Four-Port Microwave Measurement System Speeds On-Wafer Calibration and Test*

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Abstract—A four-port measurement system comprising an inexpensive coaxial switch matrix and comprehensive free software package extends the capabilities of a user’s two-port automatic network analyzer and probe station to three- and four-port measurements. The software includes routines for calibration, measurement, and correction, and generates normal and differential scattering and impedance parameters in a variety of standard data formats. Any in-line, two-port calibration, including the multiline Thru-Reflect-Line method, may be used to correct the measurement data.

Introduction—In [1] we described a multiport calibration technique. This system may be calibrated with any conventional two-port method, including the accurate multiline Thru-Reflect-Line (TRL) calibration [2].

Historically, collecting accurate four-port data with a two-port automatic network analyzer (ANA) has been tedious. The multiport data are based on a series of two-port measurements of the device with the unconnected ports terminated with a precision matched load. The ensemble of two-port data is used to fill the three- or four-port scattering parameter (*S*-parameter) matrix. The analytical method of [3] can be used to correct for the imperfect loads used to terminate the unused ports during the two-port measurement. Besides the time and difficulty involved in making multiple connections to complete a single device measurement, the accuracy is limited by the repeatability of the connections and the imperfect termination impedances connected to the unused ports.

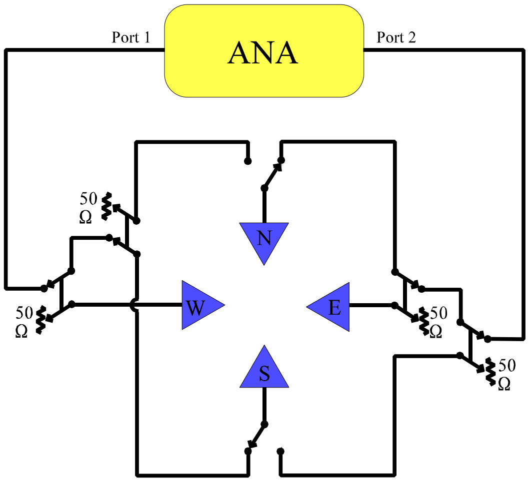

Figure 1. A schematic drawing of the 4-port measurement system.

These problems are circumvented with automated four-port measurement systems

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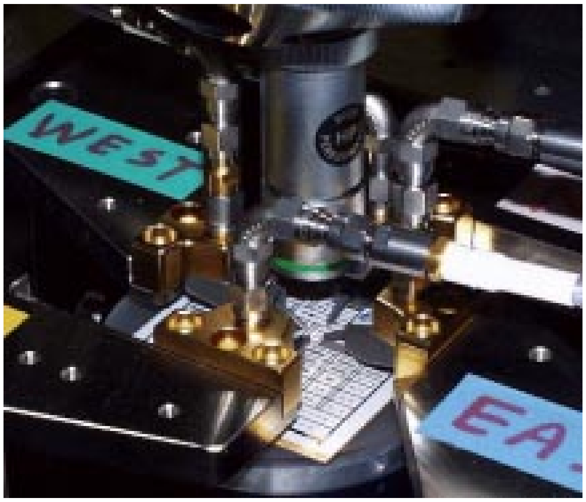


Figure 2. On-wafer four-port probe system.

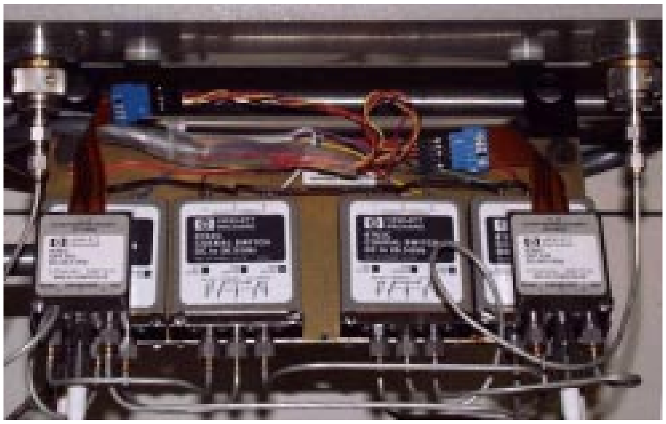


Figure 3. Coaxial switch matrix that implements the four-port system shown in Figure 1. Measurement range is 50 MHz to 26.5 GHz.

