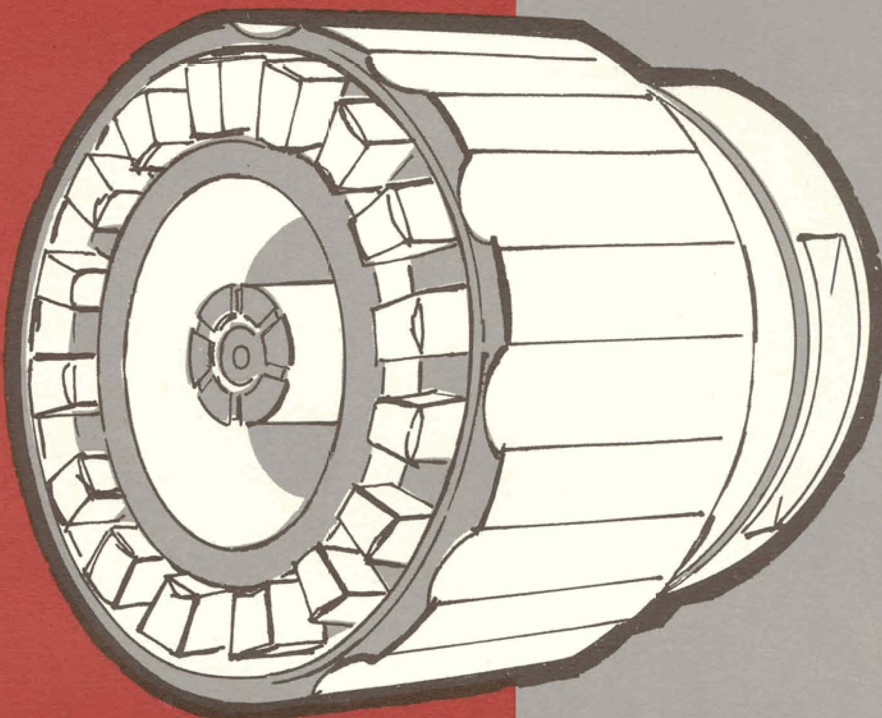
GR900®



PRECISION COAXIAL CONNECTORS, INSTRUMENTS, AND LINE ELEMENTS

GENERAL RADIO / ENGINEERING DEPARTMENT / E-115

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A COAXIAL CONNECTOR FOR HIGH-PRECISION MEASUREMENTS

For many years the accuracy of coaxial VSWR measurements has been limited to a few percent by the deficiencies of coaxial connectors. With the introduction of the GR900® line of coaxial measuring equipment, the limit is lowered by an order of magnitude, and VSWR measurements can be made to an accuracy of a few tenths of one percent. The principal factor in this substantial improvement is the GR900 Precision Coaxial Connector, with excellent repeatability and VSWR below 1.004 to 3 GHz and 1.01 to 8.5 GHz. Without such a precision connector, highly accurate measuring equipment was not only impossible to design but also not worth designing, since any improvements would be obscured by the connector deficiencies. The development of the GR900 Connector has overcome these problems and a line of precision coaxial instruments and components has been developed.

These instruments and components can also be used to advantage for measurements on systems fitted with other types of connectors through the use of adaptors. The errors introduced by these adaptors are small compared to the errors and uncertainties in the characteristics of most other connectors.

Description

The Type 900-BT Connector is intended for use on rigid air-dielectric, (14-mm) 50-ohm coaxial transmission line (principal dimensions: 0.5625 inch and 0.24425 inch). The connector (Figure 1) consists of (1) a solid silver-alloy inner conductor and spring contact, (2) a solid coin-silver outer conductor, stainless-steel centering gear ring, and locking nut, and (3) a solid Teflon* bead support. The connector is attached to the air line by a coupling nut and retaining ring on the outer conductor; the inner conductor is threaded into an 8-32 tapped hole in the center conductor of the air line. Silver is used extensively throughout the connector, and all silver parts are plated with a few microinches of gold to keep them from tarnishing.

Mating Surfaces

When two of these connectors are mated, the centering gear rings interlock and overlap in order to center each of the connectors with respect to the other, and also to provide indexing in one of 16 possible positions. The outer conductors have solid coin-silver flange-type surfaces, which are butted tightly together by the pressure of the locking nut. Only one of the locking nuts is necessary for the connection; the unused one is backed off into a storage position. The over-all diameter of the mated pair is only 1-1/16 inches.

The front surfaces of the inner conductors are recessed by 0.001 inch with respect to the surfaces of the outer conductors to insure that the outer conductors will always meet first. Inner conductor contact is made by a spring-contact assembly, which projects slightly beyond the surface of the outer conductors until the connector is mated (see Figure 2).

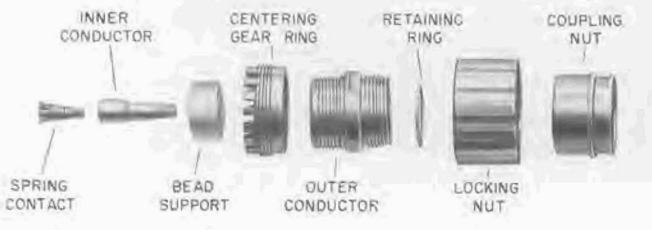


Figure 1. Exploded view of the Type 900-BT Precision Coaxial Connector.

The inner conductor contact is an extremely important element of a precision coaxial connector. The spring-contact assembly consists of six solid silver-alloy segments, independently sprung. Upon mating, these contacts are forced back and spread, making wiping contact both with one another and with the inside surface of the inner conductor. This method of mating inner conductors avoids the disadvantages of slots placed in the electric field, and it does not affect the diameter of the inner conductor. Only one spring contact is necessary for a good electrical connection; the spring contact will mate just as well with a flat surface.

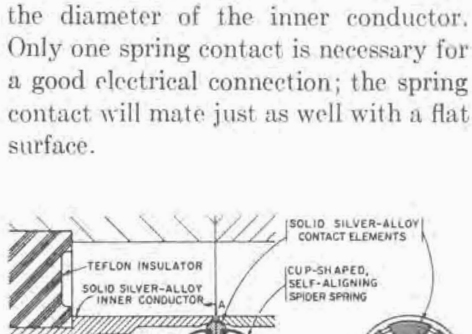


Figure 2. Cross-section view of the connector showing contact surfaces of two mated inner conductors.

With this contact design, extremely low junction impedance and excellent repeatability in VSWR and insertion loss are obtained.

When two connectors are mated, the conductors meet in the center of the connection, and this provides a very convenient electrical reference plane. (For instance, a reference short circuit consists of simply a disc, whose electrical position coincides exactly with the centerline of the mated pair.)

The outer conductors are held in alignment to within 0.001 inch by the centering gear rings and form a continuous

*Registered trademark of E. I. du Pont de Nemours and Company.

tube through the centerline of the joint. In this respect, the connection is as precise as that formed by the junction of two waveguide flanges of the type used in precision waveguide standards. Unlike waveguides, however, the mating surfaces are protected from accidental damage by the teeth of the gear ring, which extend well beyond these surfaces. If the surface of the outer conductor is damaged or soiled, the gear ring and the spring contact can be removed without disassembling the connector, and the mating surface can be lightly lapped to restore it to its original condition.

Bead Support

An essential part of any generally useful coaxial connector is the bead support, and this part usually is the most troublesome to design. A new approach has been used in the GR900 Connector, in order to take advantage of the excellent electrical properties of Teflon without incurring the disadvantages associated with its difficult mechanical properties. The bead is made slightly larger than the inner diameter of the outer conductor, so that a press fit is necessary. Similarly, the bead thickness is slightly oversized, and the hole for the inner conductor undersized, so that the bead finally assumes the dimensions of the metal parts rather than its original dimensions. The faces of the bead are undercut to compensate for discontinuity capacitances at the interface. The depth of these undercuts is used to keep bead weight within close tolerance. Weight has been found to have a first-order effect on VSWR, while minor variations in dielectric constant or mechanical dimensions with weight held constant have only a second-order effect. As further advantages, the press-fit Teflon bead holds the inner and outer conductors together in a rigid assembly and keeps dirt and moisture from entering the line or component.

The electrical performance of the bead support determines the performance of the connector. The type of bead used in this connector was described by M. Ebisch.[1] The characteristic impedance inside the bead is exactly 50 ohms. Both

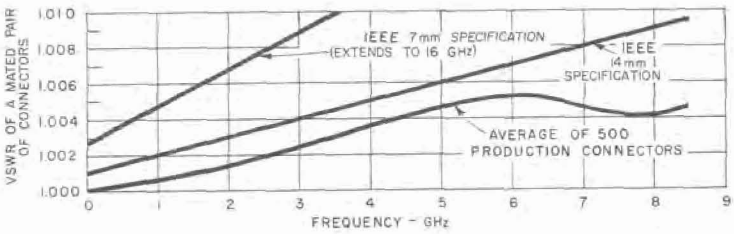


Figure 3. Type 900-BT Connector VSWR vs frequency. All connectors must meet the test specification shown.

the inner and outer conductors are stepped to accommodate the bead, for it has been found that the bead end capacitance is thus minimized. The effect of the remaining end capacitance is compensated by removal of some of the dielectric from both faces of the bead. As a result, the VSWR of a single bead support of this type can be held to less than 1.001 up to 8.5 GHz. The performance of the connector is theoretically equal to that of a beadless connector, and the only limitations are those imposed by manufacturing tolerances.

Performance

VSWR

The most important characteristic of a precision connector is, of course, its VSWR; that is, the extent to which it introduces reflections into an otherwise matched transmission line. Figure 3 shows the VSWR test specifications that each connector pair must meet ($1.001 + 0.001\, f_{GHz}$), as well as an average characteristic. Connector VSWR is measured at six frequencies up to 8.5 GHz. Since it is impossible to say how much each connector contributes to the VSWR of the pair, the test limits for the pair are used as the catalog specification for a single connector. Since the VSWR of these connectors is well below 1.01 over the entire frequency range, several new techniques and new instruments had to be developed to measure such low values of VSWR. For example, a substitution method of measuring the VSWR of precision connectors[2,3] was devised to distinguish the VSWR of the connectors from the residual VSWR's in the slotted line and termination. In this method the basic standard is a short length of rigid air line whose characteristic impedance can be accurately calculated. A slotted-line recording system was developed, which made possible the measurement of VSWR's as small as 1.0005 by a substitution method. The chart record of such a measurement is shown in Figure 4; the full-scale value of VSWR can be adjusted continuously from 1.20 to 1.008.

Repeatability

Another very important characteristic of a precision connector is repeatability, that is, the consistency of measured value as the connection is broken and remade in different orientations. The repeatability of the butt joint of the outer conductors is virtually perfect as long as the faces are kept reasonably clean and free from nicks or scratches. The connection of the inner conductors repeats to within ±.03% up to 8.5 GHz, owing mainly to the action of the spring contacts, which maintain a good connection even when there is some misalignment, without transmitting torque or bending moments across the joint. This is important because the two inner conductors are rarely perfectly centered with respect to the outer conductors, so that, as two connectors are mated in different orientations, the alignment of the two inner conductors changes. The misalignment itself is not so important as the stresses and strains introduced when "bullets" are used to force the center conductors into alignment. A chart record of a repeatability run is shown in

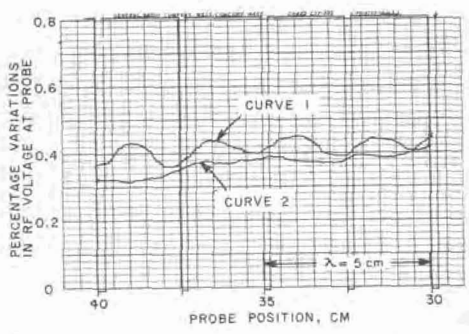


Figure 4. Chart record of the measurement of the minimum detectable VSWR. Curve 1 shows a peak-to-valley voltage variation of 0.05%, corresponding to a VSWR of 1.0005. Curve 2 shows for comparison a "flat" line, VSWR = 1.0000. The frequency is 6 GHz.

[1] See Reference 3.
[2] See Reference 19.
[3] See Reference 17.

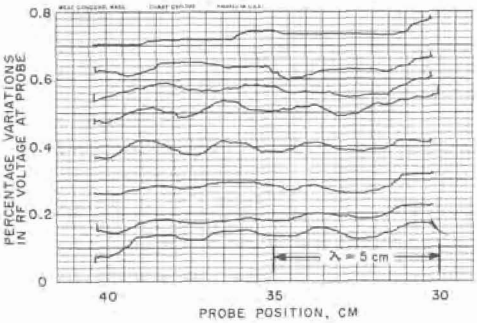


Figure 5. Repeatability of the GR900 Connector at 6 GHz. Between each pair of lines on the chart, the connection was broken, rotated 45°, and remade. The spread in measured VSWR's is less than ±0.02%.

Figure 5; between each line the joint was broken, rotated 45 degrees, and remade. The total spread is less than ±0.02%.

Leakage

The leakage of energy from a coaxial connector can be of great importance in measurements at low levels, or when large amounts of attenuation are present in the system. For example, energy could be lost at the input connector of an attenuator and recovered at the output connector, causing an erroneous indication of attenuation. The leakage of the GR900 Connector is compared with that of other types of connectors in Figure 6, and is lower than that of any other commonly used coaxial connector.[4]

[4] See Reference 34.

This is due to the triple shielding action of (1) the butt contact of the outer conductors, (2) the interlocking and overlapping of the centering gear rings, and (3) the outer locking nut.

Insertion Loss, Electrical Length, and DC Resistance

The insertion loss or attenuation of the GR900 Connector is minimized by the use of Teflon for the bead and solid silver alloys for both the inner and outer conductors (silver-plated surfaces are relatively poor conductors in contrast to these alloys). The insertion loss of a mated pair depends on frequency, according to the following approximate formula:

$$\text{Loss} = \sqrt{f_{GHz}} \times 0.002\,\text{dB}.$$

This is virtually the same as the loss in an equivalent length of silver, air-dielectric transmission line.

The electrical length of a pair of Type 900-BT Connectors is 3.50 cm and is virtually independent of frequency. The dc resistance of a mated pair is typically 0.4 milliohm for the inner conductors, and 0.04 milliohm for the outer conductors.

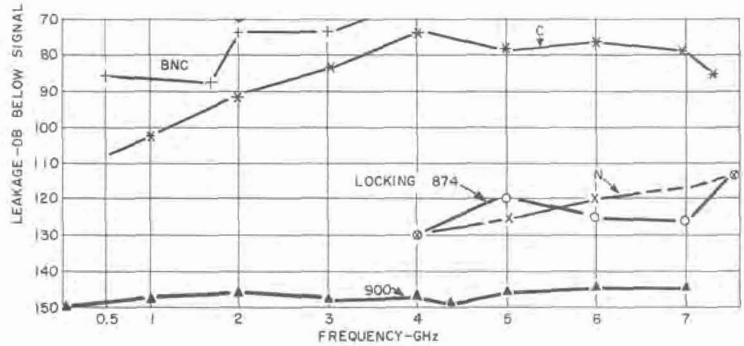


Figure 6. Leakage of coaxial connectors as a function of frequency.

SPECIFICATIONS

Frequency Range: DC to 8.5 GHz.

VSWR: Less than $1.001 + 0.001 \times f_{GHz}$ per connector. (Connectors are tested by pairs, and this figure is used as the test limit for a *pair* of connectors.)

Repeatability: Within 0.05%.

Leakage: Better than 130 dB below signal level.

Insertion Loss: Less than $0.003\sqrt{f_{GHz}}$ dB per pair.

