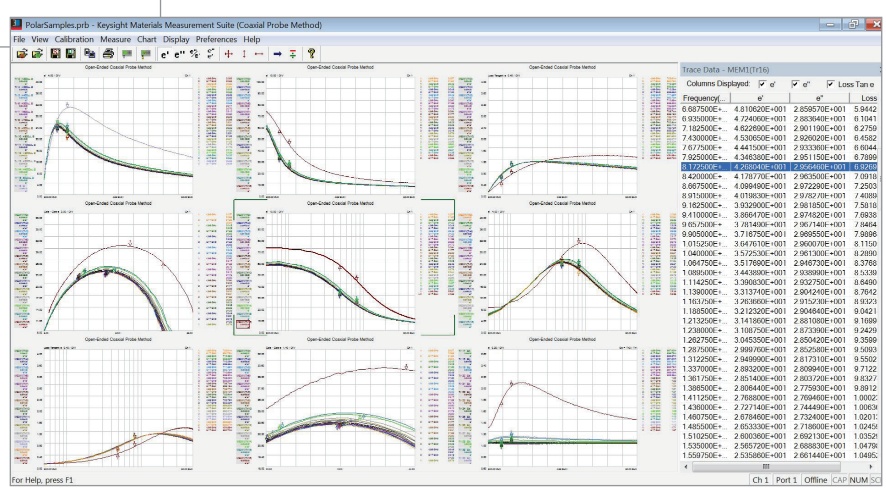


Figure 10. Example of coaxial probe measurement results

Calibration refresh reduces drift errors

The automated electronic calibration refresh feature recalibrates the system automatically, in seconds, just before each measurement is made. This virtually eliminates cable instability and system drift errors.

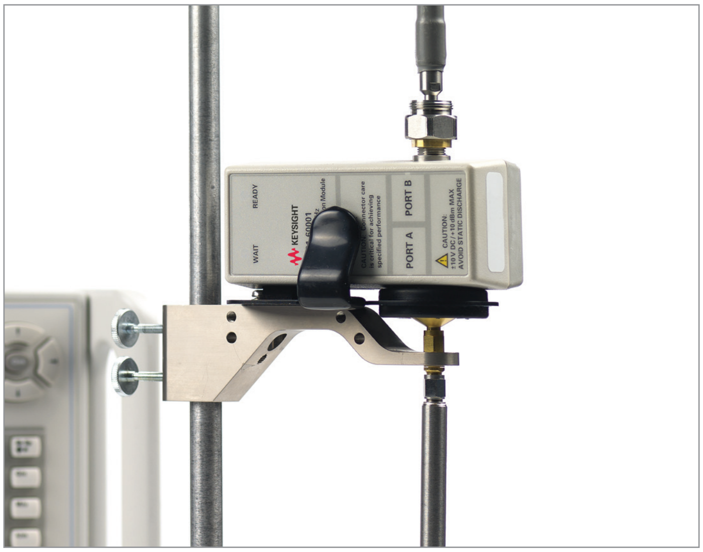


Figure 11. Ecal module connected in line for electronic

How it works:

A Keysight electronic calibration module (ECal) microwave ports are connected in line between the probe and the network analyzer test port cable. The ECal module USB communication port is connected either to the PC, PNA or ENA Series network analyzer running the N1500A software. The software guides you through a normal “three standard” calibration, (usually open, short, water), performed at the end of the probe. This calibration is then transferred to the ECal module. The ECal module remains in line and a complete ECal calibration is automatically performed before each measurement. Errors due to test port cable movement and system drift are removed by the new calibration.