[4]. However, the most common method of calibrating these automated systems involves performing six two-port Short-Open-Load-Thru (SOLT) calibrations—one calibration between each pair of ports. In an on-wafer testing environment, the port orientations are orthogonal and it is not possible to connect a Thru standard between orthogonal probes. Furthermore, on-wafer SOLT calibrations can reduce accuracy at higher frequencies [5].

Calibration Method—Our new multiport calibration procedure is based on the method of [1] and utilizes the four-port wafer-probe system architecture shown in Figure 1. This system consists of a conventional two-port ANA and six computer-controlled coaxial switches to route signals from port 1 of the analyzer to what we label the north (N), south (S), and west (W) probes, and signals from port 2 of the analyzer to the north (N), south (S), and east (E) probes. The system is arranged so that a unique termination impedance is applied to each probe when it is not being used to connect the device under test to the analyzer.

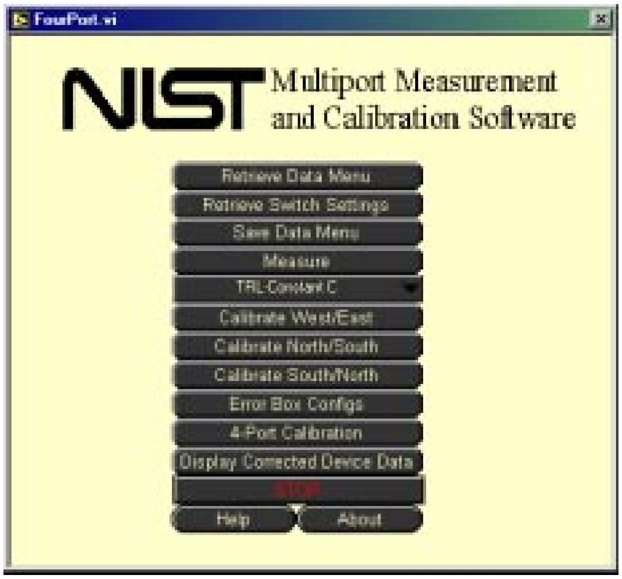
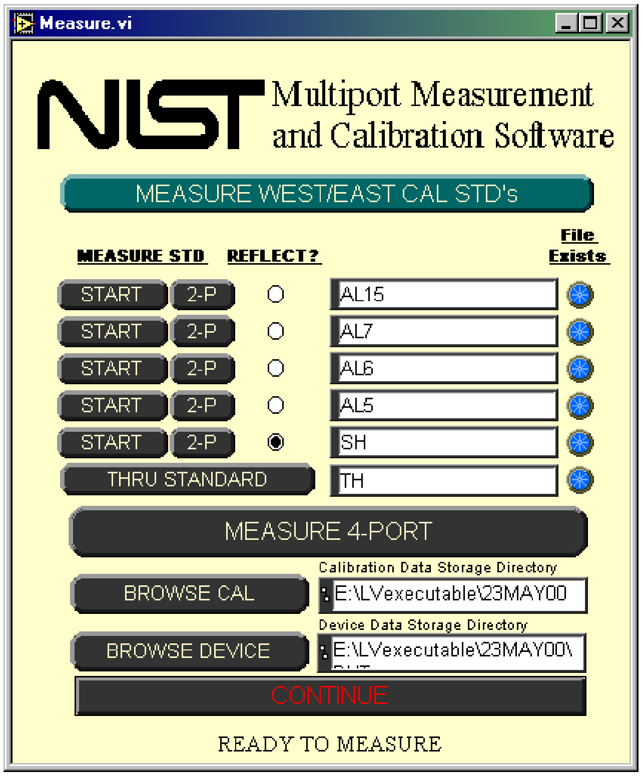


Figure 4. Multiport software front panel.

Calibrating the system requires three conventional in-line two-port calibrations. The calibrations are performed with port 1 connected to W and port 2 to E, port 1 connected to N and port 2 to S, and port 1 connected to S and port 2 to N. This reduces to an absolute minimum the number of connections made to the standards. Only two connections to the calibration standards are required. The third in-line measurement is made using the switches to swap the N and S ports.