Electrical Length: 3.500 ±0.005 cm per pair.

DC Contact Resistance: Inner conductor, less than 0.5 milliohm; outer conductor, less than 0.07 milliohm.

Dimensions: Length of one connector, 1-3/16 inches (31 mm); maximum diameter, 1-1/16 inches (27 mm).

Net Weight: 2 ounces (60 grams).

PRECISION COAXIAL CONNECTOR PAIRS WITH CALIBRATION CERTIFICATE

Since the introduction of the Type 900-BT Precision Coaxial Connector in 1963, every one of these connectors has been VSWR-tested before shipment. Connectors are tested in *pairs* at 1.5, 3, 4.5, 6, 7.5, and 8.5 GHz and are then separated and sold singly, with the actual test specification for the pair used as the guaranteed specification for the single connector. The VSWR of two connectors bought singly could be as high as twice that specified for a single connector, even though it is almost certainly much lower than that. On the other hand, if one could be sure of buying the same two connectors that were tested together, he would effectively halve the guaranteed VSWR of the pair. For the benefit of those whose applications demand exact calibration data or connector-pair performance guaranteed within the specifications of the IEEE Recommended Practice,[1] we are now offering pairs of Type 900-BT Connectors, together with calibration certificates.

The 0900-9407 Connector Pair comprises a pair of serial-numbered connectors and a certificate of compliance with VSWR specifications. Specified VSWR data apply whether the two connectors are mated together or mounted on opposite ends of low-loss, low-VSWR lines, 10, 20, 30, or 40 cm long (including connectors). When the connectors are installed on lines of other lengths, the insertion VSWR may differ from the calibration values. This is also true when only one connector of the pair is used. In practice, this discrepancy is small because of the excellent basic design of the connector.

The discontinuities in the connectors are small, and the connectors are relatively short electrically; it is therefore valid to connect the six calibration points with a continuous curve on the calibration chart (see Figure 1).

Test Procedure

The connectors are mounted on precision 50-ohm air-line sections and are

[1] "Coaxial Microwave News," *The General Radio Experimenter*, February–March 1965.

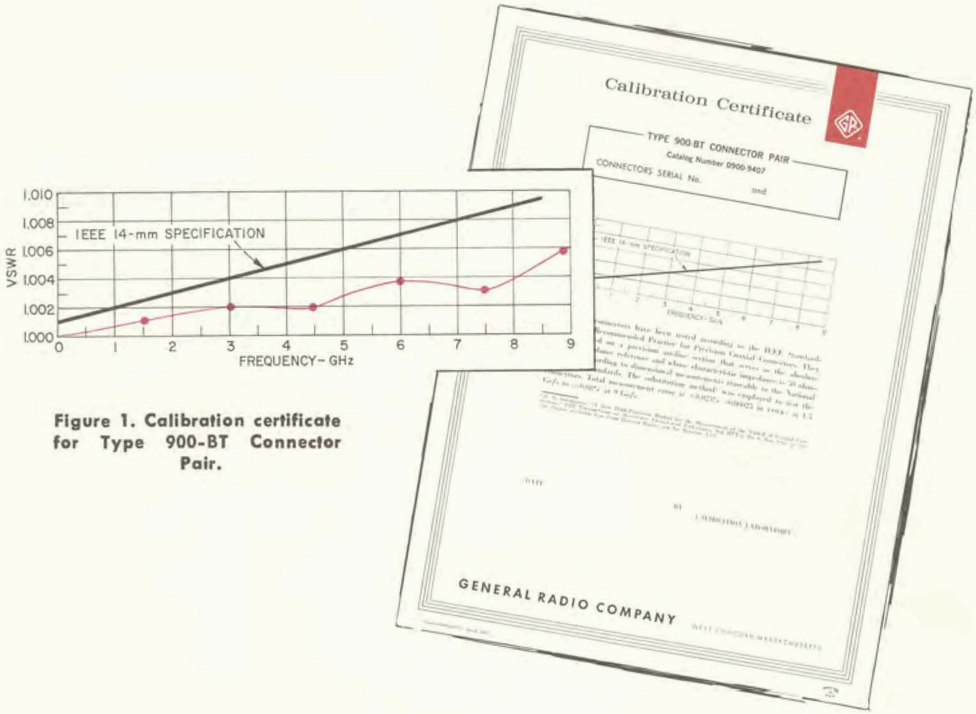


Figure 1. Calibration certificate for Type 900-BT Connector Pair.

tested by the substitution method.[2,3] The air lines, including the connectors, are 10 cm long and are therefore half-wave multiples at the test frequencies. Characteristic impedance of the air-line section is held to better than ±0.015%. Except for the influence of skin effect, the impedance of a rigid air line is strictly a function of its diameters. These diameters are measured with precision gauges, whose accuracy is traceable to the National Bureau of Standards. The total measurement error including repeatability is 0.025% at 1.5 GHz, increasing linearly to 0.08% at 8.5 GHz.

At lower frequencies, the test-line impedance deviates from 50 ohms because of skin effect. In precision applications, the connectors are installed on air-line sections similar to those on which the connectors were tested. Therefore, the skin-effect impedance deviation does not introduce reflections in the transmission-line system. Skin-effect corrections are, however, required for some applications at frequencies below about 500 MHz. Such corrections have been discussed in the literature.[4]

Applications

The 0900-9407 Connector Pair is recommended for use where a mated pair of connectors having an accurately known VSWR is required, where guaranteed compliance with the pertinent sections of the IEEE Recommended Practice is sought, and in the testing of transitions, connectors, adaptors, and other low-loss transmission devices (see Figure 2).

[2] See Reference 19.
[3] See Reference 17.
[4] See Reference 33.

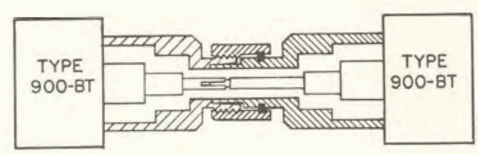


Figure 2. Use of calibrated connector pair to test UG adaptor pair. Electrical length of complete test device should be multiple of 10 cm.

PRECISION CONNECTOR FOR COAXIAL CABLE

The GR Type 900-C9 is a precision coaxial connector for flexible cable.

Why is such a connector needed? Connector manufacturers argue that there is a limit to how good a cable connector need be because cables are generally poorer (some cable manufacturers indicate that cable VSWR of 1.20 is considered good). Some cable manufacturers hold that the cables are good and the connectors have been generally poor (recent MIL connector VSWR specifications are 1.200—1.30). Actually, both views are valid. Most flexible cables have random characteristic-impedance variations that produce significant reflections at microwaves; but nevertheless, very good pieces of cable can be selected. The connector reflections in this case may limit the performance. Hence the need for a good flexible-cable connector. The Type 900-C9 Precision Cable Connector meets this need.

DESIGN CONSIDERATIONS

The principal performance goal in the design of the Type 900-C9 Cable Connector was the achievement of low VSWR and its maintenance by means of reliable techniques for assembly and for attachment to the cable. These were the same goals sought in the GR874 "A" series cable connectors [1] but which could not be fully realized there because of the general requirement for the crimped-ferrule method of attachment.

Crimping, which is used with many UG connectors, compresses the cable and produces a significant reflection at the joint. In the Type 900-C9 a new

[1] J. Zorzy, "New Coaxial Cable Connectors," *General Radio Experimenter*, August–September, 1962.

method of attachment is used, which eliminates this compression.

The assembly procedure is an important design consideration. The principal aims are precise axial location of the internal connector parts and a good solder joint without flow of cable dielectric. These aims have been achieved in the Type 900-C9 by the use of an assembly that is self-aligning, the use of a Teflon heat-barrier

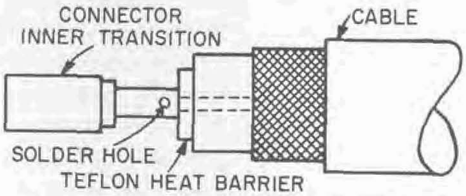


Figure 1. Inner-transition assembly showing Teflon disk.

disk [2], and the use of low-temperature solder, which is furnished with each connector. The disk in position is shown in Figure 1.

Three important requirements affect the design of the mechanical attachment for the cable braid and jacket: (1) the electrical connection between the braid and the connector must not produce discontinuities; (2) the assembly must stand up under typical use by resisting twisting and/or pulling forces; and (3) the cable must not be compressed. These requirements are met by the attachment method shown in Figure 2. The braid is captured by a combination of butt and radial forces. The outer transition has a diamond-pattern knurl similar to that used on the GR874-series connectors. The radial forces come into play as the rubber gasket presses both the jacket and the braid against the knurled portion of the outer transition when the retainer body is threaded up tight. To obtain continuous and reliable electrical connection between the cable braid and the outer transition, the end of the transition is faired in, and the rubber gasket is extended into this region to press the braid against the faired-in edge.

The resulting joint is strong and resists the pull and torsion ordinarily encountered in use of a cable connector. In a pull test the connector assembly supported the 170-pound weight of the writer.

[2] *Op. Cit.*

A low-VSWR junction is achieved at the braid joint, and it does not deteriorate with use.

The inner and outer transitions are accurately positioned in the connector by means of the modified GR900 connector to which these are assembled. Axial relations are maintained automatically; nothing is left to skill or special tools. After assembly of the connector, the retention system described above is tightened, and the braid is automatically positioned as the connection is tightened.

The GR900 connector used is similar to the Type 900-BT except that the Teflon support, instead of being a press-fit into the body, is a sliding fit, which is necessary to facilitate the assembly of the cable connector.

VSWR PERFORMANCE

In order to assess the VSWR characteristics of this connector, a good piece of RG-214/U cable was obtained. Its characteristic impedance was $50 \pm 1\%$, and it was free of any significant impedance nonuniformities. The VSWR characteristics of the Type 900-C9 Connector mounted on this cable are shown in Figure 3. The cable was taken as infinite in length.

APPLICATIONS

The Type 900-C9 Cable Connector is recommended for any indoor flexible-cable application when an extremely low VSWR connection is required or when a connection to other GR900 components is required. This connector also makes possible the accurate measurement of the VSWR characteristics of cables at microwaves and VSWR tests of cable connectors to new MIL specs, such as MIL-C-39012.

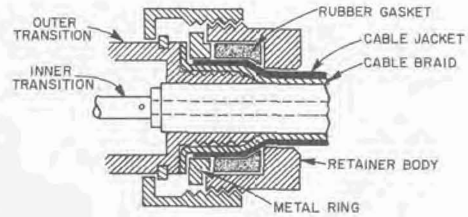


Figure 2. Braid and jacket-retention system shown before coupling ring is tightened.

It is difficult to get a perfect 50-ohm termination for a cable. The so-called infinite cable termination is a poor one, because most cables have both random and periodic impedance variations. A relatively short piece of cable (in a short piece, the multitudes of small reflections cannot add up to cause a large reflection), terminated in the Type 900-C9 and the Type 900-W50 Termination, is better.

The Type 900-C9 Precision Cable Connector was designed for use with the RG-214/U and for the RG-9 cables. It can be used with other popular cables of this size, for example, the RG-213/U or the RG-8 cables, but, because these cable diameters are smaller, the hole in the retainer body provides too much clearance. A turn or two of electrical tape, however, will build up the diameter to fit. The connector can be used with still other cables, but the mechanical clamping may not be effective because of deviations of over-all diameter or, with armored cable, lack of means for clamping the armor.

SPECIFICATIONS

Frequency Range: DC to 8.5 GHz.
Characteristic Impedance: 50 Ω.
Leakage: Better than 130 dB below signal.
Insertion Loss: Less than $0.006\sqrt{f_{GHz}}$ dB per pair.
Maximum Voltage: 1500 V peak.
Dimensions: Length of one connector, 2⅛ inches (54 mm); maximum diameter, 1 1/16 inches (27 mm).
Net Weight: 2½ oz (75 g).

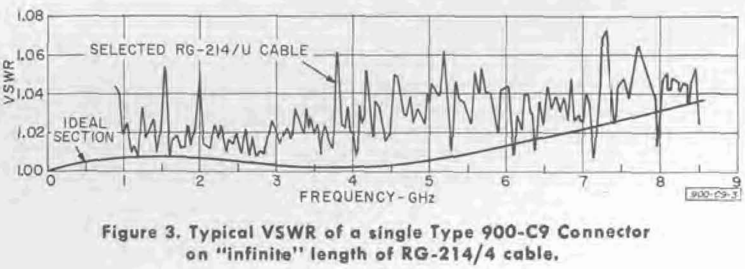


Figure 3. Typical VSWR of a single Type 900-C9 Connector on "infinite" length of RG-214/4 cable.

PANEL MOUNTING KIT FOR PRECISION COAXIAL CONNECTORS

The TYPE 900-PKM Panel Mounting Kit is a simple conversion kit for adapting a GR900 connector, or any component equipped with a GR900 connector, to panel mounting. This application includes adaptation of GR-900 connector devices as panel feed-through or "bulkhead" connectors.

The kit comprises one gear-ring assembly; four 4-40 screws, ½ inch long; four nuts and lockwashers; and a detailed instruction sheet.

A centering (gear) ring is modified to include a flange, as shown in Figure 1. It is installed directly on any GR900 connector after removal of the existing centering ring and locking nut.

The resulting panel connector does not contain a locking nut, since the locking nut on the mating connector is usually all that is needed. When two panel connectors are to be mated, a TYPE 900-L Air Line can be used.

Examples of applications of this kit are shown in Figures 1 to 4. Note that the flange mounted on the front face of the panel (Figure 2) provides the greatest accessibility and ease of connection. If necessary, the flange can be mounted behind the panel at the expense of accessibility and possibly appearance. Accessibility, in this case, is a matter of how much of the locking nut of the mated connector can be grasped during tightening. This recessed mounting configuration is shown in Figure 4.

Specific applications include: panel connector for frequency- or time-domain reflectometers or similar test sets, equipment modules, and rack-mounted assemblies where a feed-through from the rear to the front of the rack is required.

Over-all panel space required by the flange of the unit is 1$\frac{3}{16}$ inches on each side.

Weights: Net, 1 oz (30 g); Shipping, 8 oz (230 g).

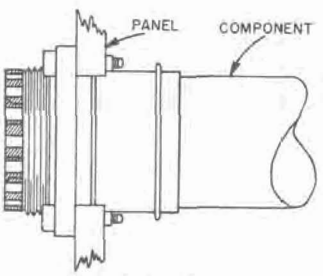


Figure 1. Panel connector mounted with air line.

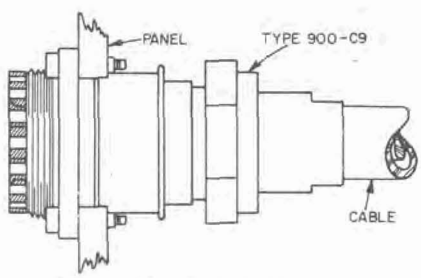


Figure 2. Panel connector mounted with coaxial cable.

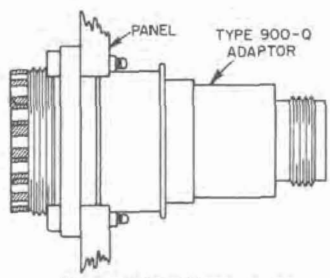


Figure 3. Panel connector mounted with a Type 900-Q Adaptor.

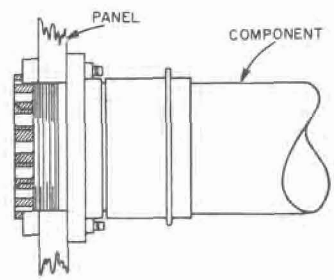


Figure 4. Panel connector mounted with flange behind panel.