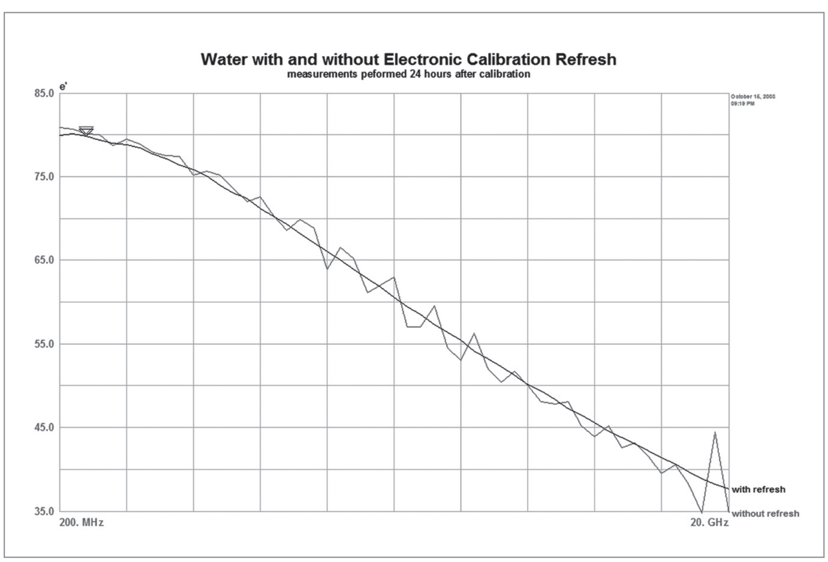


Figure 12. Water with and without electronic calibration refresh

This measurement shows the effects of system drift and cable instability on a dielectric measurement of water and the improvement with electronic calibration refresh. Both measurements were made 24 hours after the original calibration. The lighter colored, noisier, trace was made before the electronic calibration refresh was turned on. The darker, smoother, trace shows the improvement made after the electronic calibration refresh was turned on.

For systems without an ECal module, a simpler, “one standard” refresh calibration feature is also available, which can reduce the effects of system drift over time or temperature. After the initial “three standard” probe calibration is performed, the calibration can be refreshed at any time with the connection of a single standard. Any one of the three calibration standards can be defined as the refresh standard.

Suggested frequency range	200 MHz to 50 GHz with network analyzer 10 MHz to 3 GHz with E4991A impedance analyzer
Material properties	Dielectric only (non-magnetic)
Sample form	Best used for liquids or soft conformable solids
Typical accuracy	5-10%
Data formats	Permittivity: ε_r', ε_r'', tan δ S-parameters: log mag, linear mag, phase, unwrapped phase, group delay, smith chart, polar chart, real, imaginary, and SWR. Trace math functions: +, -, *, /, mean and standard deviation. Data pane view: displays trace data in tabular format.
File formats	Data and Setup: .prb, .tst Data: .prn, .csv Measurement report: .pdf S-parameters: .s1p, .ts

Ordering information

N1500A Materials measurement suite

License includes 1 year software update service

N1500A-UL8 USB software security key – required for first time N1500A buyers to run software suite. One key works with multiple method options.

Choose one or more method options:

- N1500A-001 Transmission line and free space method
- N1500A-002 Arch reflectivity method
- N1500A-003 Resonant cavity method
- N1500A-004 Coaxial probe method

Required, but not included:

- Compatible network analyzer – for a complete up to date list of supported analyzers, please see **http://na.support.keysight.com/materials/docs/N1500A-VNAs.pdf**
- PC (optional with ENA and PNA series network analyzers when software is installed directly on analyzer).
  - Windows XP, Windows 7 or Windows 8 Operating System
  - Keysight IO Libraries Suite version 16.1 or later
  - GPIB, LAN or USB interface depending on network analyzer. For network analyzer interface information, please see **http://na.support.keysight.com/materials/docs/N1500A-VNAs.pdf**
- Internet access for license redemption
- Appropriate fixtures and cables for chosen measurement method. Please see method option descriptions in this document for more information.

N1500AU Materials measurement suite -- 1 year software update service (SUS)

Choose one or more method options:

- N1500AU-001 Transmission line and free space method SUS
- N1500AU-002 Arch reflectivity method SUS
- N1500AU-003 Resonant cavity method SUS
- N1500AU-004 Coaxial probe method SUS

Upgrade Information

Customers who own 85070E or 85071E licenses can upgrade to N1500A by purchasing the N1500AU materials measurement suite software update service and desired options. Licenses will be tied to the 85070E or 85071E USB software security key.

Customers who own the 85070A/B/C/D or 85071A/B/C/D must purchase 85070EU or 85071EU upgrade kit in addition to N1500A software update service.

To Upgrade From	Order
85070E	N1500AU-004
85071E	N1500AU-001
85071E-100	N1500AU-001
85071E-200	N1500AU-002
85071E-300	N1500AU-003
85070A/B/C/D	85070EU-070 85070EU-UL8 N1500AU-004
85071A/B/C/D	85071EU-071 85071EU-UL8 N1500AU-001

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