Since we never need to connect standards between orthogonal probes, this procedure



START 2-P ○ AL15
START 2-P ○ AL7
START 2-P ○ AL6
START 2-P ○ AL5
START 2-P ● SH
THRU STANDARD TH

Calibration Data Storage Directory: E:\LVexecutable\23MAY00
Device Data Storage Directory: E:\LVexecutable\23MAY00\

READY TO MEASURE

Figure 5. Multiport measurement window.

allows on-wafer multiport measurements to be corrected by any standard two-port calibration, including SOLT, LRM, LRRM, plus the most accurate on-wafer calibration, multiline TRL [6]. Following calibration, we can test any device with one to four ports.

This “three calibration” algorithm works by first correcting all measurements with a W-E one-tier calibration. To translate a measurement made at a N or S port, we need to cascade the scattering-parameter matrix describing the signal path from that port back to the W or E port as required onto the first-tier W-E-corrected scattering-parameter matrix. Therefore, we need four unique matrices describing the translations N to W, N to E, S to W, and S to E. We generate these matrices by performing two second-tier calibrations, one in the N-S orientation and the other in the S-N orientation, on top of the first-tier W-E calibration. However, these two second-tier calibrations require only one physical connection because the switches swap the N and S ports automatically for the operator.

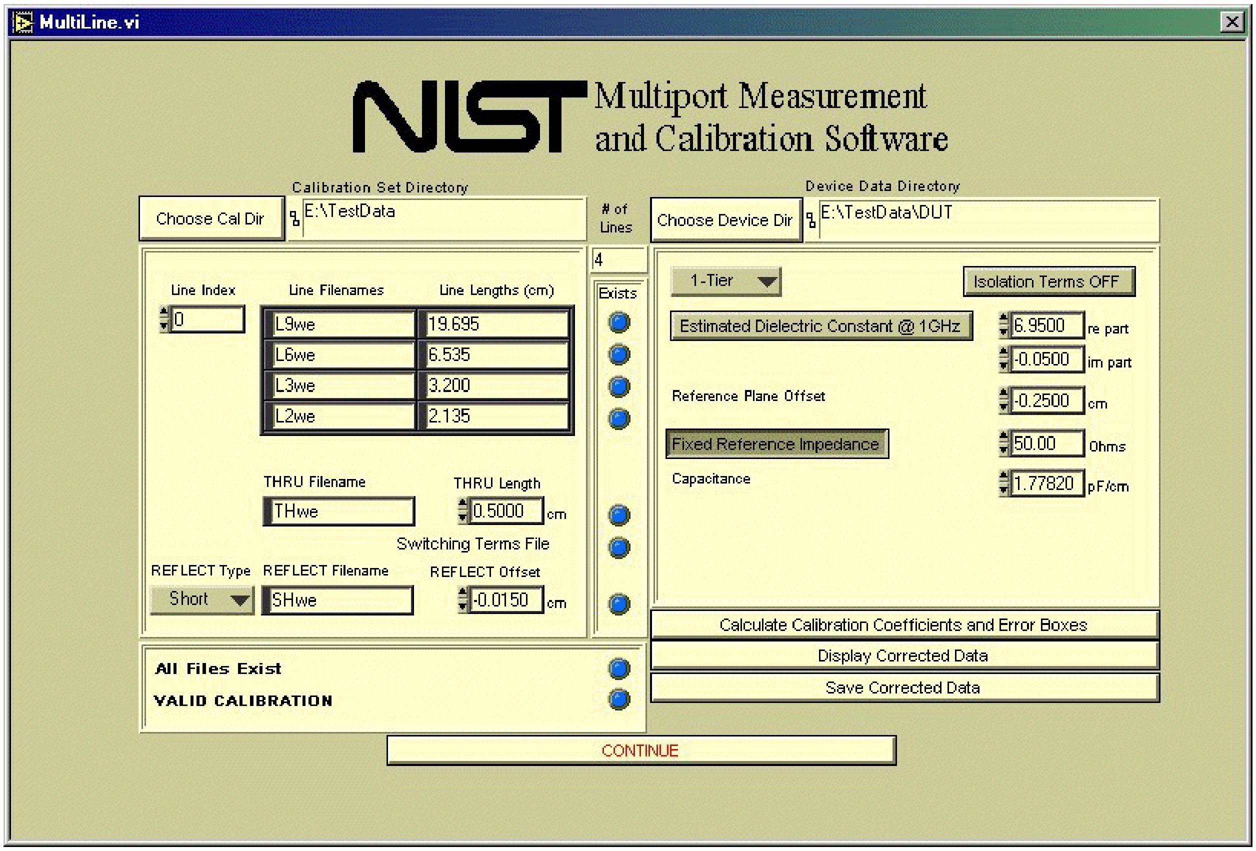
Hardware–Our system performs four-port measurements from 50 MHz to 26.5 Ghz. Figure 3 shows the automated 3.5 mm coaxial switches, which are off-the-shelf components. Four of the six switches incorporate internal 50 Ω loads that uniquely terminate the test port not in use. These termination impedances are not necessarily 50 Ω, so we measure the actual impedances during the calibration procedure and apply a correction when deembedding.