CONNECTOR KITS FOR CUSTOM LINES

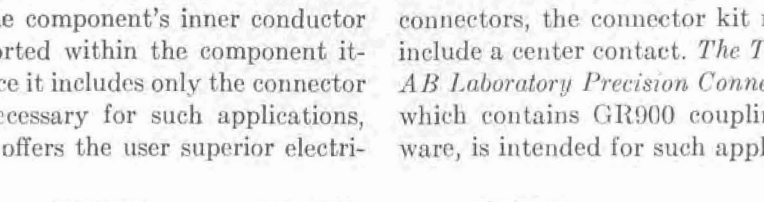
Three new connector kits permit custom fabrication of reference air lines and components compatible with GR-900 connectors.

The Type 900-AP Laboratory Precision Connector Kit is designed for use with coaxial elements with unsupported inner conductors. A reference air line of custom length, for instance, can be assembled from a pair of these kits and appropriate lengths of precision rod and tubing (General Radio No. 0900-9507 and 0900-9509, respectively).

The Type 900-AC Laboratory Precision Connector Kit contains the coupling hardware and center contact of a standard GR900 connector. It can be used in place of a TYPE 900-BT connector when the component's inner conductor is supported within the component itself. Since it includes only the connector parts necessary for such applications, this kit offers the user superior electrical performance at a considerable saving in cost.

One center contact of the GR900 connector is all that is necessary for the electrical connection of two GR900 connectors. Therefore, when a component is to be used exclusively with GR900 connectors, the connector kit need not include a center contact. *The Type 900-AB Laboratory Precision Connector Kit,* which contains GR900 coupling hardware, is intended for such applications.

Figure 1. Cross-section view of coaxial line sections fitted with Types 900-AP, 900-AC, and 900-AB Precision Coaxial Connector Kits. Type 900-AP connection is same as that used in the Type 900-LZ Reference Air Lines.



ADAPTOR FLANGE FOR GR900

This flange is a general-purpose device which converts any GR900 component connector to a flange connector, making use of the fact that the inner contact of the TYPE 900-BT works suitably against any flat surface with no special additional contacting device or bullet required. The configuration is shown in Figure 1.

Applications

For connecting to a coaxial system ending in flat, flush surfaces, typically in special bridges.

SPECIFICATIONS

Mounting Holes: 0.157 ± 0.005-inch dia, 120° ± 0.5° apart on a radius of 0.812 ± 0.003 inch.

Net Weight: 3 ounces (85 grams).

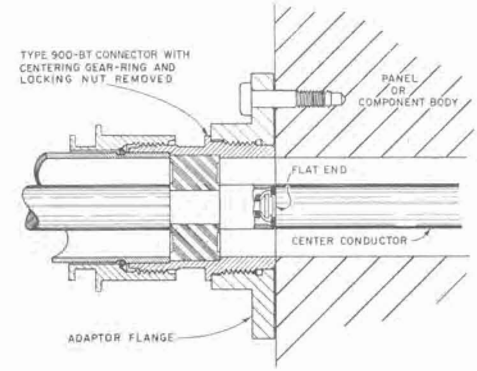
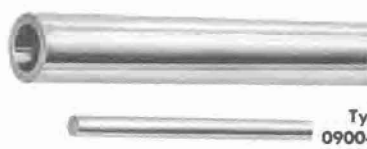


Figure 1. Flange adaptation on Type 900-BT Connector.

PRECISION ROD AND TUBING



Type 0900-9509

Type 0900-9507

For those who wish to assemble coaxial systems using the GR900 Connector, coaxial air-line rod and tubing having extremely tight diameter tolerances are now offered by General Radio Company. The rod is brass with a layer of silver approximately 0.0005-inch thick and a finished diameter of 0.24425 inch ±65 microinches. The tube has a layer of silver approximately 0.0005-inch thick and a finished inner diameter of 0.5625 inch ±140 microinches. Both tubing and rod are stress-relieved to minimize diameter changes due to machining and are straightened. The instruction sheet provides directions for machining the material for use with the TYPE 900-BT Connector, including procedures for minimizing dimensional changes. At frequencies where skin depth is negligible, the characteristic impedance of a transmission line made from this material is 50 ±0.0013 ohms, or ±0.065%. The skin-depth deviation as a function of frequency[1] is shown in Figure 1.

[1] See Reference 33.

There is a practical limit to the length of the precision air line that can be made from this material because of inner conductor sag. An expression for the sag is given below. This expression is pessimistic because the connectors provide some cantilever support. The characteristic impedance of a coaxial transmission line with an eccentric inner conductor is given by

$$Z_o = A \cosh^{-1}\left[\frac{b}{2a}\left(1 - 4\frac{\epsilon^2}{b^2}\right) + \frac{a}{2b}\right]$$

where

A = 59.9368

b = coaxial line outer conductor ID

a = coaxial line inner conductor OD

ϵ = amount by which conductor is off center

The sag, ϵ, at the center is given approximately by,

$$\epsilon \cong \frac{l^4}{15 \times 10^6} \text{ inches}$$

where l is the length of the inner conductor in inches.

For a 16½-inch length, the sag, ϵ, is 0.005 inch at the center.

The characteristic impedance error calculated from the above formula along an incremental length of line at the center is −0.046% for this amount of sag (see Figure 2). Therefore, 16½ inches may be considered the longest permissible air-line section for precision work. With TYPE 900-BT Connectors at each end, the corresponding air line is 45.5 cm long, electrically.

When maximum accuracy is desired for the longer line sections, the line should be mounted vertically.

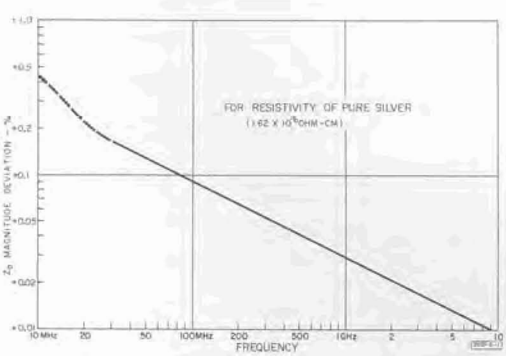


Figure 1. Skin-effect characteristic-impedance error as a function of frequency.

Applications

Precision rods and tubing can be used to construct precision sliding loads and shorts, air lines, and precision 50-ohm impedance and time-delay standards. They can also be used as general components.

SPECIFICATIONS

Net Weight: Rod, 7 ounces (0.2 kg); tube, 2½ pounds (1.2 kg).

Length of Each Rod: 13 inches (330 mm); two rods supplied.

Over-all Length of Tube: 27 inches (690 mm).

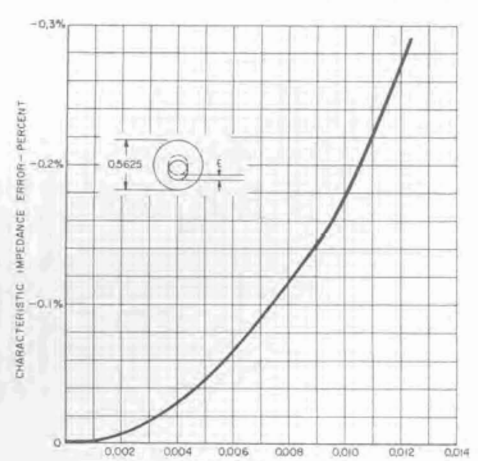
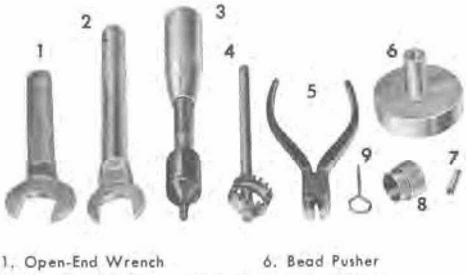


Figure 2. Characteristic-impedance error vs sag in inner conductor.

TOOL KIT



1. Open-End Wrench
2. Coupling-Nut Torque Wrench
3. Inner-Conductor Torque Wrench
4. Gear Wrench
5. Inner-Conductor Plier
6. Bead Pusher
7. Inner-Conductor Injector
8. Bead Compression Sleeve
9. Spring-Contact Wrench

The TYPES 900-BT and 900-C9 Precision Coaxial Connectors should be assembled with the TYPE 900-TOK Tool Kit, both for the best precision and for avoidance of damage to connector. The tool kit, designed for this purpose, includes all the tools required to assemble the GR900 Connector and the devices needed to reassemble a connector that has been inadvertently disassembled or to replace damaged parts. The tool kit contains an open-end wrench, a coupling-nut torque wrench, an inner-conductor gripping plier, and a contact Allen wrench. In addition, for connector reassembly, it contains an inner conductor injector, a bead compressor sleeve, and a bead pusher.

For some users, purchase of the complete tool kit may not be wholly justifiable. It is possible to install the connectors on components with ordinary tools, listed below. It is not possible, however, to reassemble a connector that has been completely disassembled because the parts are press-fitted together with the assembly tools furnished in the TYPE 900-TOK Tool Kit.

The following tools may be employed to install connectors. Extreme care must be used, so as not to apply excessive torque and thus damage connector parts.

1. Two 11/16″ open-end wrenches with 3/32″-wide blade (bicycle type).

2. One, and in some cases two, 5/32″ Allen wrenches.

3. One inner-conductor gripper, a plier device with a padded 0.244″-dia hole to hold the inner conductor upon which the connector is to be installed. Alternately, a gripping device can be made from two strips of plastic, held firmly together in a vise and drilled with a 15/64″ drill. The inner conductor is installed in the hole and gripped in the vise.

4. One 1/16″ Allen wrench.

PRECISION ELL

In precision coaxial measuring systems, the simple matter of going around corners is not so simple, and very careful design is necessary to achieve a right-angle turn that will not introduce reflections. With the introduction of a GR900 precision ell, it is now possible to make a 90-degree turn with a residual VSWR of less than 1.01 at 1.5 GHz and less than 1.02 at 4 GHz.

The change in direction takes place in a transmission line whose axis describes a 90° circular arc. The uniformly varying change in direction along the arc results in an essentially uniform characteristic impedance.

In the curved region of the ell, the conductors have square cross sections. Where these sections join the standard 14-mm line of round cross sections, coplanar compensation is employed. The ell is, of course, equipped with GR900 precision connectors.

The electrical length of the ell is nominally 10 cm, but, because of the finite curvature, the electrical length increases with increasing frequency.

Uses

The ell is especially useful in systems involving complex interconnections where it is necessary to minimize reflections and to maintain phase linearity as, for instance, in precision phase- and attenuation-measuring systems.

For measurements of dielectric properties with the 900-LB Slotted Line,[1] it is not always convenient to connect the sample holder directly to the slotted line. If, for instance, the dielectric to be measured is a liquid, the sample holder usually must be vertical. Vertical orientation is also often necessary for sample holders placed in environmental chambers. In such applications the ell connects the sample holder to the slotted line with very little loss in accuracy.

[1] See page 30.

VSWR characteristics of precision ell.

SPECIFICATIONS

Frequency Range: Dc to 8.5 GHz.

Characteristic Impedance: 50 Ω ±0.4% at frequencies where skin effect is negligible.

VSWR: Less than $1.004 + 0.004 f_{GHz}$. See curve.

Electrical Length: $[10.00 + 0.0014 (f_{GHz})^2 \pm 0.02]$ cm.

Insertion Loss: Less than $0.017\sqrt{f_{GHz}}$ dB.

Maximum Voltage: 1500 V peak.

Maximum Power: 10 kW up to 1 MHz; $10\ kW/\sqrt{f_{MHz}}$ above 1 MHz.

Mating Dimensions: 2.066 in. (5.246 cm) from center line of one connector to reference plane of second connector.

Over-all Dimensions: 2 11/16 by 2 11/16 by ⅞ in. (68 by 68 by 22 mm).

Net Weight: 10 oz (280 g).

REFERENCE AIR LINES

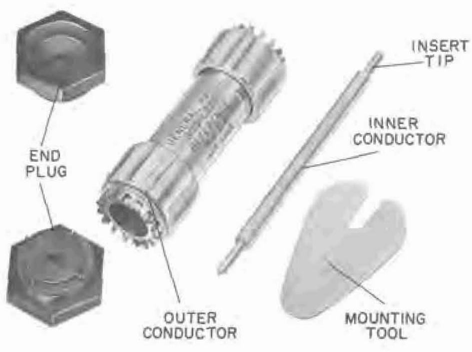


Figure 1.

GR900 Reference Air Lines derive exceptionally low VSWR chiefly by the elimination of bead supports. The inner conductor is suspended instead by the center contacts of the GR900 connectors with which the air line is mated. Use of the beadless GR900 connection helps make the accuracy of these air lines several times that of the Type 900-BT Connector. Thus GR900-equipped instruments and components can now be quickly and conveniently calibrated with respect to the new standards. For example, the TYPE 900-LB Precision Slotted Line, whose VSWR accuracy specification is 1.001 + $0.001 f_{GHz}$, can typically be calibrated to an accuracy of 1.0008 or better with the TYPE 900-LZ Reference Air Lines and a TYPE 900-TUA or -TUB Tuner. With this new calibration system, the customer can now verify the performance of any GR900 device and, if he desires, correct measured data for the effect of the small residual VSWR's that are present. Furthermore, the reference air lines are themselves "checkable" by means of electrical half-wave-substitution measurements and mechanical measurements of diameter and length (in turn traceable to the National Bureau of Standards).

The ultimate standard of 50-ohm impedance upon which the entire GR-900 line is based is the characteristic impedance of the TYPE 900-LZ Reference Air Lines shown in Figure 1. These are coaxial transmission lines of very accurately controlled mechanical dimensions, and thus of known characteristic impedance and electrical length. The characteristic impedance depends primarily on the ratio of diameters of the inner and outer conductors and is controlled to 50 ohms ±0.05% with tolerances of 100 and 50 microinches on outer and inner conductors, respectively.[1] Both inner and outer conductors are overlaid with pure silver for minimum loss. The electrical lengths are controlled to ±0.002 cm and are slightly shorter than the nominal length to allow for the dielectric constant of air (1.0007) and for the fact that the velocity of light is not exactly 3×10^{10} cm/second but 2.997925×10^{10} cm/second. This adjustment makes the line lengths exactly integral numbers of wavelengths at integral frequencies (1 GHz, 2 GHz, etc) for convenience in calibrations. Since the time delay and capacitance of each line also come out in round numbers, the air lines are convenient standards of these parameters as well as of impedance. The specifications table lists quarter-wave-length frequencies, capacitances, and time delays for the six reference air lines presently available (5, 6, 7.5, 10, 15, and 30 cm).

[1] For skin-effect corrections, see Reference 33.

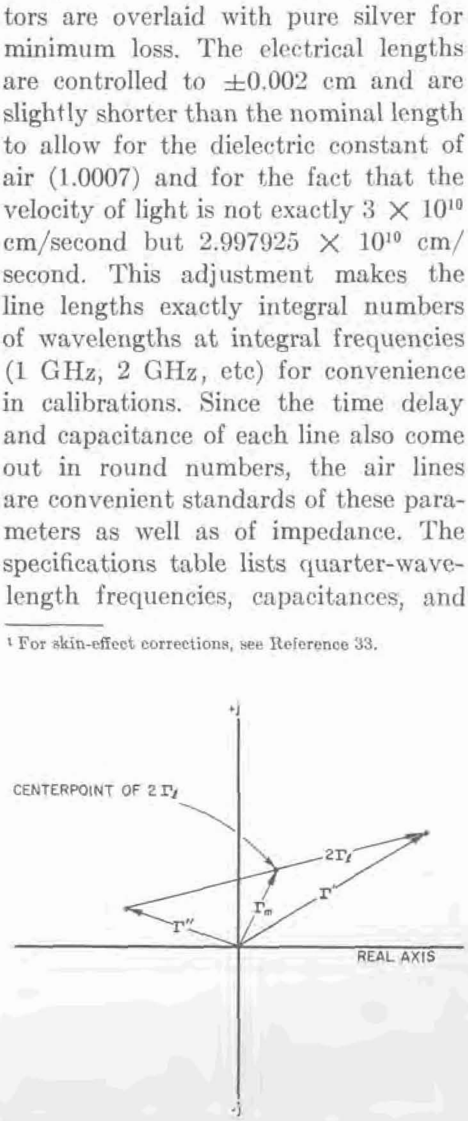


Figure 2. Smith-chart determination of instrument reflection coefficient (Γ_m) and load reflection coefficient (Γ_l) from measured values of Γ' and Γ'', with quarter-wave reference air line.

The inner conductor of the reference air line derives its support from the connectors in the system under test, obviating the need for dielectric bead supports within the air line. The inner and outer conductors are of equal length and without steps, joints, or slots, which would destroy their usefulness as calculable standards of microwave impedance. When connected to a system under test, the reference air line is an ideal section of transmission line from the reference plane on the input connector to the reference plane on the output connector.

Applications

(1) The use of ideal sections of transmission line, for example, the 900-LZ Reference Air Lines, to calibrate measuring instruments and components is illustrated in Figure 2. When a termination with a finite reflection coefficient is measured on an instrument having a finite error, the measured reflection coefficient equals the *vector* sum of the reflection coefficients of the two devices. The equation for small reflection coefficients ($\Gamma < 0.1$) is:

$$\Gamma' = \Gamma_m + \Gamma_l \qquad (1)$$

where

Γ' = initial indicated reflection coefficient,

Γ_m = residual reflection coefficient of the instrument,

Γ_l = load reflection coefficient.

The insertion of a reference air line of electrical length L between the measuring instrument and the load has no effect upon the Γ_m vector, but rotates the phase of the Γ_l vector by $4\pi L/\lambda$ radians about a point on the Smith chart equal to the characteristic impedance of the air line. This fact is the key to the separation of instrument error from load error and to their measurement with respect to a known and calculable rf impedance, the characteristic impedance of the reference air line.

For calibration purposes, the most convenient lengths of reference air line are the odd quarter wavelengths, for the rotation of the Γ_l vector is then π

radians, or 180 degrees, corresponding to a change of sign of the Γ_l vector. The measured value of reflection coefficient after insertion of the reference air line, Γ'', is therefore:

$$\Gamma'' = \Gamma_m - \Gamma_l. \qquad (2)$$

Vector addition of equations (1) and (2) and rearrangement yield the residual reflection coefficient of the measuring instrument:

$$\Gamma_m = \frac{\Gamma' + \Gamma''}{2} \qquad (3)$$

Vector subtraction of equation (2) from equation (3) yields the reflection coefficient of the load:

$$\Gamma_l = \frac{\Gamma' - \Gamma''}{2}. \qquad (4)$$

The corresponding VSWR's are obtained from the formula:

$$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

The above results can be generalized to apply to lengths other than odd quarter wavelengths and to two-port as well as one-port unknowns, to achieve the same high accuracy at any frequency in the measurement of any microwave component. The general formulas and required techniques are described fully in References 18 and 19.

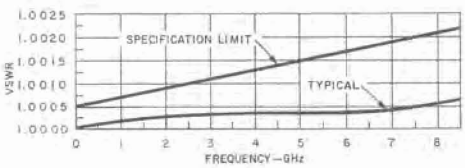
(2) The TYPE 900-LZ Air Lines can also be used in the measurements of dielectrics. Refer to article on dielectric measurements on page 31.

(3) As 50-ohm impedance standards in time-domain reflectometers to establish an extremely accurate reference. The impedance accuracy of the 900-LZ is 0.05%.

SPECIFICATIONS

Frequency Range: DC to 8.5 GHz.

Characteristic Impedance: 50 ohms ±0.050%.



VSWR characteristics.

Additional skin-effect error is calculable.

VSWR: Less than 1.0005 + $0.0002 f_{GHz}$.

Repeatability: Within $(0.010 + 0.003 f_{GHz})$%.

Leakage: Better than 130 dB below signal.

Insertion Loss: Less than $0.0008\sqrt{f_{GHz}}$ dB/cm.

Maximum Voltage: 3000 V peak.

Maximum Power: 20 kW/$\sqrt{f_{MHz}}$.

Dc Contact Resistance (each end, mated with GR900): Inner conductor, less than 0.5 milliohm; outer conductor, less than 0.07 milliohm.

Type	*Electrical Length—cm* (±0.002 cm)	*Capacitance—pF* (±0.07%)	*Time Delay—ps* (±0.1 ps)	*Odd λ/4 Frequencies** —GHz	*Physical Length* in—mm	*Net Weight* oz—g
900-LZ5	4.997	3.3333	166.7	(2n+1)1.50	2⅛– 55	4.0–115
900-LZ6	5.996	4.0000	200.0	(2n+1)1.25	2½– 65	5.0–140
900-LZ7H	7.495	5.0000	250.0	(2n+1)1.00	3 1/16– 80	5.5–160
900-LZ10	9.993	6.6667	333.3	(2n+1)0.75	4 1/16–105	7.0–200
900-LZ15	14.990	10.000	500.0	(2n+1)0.50	6 –155	10.5–295
900-LZ30	29.979	20.000	1000.0	(2n+1)0.25	12 –305	20 –555

* Frequencies at which air-line section is an odd multiple of a quarter wavelength, where n is zero or any integer.

PRECISION AIR LINES

Type 900-L30

The TYPES 900-L10, 900-L15, and 900-L30 Air Lines are precision coaxial air-line sections fitted with standard TYPE 900-BT Connectors. The air-line sections are held to extremely close dimensional tolerances. The inner conductor tolerance is ±65 microinches, and variations are restricted to ±25 microinches along a given rod. The outer conductor diameter is held to ±140 microinches.

These tolerances maintain the characteristic impedance at 50 ohms ±0.065% within the air-line section. The basic materials are brass, with a layer of silver at the conducting surfaces, and a protective gold plating.

Quarter-Wave Frequencies of Type 900-L Air Lines

900-L10 Frequency, GHz	*900-L15* Frequency, GHz	*900-L30* Frequency, GHz	
0.75	0.5	0.25	4.75
2.25	1.5	0.75	5.25
3.75	2.5	1.25	5.75
5.25	3.5	1.75	6.25
6.75	4.5	2.25	6.75
8.25	5.5	2.75	7.25
	6.5	3.25	7.75
	7.5	3.75	8.25
	8.5	4.25	8.75

Applications

TYPE 900-L Air Lines can be used:

(1) As 50-ohm quarter-wave reference standards. When the lines are used at frequencies where length is an odd multiple of λ/4, any immittance-measuring instrument, Smith-Chart plotter, etc., can be calibrated with respect to 50 ohms and the termination error isolated. The following table lists $(2n - 1)\ \lambda/4$ frequencies for the three air-line sections,

(2) As 50-ohm impedance standards in time-domain reflectometers to establish an extremely accurate reference. The impedance accuracy of the 900-L is 0.1%,

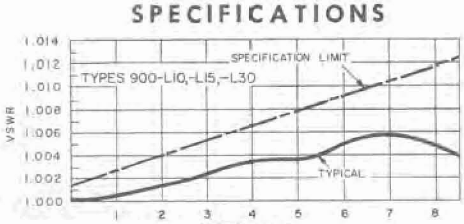
(3) As precision time-delay standards. The lines are held to an electrical length of ±0.012 cm, which is equivalent to ±0.4 picosecond,

(4) As reactance standards, with the TYPE 900-WO Open-Circuit Termination,

(5) As extension lines. The lines may be used to extend the lower frequency limit of the TYPE 900-LB Slotted Line below 300 MHz. With a sufficient length of air line, this limit can be reduced to 150 MHz,

(6) And as precise capacitance standards.

SPECIFICATIONS



VSWR: Less than 1.0013 + $0.0013 \times f_{GHz}$, up to 8.5 GHz.

Characteristic Impedance: Within air-line section, 50 ohms ± 0.065%.

Electrical Length: TYPE 900-L10 — 10.00 ± 0.02 cm; TYPE 900-L15 — 15.00 ± 0.02 cm; TYPE 900-L30 — 30.00 ± 0.02 cm.

Time Delay: TYPE 900-L10, 0.333 nsec; -L15, 0.5 nsec; -L30, 1.0 nsec; all ± 0.4 psec.

Net Weight: TYPE 900-L10, 6½ ounces (185 grams); -L15, 10 ounces (285 grams); -L30, 15 ounces (425 grams).

Over-all Length: TYPE 900-L10, 4 inches (105 mm); -L15, 6 inches (155 mm); -L30, 12 inches (305 mm).

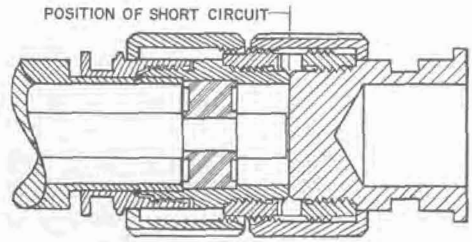
PRECISION SHORT-CIRCUIT TERMINATIONS

There are four low-loss short-circuit terminations in the GR900 family: TYPES 900-WN, 900-WNC, 900-WNE, and 900-WN4. Use of the proper short-circuit termination can simplify many measurements and make others possible. The TYPES 900-WN, 900-WNC, and 900-WNE are described below. TYPE 900-WN4 is discussed on page 15.

Type 900-WN Precision Short-Circuit Termination

The 900-WN is a silver-plated brass slug with the necessary GR900 external hardware. The inner connector shorting contact is achieved by the flat surface of the slug pressing against the TYPE 900-BT contact, providing a short circuit at the mating plane of the 900-BT. The reflection coefficient is 0.999 or better from dc to 8.5 GHz. The 900-WN does not contain a standard GR900 center contact.

The 900-WN Precision Short-Circuit Termination is used to establish reference planes for impedance measurements made through TYPE 900-BT connectors. It is also used as a low-loss short-circuit termination in measurements, including loss measurements, of networks with more than one port. The 900-WN termination can be used with the TYPE 900-L Precision Air Lines to provide coaxial-line reactance standards.

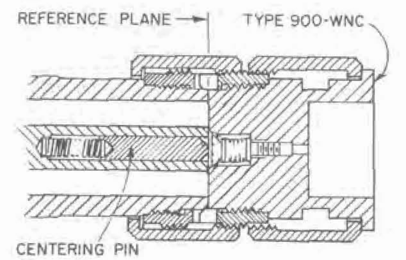


Cross section of a Type 900-WN Short-Circuit Termination mated with a Type 900-BT Connector.

Type 900-WNC Reference-Line Short-Circuit Termination

The 900-WNC Reference-Line Short-Circuit Termination is similar to the 900-WN except that it includes a standard GR900 center contact to support the inner conductor of a beadless 900-LZ Reference Air Line. The short circuit occurs exactly at the reference plane of the GR900 connector. The reflection coefficient is 0.999 or greater to 8.5 GHz.

The 900-WNC is used to establish reference planes for impedance measurements made through 900-LZ Reference Air Lines. This combination also provides a series of accurate coaxial reactance standards when used with the 900-LZ. The 900-WNC can also be used for any other application requiring an accurate short circuit at the reference plane of the connector, and with the 900-LZ Reference Air Lines to provide an accurate open circuit.

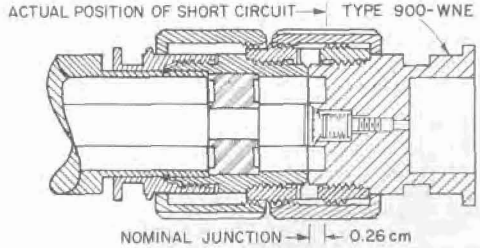


Cross section of a Type 900-WNC Short-Circuit Termination.

Type 900-WNE Precision Short-Circuit Termination

The 900-WNE Short-Circuit Termination is a low-loss short circuit offset electrically 0.26 cm beyond the reference plane of the GR900 connector to match the offset in the 900-WO Precision Open-Circuit Termination caused by fringing. The short circuit thereby facilitates exact reference-plane duplication in precision phase and wavelength measurements. The reflection coefficient is greater than 0.998 to 8.5 GHz. This termination contains a standard inner contact to support the inner conductor of a 900-LZ Reference Air Line.

The 900-WNE is used with the 900-WO Open-Circuit Termination to establish coincident open- and short-circuit reference planes for impedance measurements made through GR900 connectors. This combination is also useful for loss measurements based on reflection measurements, and to calibrate reflection-coefficient measuring instruments. The coplanar terminations are generally useful in the measurement of the scattering coefficients of multiple-port coaxial devices. The 900-WNE can also be used for general non-critical short-circuiting applications.



Cross section of a Type 900-WNE Short-Circuit Termination mated with a Type 900-BT Connector.

SPECIFICATIONS

Type 900-WN

Frequency Range: DC to 8.5 GHz.
Reflection Coefficient: Greater than 0.999.
Location of Short Circuit: At the GR900 Connector junction.
Leakage: Better than 130 dB below signal.
Dimensions: Length, 1-1/16 inch (27 mm); maximum diameter, 1-1/16 inch (27 mm).
Net Weight: 2-1/2 ounces (75 grams).

Type 900-WNC

Frequency Range: DC to 8.5 GHz.
Reflection Coefficient: Greater than 0.999.
Location of Short Circuit: At the GR900 Connector junction.
Leakage: Better than 130 dB below signal.
Dimensions: Length, 1-1/16 inch (27 mm); maximum diameter, 1-1/16 inch (27 mm).
Net Weight: 2-1/2 ounces (75 grams).

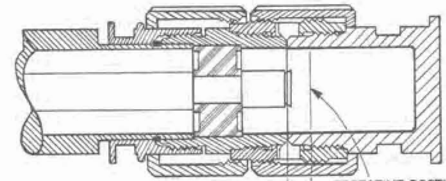
Type 900-WNE

Frequency Range: DC to 8.5 GHz.
Reflection Coefficient: Greater than 0.998.
Location of Short Circuit: 0.26 ±0.005 cm beyond the GR900 Connector junction.
Leakage: Better than 130 dB below signal.
Dimensions: Length, 1-1/16 inch (27 mm); maximum diameter, 1-1/16 inch (27 mm).
Net Weight: 2-1/2 ounces (75 grams).

PRECISION OPEN-CIRCUIT TERMINATIONS

The GR900 family contains two open-circuit terminations: 900-WO and 900-WO4. The 900-WO is the standard open circuit and the 900-WO4 is designed for use with the 900-WN4 Precision Short-Circuit Termination and other terminations presenting a reference plane 4.00 cm beyond the GR900 connector mating surface. The 900-WO4 is discussed on page 16.


900-WO 900-WO4



Cross section of a Type 900-WO Open-Circuit Termination mated with a Type 900-BT Connector.