Software— Calibrating, measuring, viewing, and formatting multiport data is accomplished with a self-contained Windows^{tm}-compatible LabVIEW^{tm} executable library [7]. The front panel, shown in Figure 4, is used to set up, save, and retrieve a calibration menu, and call up the measurement and calibration routines.

Figure 5 shows the measurement menu. The top toggle key, which is labeled “Measure West/East Cal. Stds.” in Fig. 5, selects the switch configuration and standards to be measured. In the West-East configuration, port 1 of the analyzer is connected to the West probe and port 2 is connected to the East probe, and the analyzer performs a single two-port measurement. Toggling the top key changes the system to “Measure North/South Cal. Stds.” mode. In this configuration, the software automatically uses the switch matrix to measure each standard twice, first with port 1 connected to North and port 2 connected to South, and then with port 1 connected to South and port 2 connected to North.

Independent file paths for storing the calibration standard measurements and for device (DUT) measurements, shown towards the bottom of the measurement window in Fig. 5, ease the organization of complex measurement protocols.

Figure 6 shows the TRL calibration menu. Parameters corresponding to particular properties of the calibration standards, estimated dielectric constant or waveguide cutoff frequency, and output reference impedance may be edited and saved to a calibration menu. Following execution, de-embedded measurements can be displayed to facilitate troubleshooting and help the user verify that the calibration is satisfactory. The measurement software also accommodates port extensions or added adapters, as shown in Figure 7. This feature may be used to account for additional test fixtures or probe-head transitions between the measurement reference planes and the multiport device.