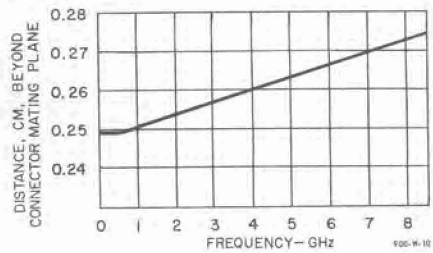
Type 900-WO Precision Open- Circuit Termination

The 900-WO Precision Open-Circuit Termination is a low-loss open circuit consisting of a closed section of outer conductor equipped with the GR900 coupling mechanism. This termination presents a well-shielded open circuit 0.26 cm from the plane of the mating 900-BT connector. It has a reflection coefficient of 0.999 or greater to 8.5 GHz.

The open circuit cannot be established exactly at the mating plane of the connector because of the end effect involved. This end effect can be represented closely by an additional length of line or by a capacitance shunting the end of the line. The representation is not exact, however, and a small increase in effective electrical length occurs with an increase in frequency. The low frequency fringing capacitance is 0.172 pF.

The 900-WO Precision Open-Circuit Termination can be used to establish a reference plane for impedance measurements made through 900-BT connectors. It can also be used as a low-loss open-circuit termination in the measurements of networks with more than one port. When used with the 900-L Precision Air Lines, 900-WO Open-Circuit Terminations provide coaxial-line reactance standards. The companion short-circuit termination, the 900-WNE, provides a short circuit 0.26 cm beyond the reference plane of the GR900 Connector for use with the 900-WO.

Frequency Range: DC to 8.5 GHz.
Reflection Coefficient: Greater than 0.999.
Location of Open Circuit: 0.26 ±0.02 cm beyond the GR900 Connector junction.
Leakage: Better than 130 dB below signal.
Dimensions: Length, 1-1/16 inch (27 mm); maximum diameter, 1-1/16 inch (27 mm).
Net Weight: 2 ounces (60 grams).



Typical effective open-circuit position for the Type 900-WO.

Calibration Standards for Precision Coaxial Lines

TYPE 900-W50 PRECISION 50-OHM TERMINATIONS

The TYPE 900-W50 Termination is a broadband device with extremely low VSWR, useful from dc to 9 GHz. It comprises an accurately derived, continuous transition and a precision cylindrical resistor. The connector is a TYPE 900-BT. Typical VSWR characteristics are given in Figure 1.

Applications

The 900-W50 is an accurate 50-ohm standard for the calibration of bridges, slotted lines, impedance plotters, swept-frequency reflectometers, and time-domain reflectometers. It is used as a termination in the measurement of networks with more than one port and in substitution measurements, and as a precision dummy load. When used with the series of low-VSWR adaptors described on pages 19 to 22, the 900-W50 becomes a low-VSWR termination for type N, BNC, TNC, C, SC, and OSM*/BRM line sizes.

* Registered trademark of Omni Spectra, Inc.

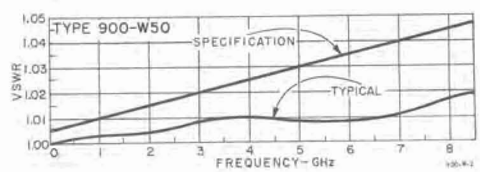


Figure 1. VSWR Characteristics.

SPECIFICATIONS

Frequency Range: DC to 8.5 GHz.
Leakage: Better than 130 dB below signal.
VSWR: 1.005 + 0.005 x f_{GHz} up to 8.5 GHz.
DC Resistance: 50 ohms ±0.3%.
Maximum Power: 1 watt with negligible change; 5 watts without damage.
Temperature Coefficient: Less than 150 ppm/°C.
Dimensions: Length, 2 inches (51 mm); maximum diameter, 1-1/16 inch (27 mm).
Net Weight: 3-1/2 ounces (100 grams).

TYPE 900-W STANDARD TERMINATIONS

These broadband resistive terminations are standards of impedance, which can be used to calibrate swept-frequency impedance-measuring systems, impedance plotters, slotted-line systems, bridges and time-domain reflectometers.

In contrast to the Type 900-WR Standard Mismatches, the Standard Terminations are calibrated in phase as well as magnitude; that is, the position of the standard resistance with respect to a reference point in the connector is accurately known. These terminations, therefore, find their greatest use in the calibration of impedance-measuring systems, although they are also standards of VSWR.

The Types 900-W100 and -W200 Standard Terminations are 100- and 200-ohm terminating resistances for a 50.0-ohm system. The resistances introduced remain very nearly equal to their dc resistances over the frequency band from dc to 8.5 GHz, as illustrated in Figure 2. These units are similar in construction to the Type 900-WR Standard Mismatches.

The reference plane at which the termination is introduced into the 50.0-ohm system is 4 cm behind the reference plane of the GR900 Connector, as shown in Figure 3. Calibration charts supplied with each unit include measured data on the position at which the resistance effectively appears in addition to the measured resistance at dc and at 5 points in the frequency band.

APPLICATIONS

Calibration of Slotted-Line and Reflectometer Systems

The Type 900-W Standard Terminations, like the Type 900-WR Standard Mismatches, are used to perform direct rf calibration of slotted-line systems. At the 100-ohm and 200-ohm levels (mismatches of 2 and 4, respectively), the errors introduced by variations in the detector-response law, uncertainties in the indicator calibration, and, most important, probe reflections in the slotted line can be appreciable. The Type 900-W Terminations permit a rapid, yet accurate, test of a system's performance, without the necessity of time-consuming check-out procedures.

Similarly, with reflectometer systems, these standard terminations provide important calibration points. Since the terminations are calibrated in both magnitude and phase, they are most useful in the calibration of complex reflection-coefficient measuring instruments such as automatic impedance plotters. Because of the phase calibration of the terminations, they can be combined with sections of precision air line to produce many known complex impedances. For example, a Type 900-W100 Termination in combination with a 6-cm air line produces (at the air-line input connector mating plane) an impedance of 40.0 − j30.0 ohms at frequencies given by

$3\left(\frac{1+4n}{8}\right)$ GHz and 40.0 + j30.0 ohms at frequencies given by $3\left(\frac{3+4n}{8}\right)$ GHz,

where n is zero or a positive integer. The Type 900-L Precision Air Lines and the Type 900-LZ Reference Air Lines[1] are recommended for such applications.

Calibration of Bridges

The Type 900-W Standard Terminations are used to calibrate bridges in much the same manner as described for slotted lines and reflectometers. For some bridges, the termination reference plane 4 cm away from the GR900 Connector mating plane may not be the most convenient reference plane to use. Below about 200 MHz, however, the resistive component of the impedance presented at the connector reference plane departs only slightly from that presented at the 4-cm reference position. This resistance (at the GR900 Connector reference plane) is given as a function of frequency, approximately, by:

$$R' = R\left[1 - \left(\tan^2\frac{4\pi f}{15}\right)\left(\left[\frac{R}{50}\right]^2 - 1\right)\right]$$
$$= R(1 - K)$$

where R is the calibrated dc resistance of the termination in question and f is the frequency in GHz.

[1] See pages 9 and 10.

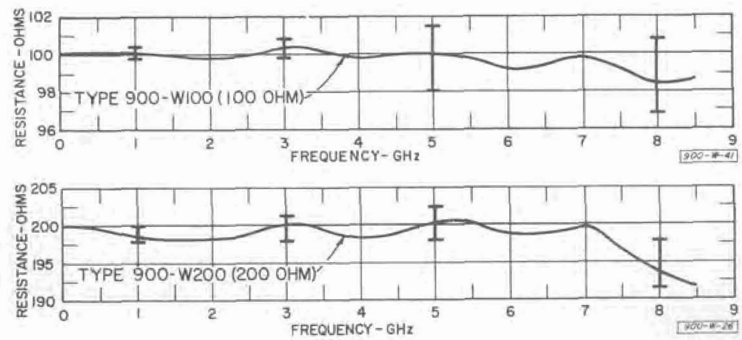


Figure 2. Average resistance of 25 units each of Type 900-W100 and Type 900-W200. Spreads in the measured data are shown at 1, 3, 5, and 8 GHz. Measurement accuracy is better than 1%.

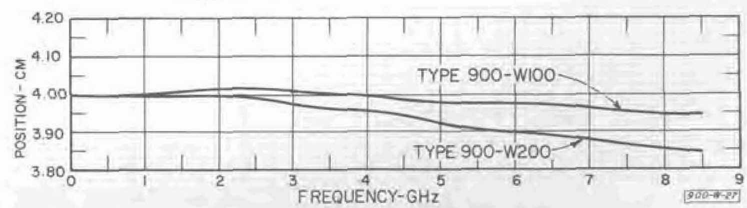


Figure 3a. Average position behind GR900 Connector reference plane at which resistance is applied for the units of Figure 2.

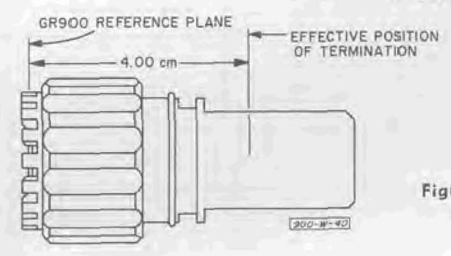


Figure 3b. Sketch showing relation of termination position and reference plane.

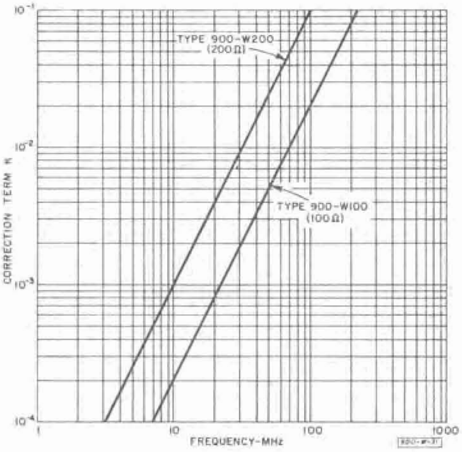


Figure 4. Correction term, K, for the 4-cm difference between the GR900 Connector reference plane and the effective position of the resistance.

The correction term

$$K = \left(\tan^2 \frac{4\pi f}{15}\right)\left(\left[\frac{R}{50}\right]^2 - 1\right)$$

is a result of the distributed capacitance of the 4-cm length of line between the two reference planes and is plotted in Figure 4 for resistances of 100 and 200 ohms.

SPECIFICATIONS

TYPE 900-W100 100-OHM STANDARD TERMINATION

Frequency Range: DC to 8.5 GHz.

DC Resistance: 100 Ω ±0.5%.

RF Resistance

Up to 1 GHz: $100.00 \pm (0.50 + 1.00\, f_{GHz})$

1 to 8.5 GHz: $100.00 \pm (1.05 + 0.45\, f_{GHz})$

Position at Which Resistance Specification Applies

Up to 2 GHz: (4.00 ± 0.05) cm beyond the GR900 Connector reference plane.

2 to 8.5 GHz: $(4.02 - 0.01\, f_{GHz} \pm 0.05)$ cm beyond the GR900 Connector reference plane.

Leakage: Better than 130 dB below signal.

Maximum Power: 1 W with negligible change; 5 W without damage.

Temperature Coefficient: Less than 150 ppm/°C.

Dimensions: Length, 2 in (51 mm); maximum diameter, 1 1/16 in (27 mm).

Net Weight: 3½ oz (100 g).

TYPE 900-W200 200-OHM STANDARD TERMINATION

Same as Type 900-W100, except:

DC Resistance: 200 Ω ±0.5%.

RF Resistance

Up to 1 GHz: $200.00 \pm (1.00 + 2.00\, f_{GHz})$

1 to 7 GHz: $200.00 \pm (2.10 + 0.90\, f_{GHz})$

7 to 8.5 GHz: $200.00 \text{ or } {+8.40 \atop -(8.40 + 7.20[f_{GHz} - 7])}$

Position at Which Resistance Specification Applies

Up to 2 GHz: (4.00 ± 0.05) cm beyond the GR900 Connector reference plane.

2 to 8.5 GHz: $(4.04 - 0.02\, f_{GHz} \pm 0.05)$ cm beyond the GR900 Connector reference plane.

TYPE 900-WR STANDARD MISMATCHES

These broadband mismatches are standards of VSWR, for use in the calibration of slotted-line systems, reflectometers, and other VSWR and reflection-coefficient measuring devices The Types 900-WR110, -WR120 and -WR150 Standard Mismatches introduce VSWR's of 1.1, 1.2, and 1.5, respectively, and each of these units exhibits nearly uniform VSWR characteristics from dc to 8.5 GHz. (See Figure 5.) Each unit comprises a 50.0-ohm GR900 Precision Coaxial Connector, a low-reflection continuous transition, and a precision cylindrical resistor. The position at which the mismatch is introduced into the 50.0-ohm system is approximately 4 cm behind the reference plane of the GR900 Connector.

The terminating elements are highly stable, deposited-metal-film resistors with dc resistances of 45.45, 41.67 and 33.33 ohms, respectively, ±0.3%. Calibration charts supplied with each unit give the measured resistance at dc and at five points in the frequency band. NBS calibration services are also available to 4 GHz with uncertainties of VSWR measurement from ±0.005 at 1 GHz to ±0.010 at 4 GHz.

APPLICATIONS

Direct RF Calibration of Slotted-Line Systems

Many factors contribute to inaccuracy in the measurement of VSWR with a slotted-line system. Uncertainty in the detector response law, calibration accuracy of the indicating instrument, residual VSWR and probe reflections in the slotted line — all of these introduce varying effects that are dependent on the magnitude of VSWR being measured, the frequency of operation, and the nature of the instruments. The Type 900-WR Standard Mismatches offer a simple means of establishing directly, at the measurement frequency, the over-all system accuracy.

Figure 6 shows the standing-wave patterns of design-center mismatches at VSWR levels of 1.1 and 1.2, measured at 7 GHz with the Type 1640-A Slotted Line Recording System.

Calibration of Frequency-Domain Reflectometers

The Type 900-WR Standard Mismatches are well suited for the VSWR calibration of swept-frequency reflec-

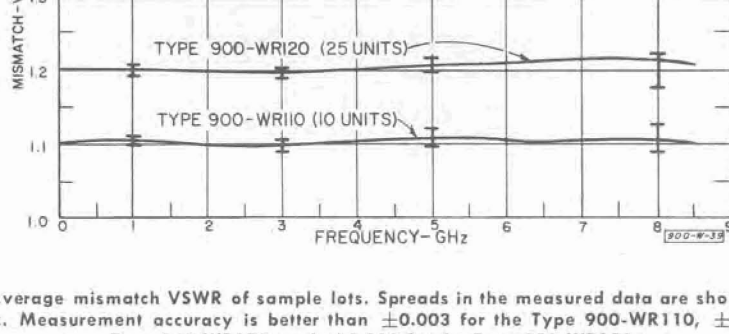


Figure 5. Average mismatch VSWR of sample lots. Spreads in the measured data are shown at 1, 3, 5, and 8 GHz. Measurement accuracy is better than ±0.003 for the Type 900-WR110, ±0.005 for the Type 900-WR120, and ±0.010 for the Type 900-WR150.

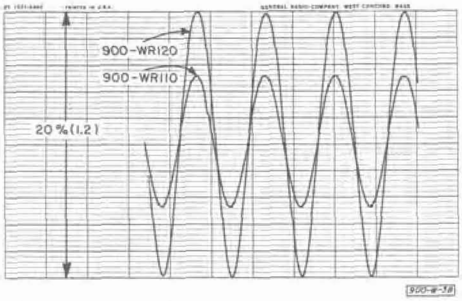


Figure 6. Standing-wave patterns of Types 900-WR110 and -WR120 Standard Mismatches as measured at 7GHz with a Type 1640-A Slotted Line Recording System.

tometers and impedance plotters based on directional couplers, hybrid junctions, magic tees, or rf bridges. Calibration through GR900 Connectors offers the greatest accuracy; however, the use of the TYPE 900-Q Adaptors makes it possible to calibrate measuring devices equipped with many other types of connectors.