Calibration Set Directory: E:\TestData

Device Data Directory: E:\TestData\DUT

# of Lines: 4

Line Index: 0

Line Filenames	Line Lengths (cm)
L9we	19.695
L6we	6.535
L3we	3.200
L2we	2.135

THRU Filename: THwe

THRU Length: 0.5000 cm

Switching Terms File

REFLECT Type: Short

REFLECT Filename: SHwe

REFLECT Offset: -0.0150 cm

1-Tier

Isolation Terms OFF

Estimated Dielectric Constant @ 1GHz: 6.9500 re part, -0.0500 im part

Reference Plane Offset: -0.2500 cm

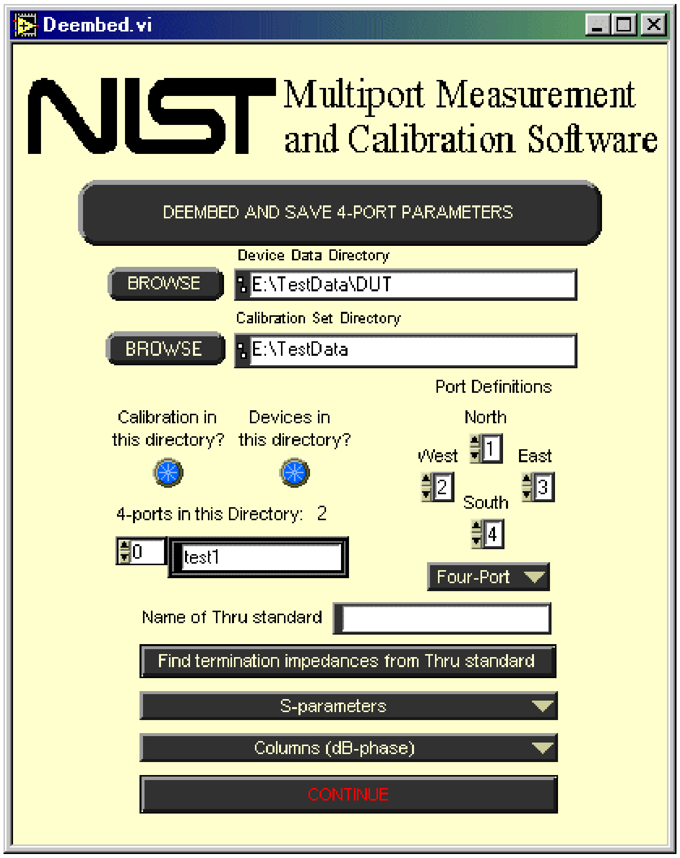
Fixed Reference Impedance: 50.00 Ohms

Capacitance: 1.77820 pF/cm

All Files Exist

VALID CALIBRATION

Figure 6. TRL calibration window.



Device Data Directory: E:\TestData\DUT

Calibration Set Directory: E:\TestData

Port Definitions: North 1, West 2, East 3, South 4

4-ports in this Directory: 2

0 test1

Four-Port

Name of Thru standard

S-parameters

Columns (dB-phase)

Figure 7. Deembed 4-port menu.

The final menu in the sequence, shown in Figure 7, is used to de-embed and save corrected multiport device data. It allows the user to assign port numbers to each probe, as well as select the number of ports used in the data output. Corrected device data may then be selected and plotted. For example, Figure 8 shows the magnitude plots for all sixteen *S*-parameters of a four-port device, divided into reflection terms and transmission terms, respectively. Various popular file formats for standard or differential *S* or Z (impedance)-parameters can be specified to facilitate analysis, design, or modeling using commercial software packages.

Applications—The system can be used to make fully calibrated measurements on any device with up to four ports. Many potential applications exist in the coaxial and on-wafer environments, including packaged components, electronic package characterization [8], and multiconductor transmission-line analysis [9]. For example, Figure 9 presents measurement results for an asymmetric coupled transmission line on a silicon substrate [10]. This graph shows the measured resistance per unit length of line (solid curve) for the two asymmetric transmission lines, labeled R_{c11} and R_{c22}, and the coupled line parameter, R_{c12}. Also plotted in dashed lines are the lower and upper 95% confidence intervals and the line parameters calculated from the quasi-analytical method of [11].