The TYPE 900-WR110 Mismatch is particularly useful for the calibration of fixed-frequency reflectometers where the residual reflection errors of the measuring instruments are tuned out. As an example, Figure 7 is the block diagram of a fixed-frequency reflectometer system built around a hybrid junction in which the error signal is proportional to the reflection coefficient of the unknown being measured. This system provides full-scale VSWR indications of 10%, 1%, and even 0.1%.*

The calibration procedure for this system is as follows:

(a) A TYPE 900-W50 Standard Termination is connected to the unknown port of the hybrid junction and the impedance-matching tuner (TYPE 900-TUA) is adjusted for a null in the detected signal. This makes the instrument residual reflection equal in magnitude to the residual reflection of the termination. Thus, the accuracy of the measurement is directly dependent on the accuracy of the termination. (Highly accurate calibration techniques for determining the termination accuracy are described by Sanderson.[1])

(b) The TYPE 900-WR110 Standard Mismatch (VSWR = 10%) is connected in place of the matched termination, and the signal level is adjusted for full-scale indication on the meter of the TYPE 1216-A Unit I-F Amplifier in the TYPE DNT Detector.

The unknown to be measured is now connected in place of the standard mismatch, and its VSWR is read directly from the linear scale of the i-f amplifier meter. If the setting of the amplifier attenuator switch is reduced by 20 dB, the full-scale VSWR becomes 1%, and, for 40-dB reduction, the full-scale VSWR becomes 0.1%. The assumption that the linear scales apply is not rigorously true, since the relationship between VSWR and reflection coefficient is not a linear one. However, for VSWR's up to 10%, the error is less than 1/20th of the indicated VSWR in percent.

* VSWR in percent is given by (VSWR - 1) × 100.

[1] See Reference 18.

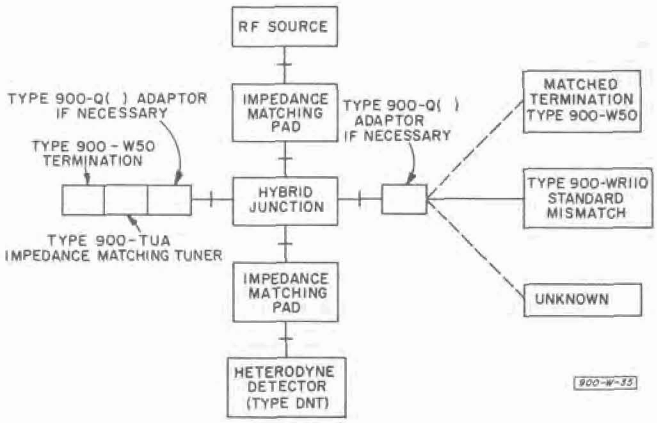


Figure 7. Fixed-frequency reflectometer for measuring VSWR's below 1.1.

SPECIFICATIONS

TYPE 900-WR110 STANDARD MISMATCH

45.45Ω ± 0.3%

Frequency Range: DC to 8.5 GHz.

Mismatch VSWR

Up to 1 GHz: 1.1000 ± (0.0055 + 0.0110 f_{GHz}).
1 to 8.5 GHz: 1.1000 ± (0.0115 + 0.0050 f_{GHz}).

DC Resistance: 45.45 Ω ±0.5%.

Leakage: Better than 130 dB below signal.

Maximum Power: 1 W with negligible change; 5 W without damage.

Temperature Coefficient: Less than 150 ppm/°C.

Dimensions: Length, 2 in (51 mm); maximum diameter, 1 1/16 in (27 mm).

Net Weight: 3½ oz (100 g).

TYPE 900-WR120 STANDARD MISMATCH

41.67Ω ± 0.3%

Same as Type 900-WR110 except:

Mismatch VSWR

Up to 1 GHz: 1.2000 ± (0.0060 + 0.0120 f_{GHz}).
1 to 8.5 GHz: 1.2000 ± (0.0125 + 0.0055 f_{GHz}).

DC Resistance: 41.67 Ω ±0.5%.

TYPE 900-WR150 STANDARD MISMATCH

33.33Ω ± 0.3%.

Same as Type 900-WR110 except:

Mismatch VSWR

Up to 1 GHz: 1.5000 ± (0.0075 + 0.0150 f_{GHz}).
1 to 8.5 GHz: 1.5000 ± (0.0155 + 0.0070 f_{GHz}).

DC Resistance: 33.33 Ω ±0.5%.

TYPE 900-WN4 PRECISION SHORT-CIRCUIT TERMINATION

The TYPE 900-WN4 Short-Circuit Termination presents a low-loss short circuit 4.00 cm beyond the reference plane of its GR900 Connector reference plane. The reflection coefficient introduced at the actual short-circuit plane is greater than 0.999, and that introduced at the connector reference plane is greater than 0.996.

APPLICATIONS

This short circuit is used with the TYPE 900-WO4 Precision Open-Circuit Termination (described below) to establish short- and open-circuit reference planes coincident within 0.02 cm over the frequency range from dc to 8.5 GHz. The reference planes so established are useful in direct impedance measure-

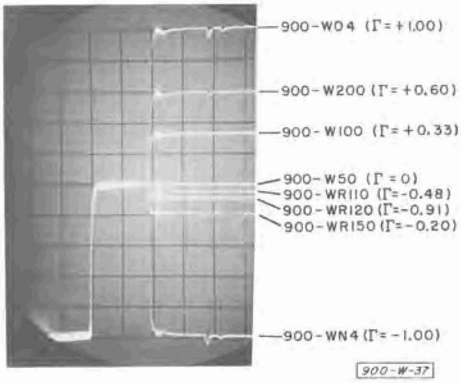


Figure 8. Multiple exposure of time-domain-reflectometer traces for the various GR900 terminations at the end of a length of 50-ohm air line.

ments, in loss measurements based on reflection measurements, in the calibration of reflection-coefficient measuring instruments, and, generally, in the measurement of the scattering coefficients of multiport coaxial devices.

Since its 4.00-cm reference plane coincides with those of the Types 900-W100 and −W200 Standard Terminations, the Type 900-WN4 can be used in conjunction with these terminations for the calibration of bridges, slotted-line systems, etc.

Figure 8 illustrates the calibration levels obtainable with the Types 900-WR, 900-W, 900-WN4 and 900-WO4 Standards. All these units are recommended for the calibration of time-domain-reflectometry systems.

Since the Type 900-WN4 comprises a single section of uniform transmission line with no disturbances or dielectric supports between the short circuit and the connector reference plane, it is a calculable inductance standard of high accuracy. This is particularly true at frequencies above about 50 MHz, where the current flows primarily in the silver overlays on the conductive surfaces.

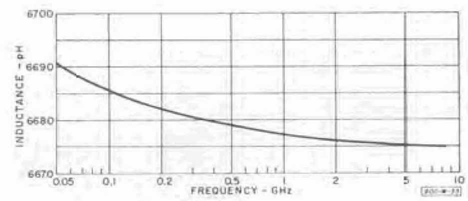
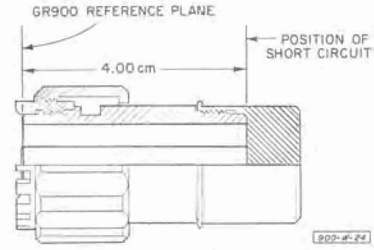


Figure 9. Inductance presented at the GR900 Connector reference plane of the Type 900-WN4 Precision Short-Circuit Termination.

Figure 9 is a plot of the calculated inductance at the connector reference plane for frequencies above 50 MHz based on a conductor resistivity of 1.7 microhm-cm, which is typical for the conductors of the Type 900-WN4.



Cross section of a Type 900-WN4.

SPECIFICATIONS

TYPE 900-WN4 PRECISION SHORT-CIRCUIT TERMINATION

Frequency Range: DC to 8.5 GHz.

Reflection Coefficient: Greater than 0.996 at the GR900 Connector reference plane.

Location of Short Circuit: 4.00 ± 0.01 cm beyond the GR900 Connector reference plane.

Characteristic Impedance of Internal Coaxial Line: 50.0 Ω ± 0.065% at frequencies where skin effect is negligible.

Leakage: Better than 130 dB below signal.

Dimensions: Length, 2 in (51 mm); maximum diameter, 1 1/16 in (27 mm).

Net Weight: 4 oz (120 g).

TYPE 900-WO4 PRECISION OPEN-CIRCUIT TERMINATION

The Type 900-WO4 presents an open circuit 4.0 cm beyond the GR900 Connector reference plane over the full dc-to-8.5-GHz frequency range, as illustrated in Figure 10. Compensation for the frequency-dependent fringing capacitance of the open-ended inner conductor is accomplished by means of a small disk on the inner conductor tip.

APPLICATIONS

As a capacitance standard, the Type 900-WO4 presents a capacitance at its connector reference plane that is given approximately by

$$C = C_o\left[1 + \left(\frac{\tan\frac{4\pi f}{15}}{\frac{4\pi f}{15}} - 1\right)\right] = C_o\,(1 + K)$$

where the capacitance C_o is a result of the 4-cm length of line between the effective open-circuit reference plane and the connector reference plane and f is the frequency in GHz. The capacitance C_o has a nominal value of 2.673 picofarads. The correction term

$$K = \frac{\tan\frac{4\pi f}{15}}{\frac{4\pi f}{15}} - 1$$

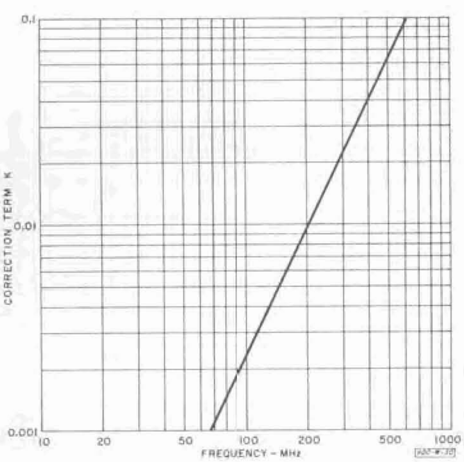
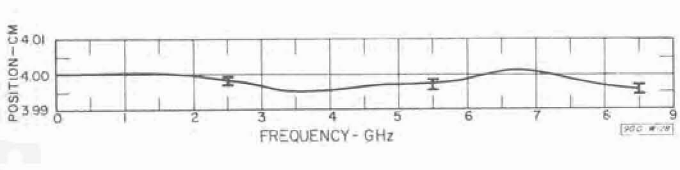


Figure 11. Correction term, K, for Type 900-WO4 Open-Circuit Termination.

is a result of the distributed nature of the capacitance, which has an appreciable effect at frequencies above 70 MHz. The correction term K is plotted in Figure 11.

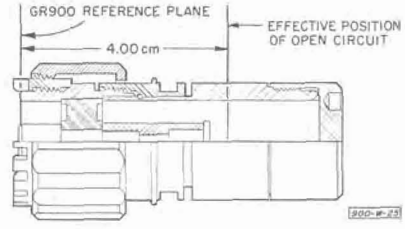
As an open-circuit termination for the Type 900-LZ Reference Air Lines, the Type 900-WO4 provides support for the inner conductors of the air lines. Since the effective reference plane of

Figure 10. Average position behind GR900 Connector reference plane at which open circuit is applied. Data are based on 25 units. Spreads are shown at 2.5, 5.5, and 8.5 GHz.



the Type 900-WO4 Open Circuit is coincident with that of the Type 900-WN4 Short Circuit, these two units, alone or in conjunction with the Type 900-LZ Reference Air Lines, form a series of accurate conjugate-reactance standards, which can be used in the calibration of impedance-measuring devices. Further, the reference plane of the Type 900-WO4 is coincident with those of the Types 900-W100 and -W200 Terminations within 0.06 cm to 2 GHz and within 0.20 cm to 8.5 GHz.

Combinations of the Type 900-WO4 Open-Circuit and the Type 900-LZ Air Lines also make an accurate series of



Cross section of a Type 900-WO4.

incremental capacitance standards for use at audio and at the lower radio frequencies. Fringing capacitance at the measuring-instrument terminals is eliminated when the Type 900-WO4 is used to establish the initial conditions. The agreement between calculated capacitance and measured capacitance at 1 kHz for a 10-picofarad (15 cm) Type 900-LZ15 Reference Air Line is better than 0.05%. The GR900 Connector repeatability at 1 kHz is better than 0.001 picofarad.

SPECIFICATIONS

TYPE 900-WO4 PRECISION OPEN-CIRCUIT TERMINATION

Frequency Range: DC to 8.5 GHz.

Reflection Coefficient: Greater than 0.996 at the GR900 Connector Reference Plane.

Location of Open Circuit: 4.00 ± 0.01 cm beyond the GR900 Connector reference plane.

Capacitance at GR900 Connector Reference Plane: 2.673 pF ± 0.3%, dc to 70 MHz.

Characteristic Impedance of Internal Coaxial Line: 50.0 Ω ± 0.1% at frequencies where skin effect is negligible.

Leakage: Better than 130 dB below signal.

Dimensions: Length, 2 5/16 in (59 mm); maximum diameter, 1 1/16 in (27 mm).

Net Weight: 4 oz (120 g).

GR900® PRECISION ADAPTORS

Figure 1. The Type 900-LB Precision Slotted Line with the complement of adaptors shown is the equivalent of 16 slotted-lines, each with a different type of connector.

In measurement and standards laboratories, many different types of coaxial connectors are encountered. For maximum utility, a basic line of measuring equipment based on precision connectors must include adaptors to other commonly used types. Recognizing this, General Radio has provided several adaptors from the GR900 Precision Coaxial Connector. This article discusses the effect of mating dimensions and gaps and, we hope, will help to answer some of the questions that have been asked about VSWR errors from these sources.

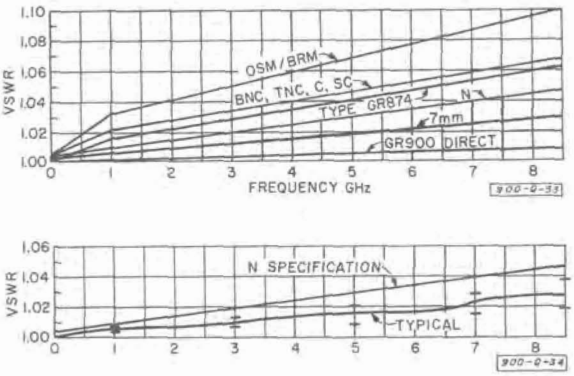
By means of precision adaptors, the excellent performance of GR900 coaxial standards and instruments can be extended to measurements on devices equipped with other types of connectors.

Each adaptor contains a GR900 Precision Coaxial Connector, a specially designed continuous transition between line sizes, and a low-vswr version of the applicable (jack or plug) connector.

Slotted-Line Measurements

With a set of GR900 Precision Adaptors in combination with a Type 900-LB Precision Slotted Line one can make accurate impedance measurements through many different coaxial connectors as shown in Figure 1: the military types N, BNC, TNC, C, and SC jacks and plugs; the OSM/BRM types or equivalents, jack and plug; the general-purpose 14-mm GR874; the precision 14-mm GR900; the precision 7-mm Amphenol APC-7; and the 7-mm Rohde and Schwarz Precifix and Dezifix A connectors. Figure 2(a) shows the specified performance of the various adaptor-slotted-line combinations; typical vswr is about half that specified, as illustrated in Figure 2(b) for a type N combination.