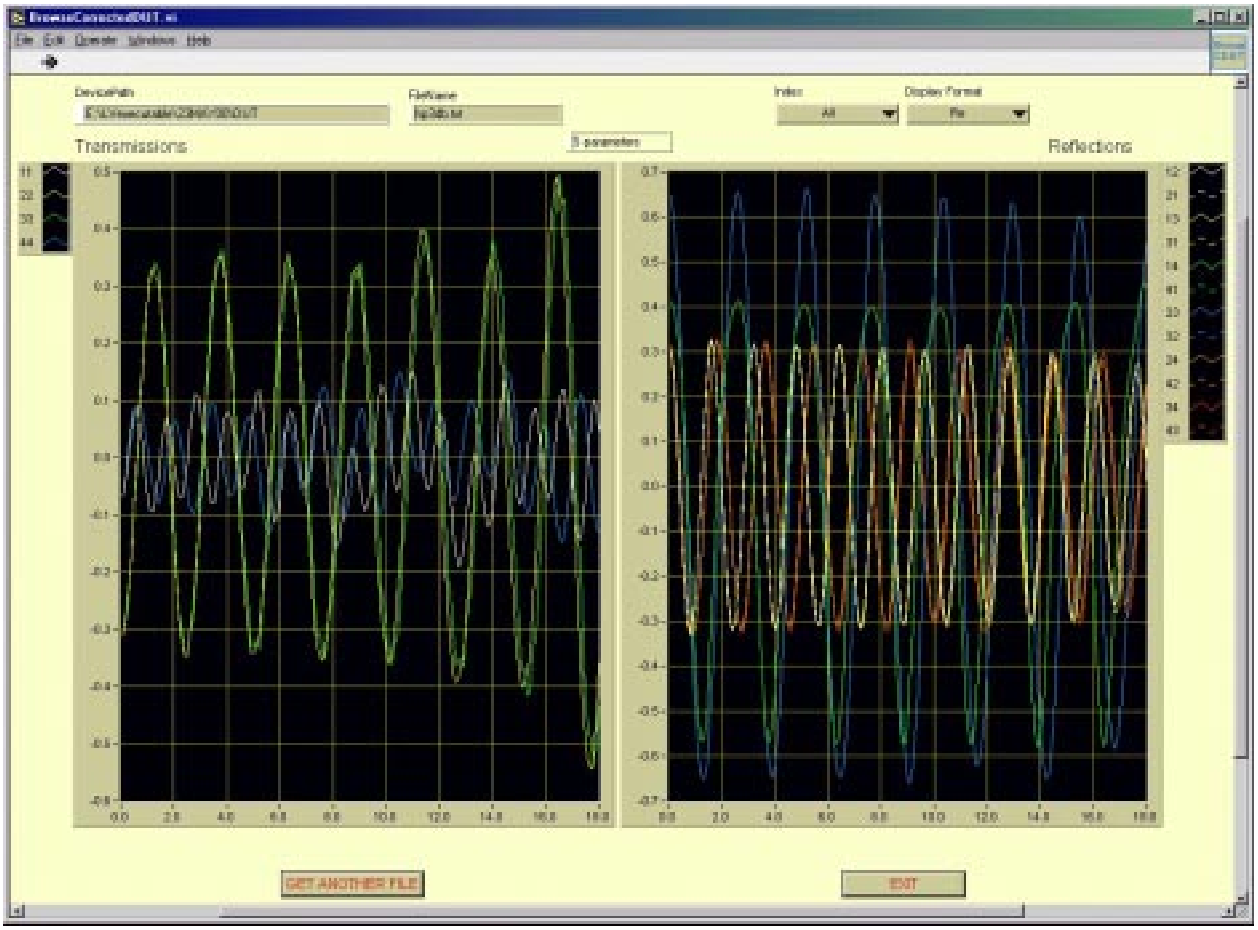


Figure 8. Select and plot correct DUT data.

For further information—
Please visit our web site, http://www.boulder.nist.gov/micro/, which features project descriptions, a comprehensive list of on-line references, and a convenient downloadable version of the multiport measurement software.

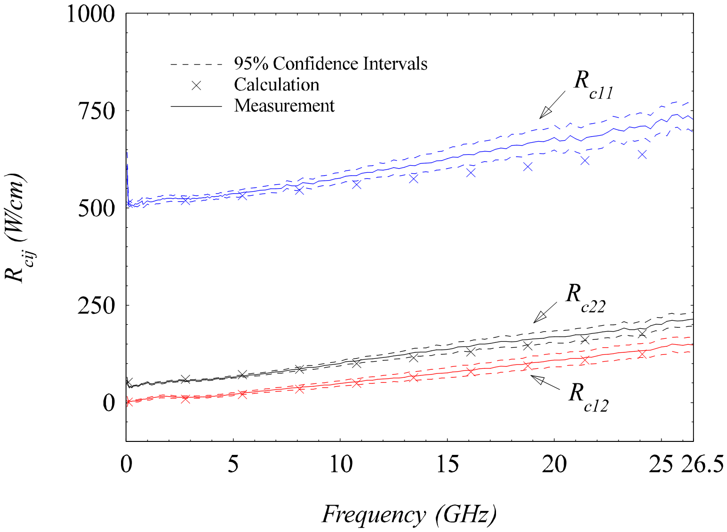


Figure 9. Resistance per unit length of a coupled transmission-line pair on a silicon substrate.

NIST Multiport Round-Robin

Accurate measurement of multiport devices has been hindered by the lack of a verifiable calibration and test methodology. This exciting multiport round robin allows you to compare your measurements to NIST's 7-mm four-port measurements. The five devices provided by NIST include a directional coupler, a 3 dB power divider, a 90° hybrid coupler, and a differential transmission line. To learn more or to participate, please visit our web site at http://www.boulder.nist.gov/micro/.

A differential transmission line; one of the multiport test devices.

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7. LabVIEW™ is a registered trademark of National Instruments Corp., Austin, Texas. Windows™ is a registered trademark of Microsoft Corporation. The use of the these trade names and software does not represent an endorsement by the National Institute of Standards and Technology, and other products may work as well or better.

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