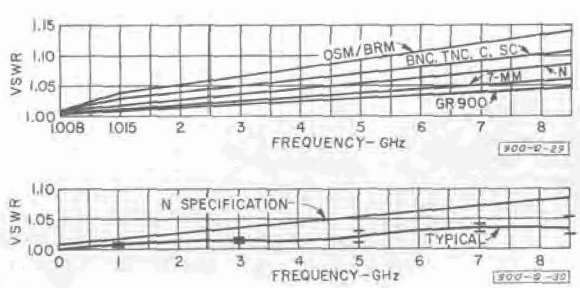
Figure 2. (a) Specified residual VSWR of the Type 900-LB Precision Slotted Line in combination with various GR900 Precision Adaptors. (b) Typical data on a sample lot of the slotted line, Type-N-jack-adaptor combination. Bars above curve at 1, 3, 5, 7 and 8.5 GHz are maximum VSWR's; bars below curve are averages.



VSWR OF GR900 DEVICES EQUIPPED FOR OTHER COAXIAL SERIES

	Slotted Line (Type 900-LB Plus GR900 Adaptor)	*50-ohm Standard Termination (Type 900-W50 Plus GR900 Adaptor)*
Types BNC, TNC, C, SC	$1.006 + 0.016f_{GHz}$ to 1 GHz $1.016 + 0.006f_{GHz}$ from 1 to 8.5 GHz	$1.010 + 0.020f_{GHz}$ to 1 GHz $1.020 + 0.010f_{GHz}$ from 1 to 8.5 GHz
Type N	$1.005 + 0.005f_{GHz}$	$1.009 + 0.009f_{GHz}$
Type GR874	$1.001 + 0.016f_{GHz}$ to 1GHz $1.011 + 0.006f_{GHz}$ from 1 to 8.5 GHz	$1.005 + 0.020f_{GHz}$ to 1 GHz $1.015 + 0.010f_{GHz}$ from 1 to 8.5 GHz
Type OSM/BRM	$1.006 + 0.026f_{GHz}$ to 1 GHz $1.023 + 0.009f_{GHz}$ from 1 to 8.5 GHz	$1.01 + 0.03f_{GHz}$ to 1 GHz $1.027 + 0.013f_{GHz}$ from 1 to 8.5 GHz
7-mm (Amphenol and Rohde & Schwarz)	$1.004 + 0.003f_{GHz}$	$1.008 + 0.007f_{GHz}$

Figure 3. (a) Specified VSWR of the Type 900-W50 50-ohm Standard Termination in combination with various GR900 Precision Adaptors. (The 900-W50/900-Q874 combination is not shown since nearly equivalent performance can be obtained directly with the Type 874-W50BL Termination.) (b) Typical data on a sample lot of the termination, Type N plug adaptor combination. Bars above curve at 1, 3, 5, 7, and 8.5 GHz are maximum VSWR's; bars below curve are averages.



Matched Terminations

Similarly, the precision adaptors in combination with a TYPE 900-W50 50-ohm Standard Termination provide low-VSWR terminations for the various connector types. Figure 3 shows the specified performance.

Advantages

There are two important advantages to utilizing precision adaptors as described above: accuracy and economy. The accuracy of measurement through each connector type is usually better than that provided by slotted lines or terminations designed specifically for the connector type of interest. This is because (1) the TYPE 900-LB Slotted Line and the TYPE 900-W50 Termination exhibit very low residual VSWR's, which can be accurately calibrated at the GR900 Connector reference planes; (2) the continuous transitions in the adaptors are nearly reflectionless, and (3) connectors of the series being adapted to are optimally designed.

The advantage of economy is obvious: the cost of one slotted line, one termination and several adaptors is far less than the cost of individual slotted lines and terminations for each connector type.

GAPS

When two connectors are mated, it is not possible to achieve a butt joint simultaneously at both the outer- and inner-conductor junctions. Because of axial mechanical tolerances, a gap will exist at one of the junctions. Usually the outer conductors are allowed to

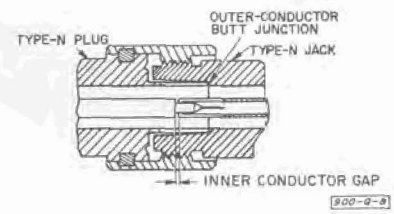


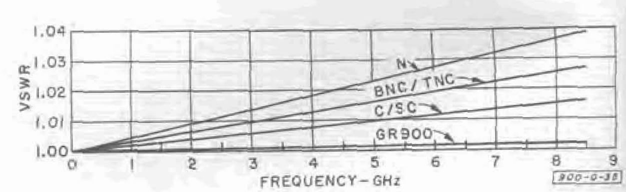
Figure 4. Gap in Type N connector junction.

butt, and the gap is left in the inner-conductor junctions (as shown in Figure 4 for the type N junction) so that mechanical damage to the connectors (or the components to which they are connected) is avoided. This presence of the gap introduces a series inductance into the line. For the connector types of interest, the VSWR resulting from this residual inductance is a linear function of frequency and of the axial dimension of the gap. The constant of proportionality is dependent on the radial dimension of the gap and on the width of any slots in the gap walls[1].

[1] See Reference 14.

Connector Type	*K*	*Spread in g (mils)*
N	0.051	2.0–9.0
BNC, TNC	0.035	2.0–9.0
C, SC	0.021	2.0–9.0
GR900	0.008	0.8–3.2

Figure 5. VSWR's introduced by the maximum gap dimensions, g, indicated in the table.



Thus,

$S = Kfg$

where: S is the VSWR in per cent,

K is the proportionality constant for the connector series of interest,

f is the frequency in GHz, and

g is the axial length of the gap in mils.

The table gives the values of K for the connector types covered by military specifications. Values of K are not included for the OSM/BRM connector types, because the steps in conductor diameters at the mating planes alter the effect, nor for the GR874 Connector, because the mating configuration is of a different kind. A value of K for the GR900 Connector is included to illustrate the improvement gained through the use of precision connectors.

The value of K is based on nominal values for the radial dimension of the gap and for the width of the slots in the gap walls. The spread in g is the spread in the axial length of the gap that results from the critical mating dimensions of the connectors. Figure 5 is a plot of VSWR versus frequency for the maximum g indicated in the table.

For a type N junction with a nominal gap (g = 5.5 mils), the VSWR introduced at 7 GHz by the gap is approximately 1.02. For a GR900 junction with a nominal gap (g = 2.0 mils), the corresponding VSWR at 7 GHz is approximately 1.001.

MATING DIMENSIONS

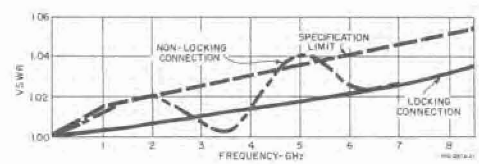
When two GR900 Precision Connectors are mated, the VSWR introduced by one of the connectors is not influenced by variations in the dimensions of the second connector. On the other hand, when two type N connectors are mated, the VSWR introduced by the jack connector is directly dependent on the diameter of the pin of the plug-connector inner conductor against which the jack inner-conductor fingers rest. Similarly, the VSWR introduced by the plug connector is directly dependent on the diameter of the shoulder in the jack outer conductor against which the plug outer-conductor fingers rest. This dependence of connector performance on the dimensions of the mating connector is common to most general-purpose connector series, and, when low VSWR's are to be specified, it becomes of major importance.

Listed on these pages are the specifications and critical mating dimensions of the adaptors used to connect equipment fitted with GR900 connectors to equipment with connectors of other types. In all adaptors, connectors other than the GR900 will mate with most of the known connector variations, including those meeting applicable MIL-C standards. However, for minimum connector-junction reflections, the mating dimensions shown should be employed. Where applicable, the suffix J indicates that the adaptor is female (contains a jack) and suffix P indicates that the adaptor is male (contains a plug).

TYPE 900-Q874 ADAPTOR

(Connects with either locking or nonlocking GR874 Connector)

The TYPE 900-Q874 Adaptor comprises a TYPE 874-BBL Locking Connector and a TYPE 900-BT Connector, mounted on a short section of precision air line. This adaptor contains a newly designed, fully compensated TYPE 874 support bead. Although the adaptor mates with both locking and nonlocking GR874 Connectors, a mechanically stable, low-leakage connection requires a locking GR874 Connector. The electrical length and reference-plane data are given in the instruction sheet that accompanies the adaptor.



Typical insertion VSWR of Type 900-Q874.

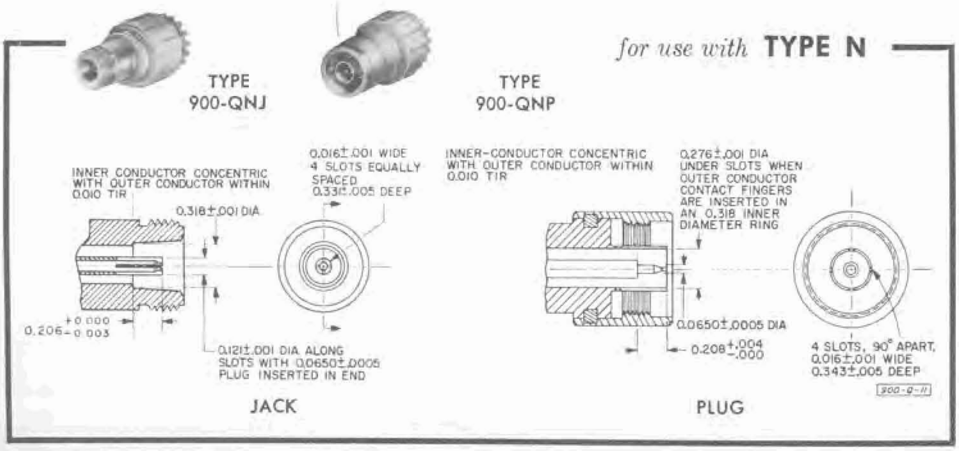
VSWR: Less than $1.00 + 0.015 f_{GHz}$ to 1 GHz; $1.01 + 0.005 f_{GHz}$, 1 to 8.5 GHz.

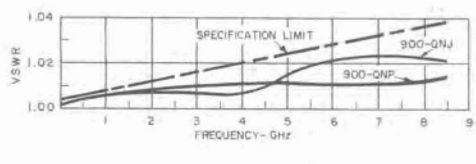
Electrical Length: 6.50 ± 0.04 cm to front face of mated nonlocking GR874 connector bead.

Over-all Length: 2-9/16 inches (65 mm).

Net Weight: 3½ ounces (100 grams).

TYPES 900-QNJ AND 900-QNP ADAPTORS





VSWR: Less than $1.004 + 0.004 \times f_{GHz}$, up to 8.5 GHz, either unit.

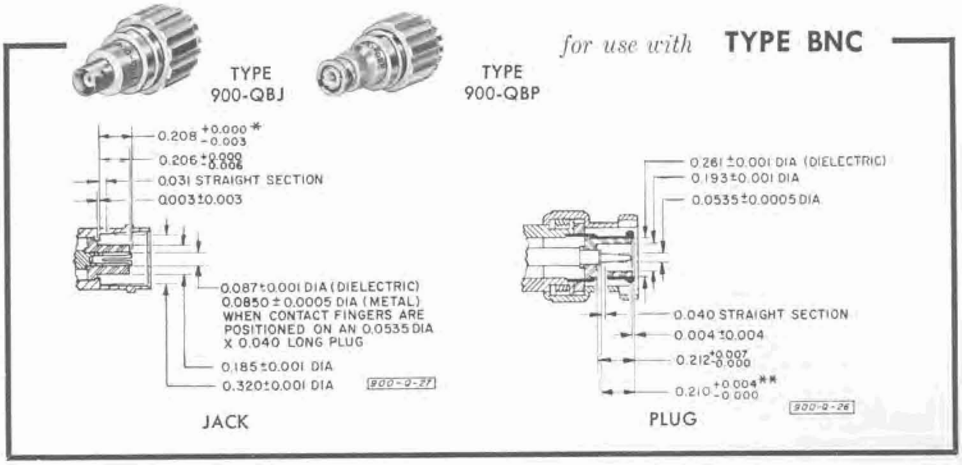
Electrical Length: TYPE 900-QNP — 5.50 ± 0.03 cm to end of male outer conductor. TYPE 900-QNJ — 5.00 ± 0.03 cm to end of female inner conductor.

Net Weight: TYPE 900-QNP, 3½ ounces (100 grams); -QNJ, 4 ounces (115 grams).

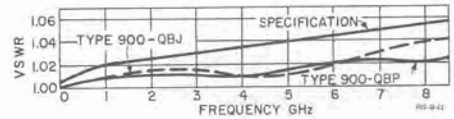
Over-all Length: TYPE 900-QNP, 2-5/16 inches (59 mm); TYPE 900-QNJ, 2¼ inches (58 mm).

Figure 6. Critical mating dimensions of low-VSWR connectors used with the GR900 Connector on the precision adaptors. (All dimensions are in inches.)

TYPES 900-QBJ AND 900-QBP ADAPTORS



* Inner conductor has 4 equally spaced slots 0.008 ±0.001 wide by 0.187 ± 0.005 deep.
** Outer conductor has 6 slots 60° apart, 0.015 ± 0.001 wide by 0.235 ± 0.003 deep; inner diameter in region of contact-fingers is 0.2650 ± 0.0005 when fingers are inserted in a 0.3200 inner-diameter ring.



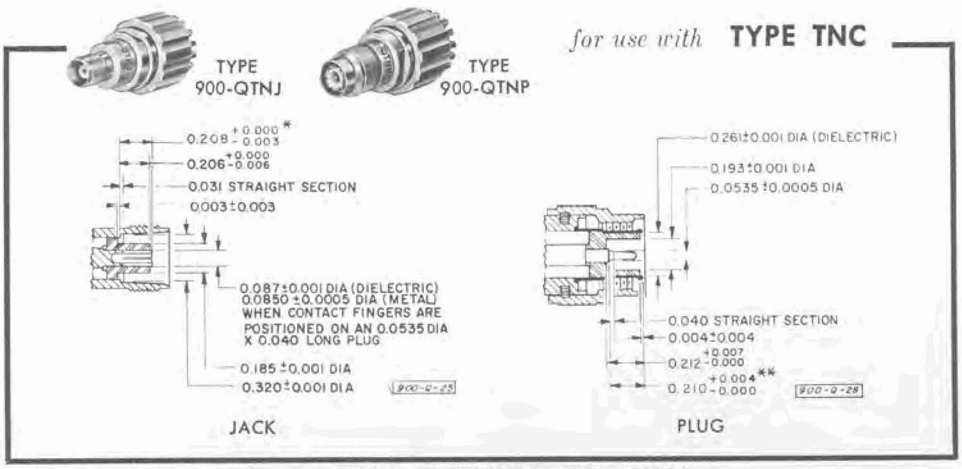
Type 900-QBJ Adaptor

Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.005 + 0.015 f_{GHz}$ to 1 GHz; $1.015 + 0.005 f_{GHz}$, 1 to 8.5 GHz.
Voltage: 500 volts peak.
Power: 3 kW up to 1 MHz; 3 kW/$\sqrt{f_{MHz}}$ above 1 MHz.
Electrical Length: 5.37 ± 0.05 cm to the end of the type BNC jack inner conductor.
Dimensions: Length, 2⅛ inches (54mm); maximum diameter, 1¹⁄₁₆ inch (27 mm).
Net Weight: 3½ ounces (100 grams).

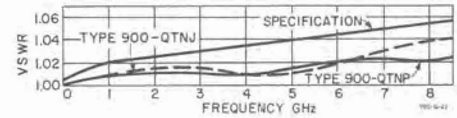
Type 900-QBP Adaptor

Same as Type 900-QBJ except:
Electrical Length: 5.70 ±0.03 cm to the end of the Type BNC plug outer conductor.

TYPES 900-QTNJ AND 900-QTNP ADAPTORS



* Inner conductor has 4 equally spaced slots 0.008 ±0.001 wide by 0.187 ± 0.005 deep.
** Outer conductor has 6 slots 60° apart, 0.015 ± 0.001 wide by 0.235 ± 0.003 deep; inner diameter in region of contact-fingers is 0.2650 ± 0.0005 when fingers are inserted in a 0.3200 inner-diameter ring.



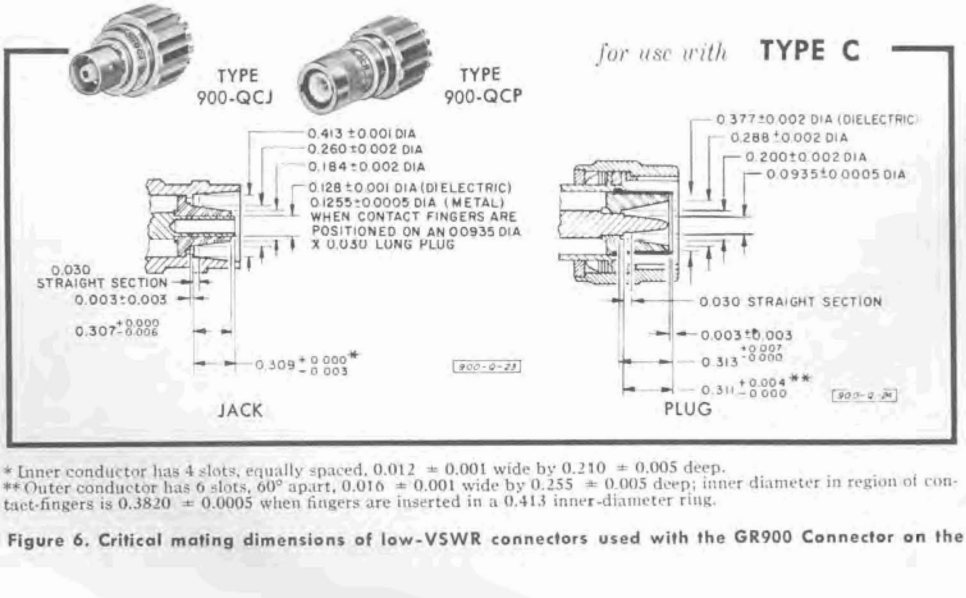
Type 900-QTNJ Adaptor

Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.005 + 0.015 f_{GHz}$ to 1 GHz; $1.015 + 0.005 f_{GHz}$, 1 to 8.5 GHz.
Voltage: 500 volts peak.
Power: 3 kW up to 1 MHz; 3 kW/$\sqrt{f_{MHz}}$ above 1 MHz.
Electrical Length: 5.37 ± 0.05 cm to the end of the type TNC jack inner conductor.
Dimensions: Length, 2⅛ inches (54mm); maximum diameter, 1¹⁄₁₆ inch (27 mm).
Net Weight: 3½ ounces (100 grams).

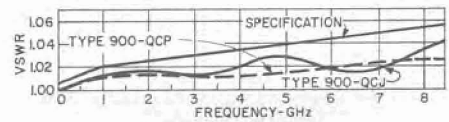
Type 900-QTNP Adaptor

Same as Type 900-QTNJ except:
Electrical Length: 5.70 ±0.03 cm to the end of the Type TNC plug outer conductor.

TYPES 900-QCJ AND 900-QCP ADAPTORS



* Inner conductor has 4 slots, equally spaced, 0.012 ± 0.001 wide by 0.210 ± 0.005 deep.
** Outer conductor has 6 slots, 60° apart, 0.016 ± 0.001 wide by 0.255 ± 0.005 deep; inner diameter in region of contact-fingers is 0.3820 ± 0.0005 when fingers are inserted in a 0.413 inner-diameter ring.



Type 900-QCJ Adaptor

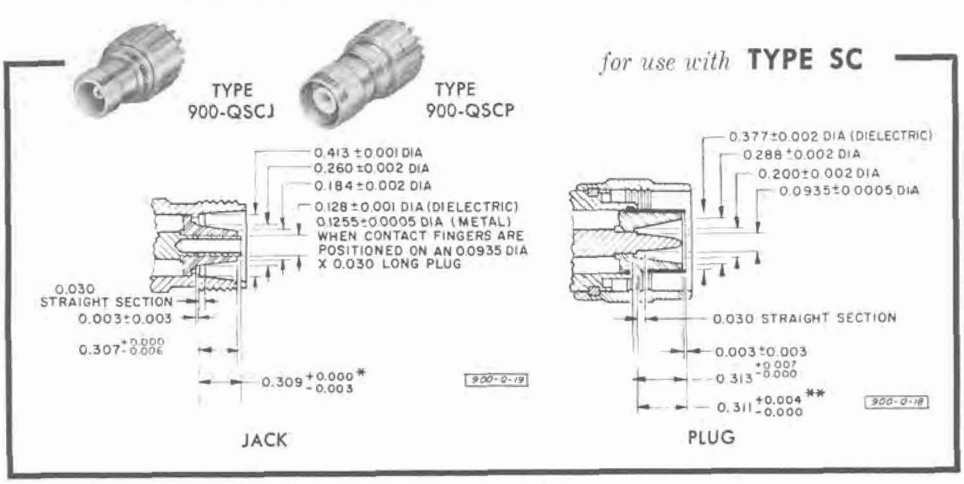
Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.005 + 0.015 \times f_{GHz}$ to 1 GHz; $1.015 + 0.005 \times f_{GHz}$, 1 to 8.5 GHz.
Electrical Length: 5.03 ±0.05 cm to the end of the Type C jack inner conductor.
Voltage: 1000 V peak.
Power (Average): 7 kW up to 1 MHz;
7 kW/ $\sqrt{f_{MHz}}$ above 1 MHz.
Dimensions: Length, 1⅞ inches (48 mm); maximum diameter, 1¹⁄₁₆ inches (27 mm).
Net Weight: 3½ ounces (100 grams).

Type 900-QCP Adaptor

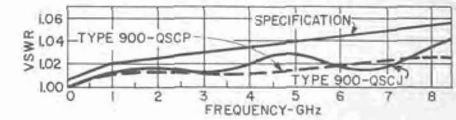
Same as Type 900-QCJ except:
Electrical Length: 5.60 ±0.05 cm to the end of the Type C plug outer conductor.
Dimensions: Length, 2¹⁄₁₆ inches (53 mm).

Figure 6. Critical mating dimensions of low-VSWR connectors used with the GR900 Connector on the precision adaptors. (All dimensions are in inches.)

TYPES 900-QSCJ AND 900-QSCP ADAPTORS



* Inner conductor has 4 slots, equally spaced, 0.012 ± 0.001 wide by 0.210 ± 0.005 deep.
** Outer conductor has 6 slots, 60° apart, 0.016 ± 0.001 wide by 0.255 ± 0.005 deep; inner diameter in region of contact-fingers is 0.3820 ± 0.0005 when fingers are inserted in a 0.413 inner-diameter ring.
All dimensions in inches.



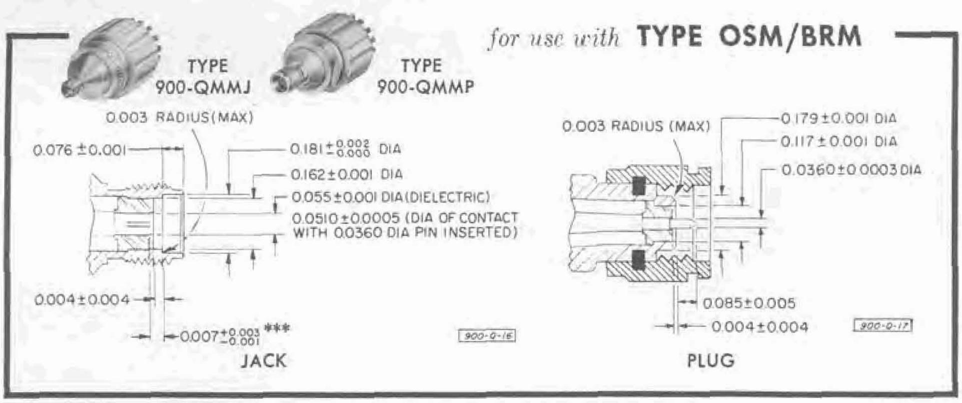
Type 900-QSCJ Adaptor

Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.005 + 0.015 \times f_{GHz}$ to 1 GHz; $1.015 + 0.005 \times f_{GHz}$, 1 to 8.5 GHz.
Electrical Length: 5.03 ±0.05 cm to the end of the Type SC jack inner conductor.
Voltage: 1000 V peak.
Power (Average): 7 kW up to 1 MHz; 7 kW/ $\sqrt{f_{GHz}}$ above 1 MHz.
Dimensions: Length, 2 inches (51 mm); maximum diameter, 1 1/16 inches (27 mm).
Net Weight: 3½ ounces (100 grams).

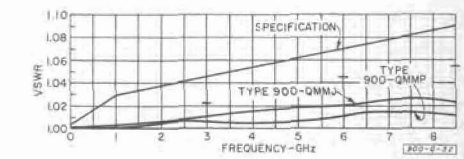
Type 900-QSCP Adaptor

Same as Type 900-QSCJ except:
Electrical Length: 5.60 ±0.05 cm to the end of the Type SC plug outer conductor.
Dimensions: Length, 2⅛ inches (54 mm).

TYPES 900-QMMJ AND 900-QMMP ADAPTORS



*** Inner conductor has 4 equally spaced slots 0.008 ± 0.001 wide by 0.078 ± 0.005 deep.
All dimensions in inches.



Type 900-QMMJ Adaptor

Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.005 + 0.025 \times f_{GHz}$ to 1 GHz; $1.022 + 0.008 \times f_{GHz}$, 1 to 8.5 GHz.
Electrical Length: 4.67 ±0.05 cm to the outer conductor junction.
Dimensions: Length, 1⅞ inches (48 mm); maximum diameter 1 1/16 inches (27 mm).
Net Weight: 2½ ounces (70 grams).

Type 900-QMMP Adaptor

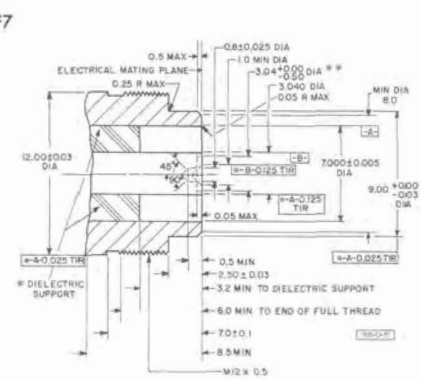
Same as Type 900-QMMJ except:
Electrical Length: 4.78 ±0.05 cm to the outer conductor junction.

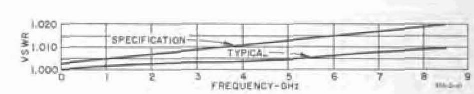
TYPES 900-QAP7 AND 900-QPF7 ADAPTORS

for use with **7 MM**

These two adaptors permit interconnection of GR900 and 7-mm coaxial connectors.

The TYPE 900-QAP7 mates GR900 with the Amphenol APC-7 connector, and the TYPE 900-QPF7 mates GR900 with the Rohde & Schwarz Precifix A and Dezifix A Connectors.





Type 900-QAP7 Adaptor and Type 900-QPF7 Adaptor

Frequency Range: Dc to 8.5 GHz.
VSWR: Less than $1.003 + 0.002 f_{GHz}$.
Electrical Length: 5.30 ±0.02 cm.
Maximum Voltage: 1000 V peak.
Maximum Power: 6 kW up to 1 MHz; 6 kW/ $\sqrt{f_{MHz}}$ above 1 MHz.
Dimensions: Length 2⅛ in. (54 mm); max dia 1 1/16 in. (27 mm).
Net Weight: 3½ oz (100 g).

* Inner- and outer-conductor diameters in the vicinity of the dielectric support may be varied to provide electrical compensation.
** Center-conductor contact shown in mated coplanar position.
All dimensions in millimeters.

Figure 6. Critical mating dimensions of low-VSWR connectors used with the GR900 Connector on the precision adaptors.

IMPEDANCE-MATCHING TUNERS FOR PRECISION COAXIAL-MEASURING SYSTEMS

In many measurements with the GR900 system, there is the need to tune out the small residual reflections of the GR900 components. For example, by matching the TYPE 900-W50 50-ohm Termination to the TYPE 900-LB Precision Slotted Line, one can effectively upgrade the performance of the termination to the level of the slotted line — a fivefold improvement.

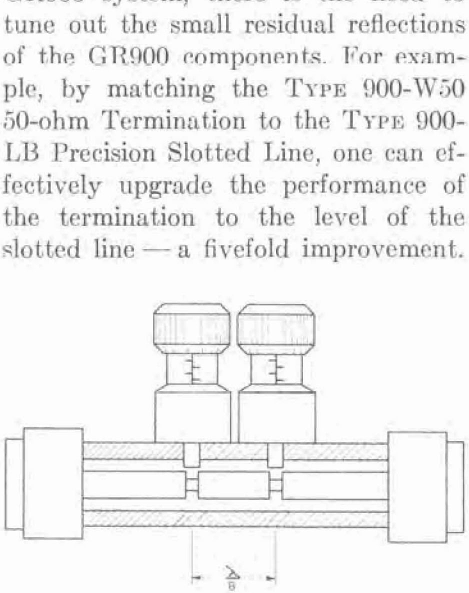


Figure 1. Cross-section view of tuner.

In substitution measurements, accuracy and speed are improved considerably when a matching tuner is used to set the initial conditions to a perfect match

The TYPE 900-TUB Tuner, for the 0.25- to 2.5-GHz frequency range, and the TYPE 900-TUA Tuner, which covers the 1- to 8.5-GHz frequency range, are designed to provide such matching. The two tuners are similar in design and construction and, in addition to their wide bandwidths, have the following desirable features:

1. A unique neutral position, from which rapid convergence to match can always be achieved

2. A fineness of control, so that VSWR's as low as 1.0002 can be tuned out with ease

3. Stability — when a residual standing-wave ratio is tuned out, it stays tuned out; if the setting is changed, the original tuning is duplicated when the original setting is restored; if the connection between line and tuner is broken and then restored, the tuning is unchanged.

Each tuner has three tuning screws, two of which are used to adjust a match (depending on frequency). Each tuning element (see Figure 1) consists of a tuning screw and an inductive groove in the inner conductor, in the same plane as the tuning screw. Turning the screw counterclockwise places a small inductance in series with the line, while turning the screw clockwise adds a small capacitance in shunt with the line; positive or negative increments are thus produced along the imaginary axis of a Smith-chart impedance plot. To produce incremental changes along the real axis, another tuning screw is placed one-eighth wavelength (or an odd multiple of one-eighth wavelength) from the first, for this separation provides orthogonality of the two adjustments on the Smith chart. The Smith-chart coverage of the two adjustments at band center is a square in the middle of the Smith chart. Off center frequency, the square becomes a diamond of smaller area but is still centered on the Smith chart (see Figure 2). The reduction of matching area limits the useful frequency range of a given pair of screws to the octave between two-thirds and four-thirds of the center frequency.

Each tuning screw can be set so that its shunt susceptance exactly cancels the series inductance of the groove, and the net effect of the two discontinuities is zero. This is called the neutral position of the tuning adjustment. Because the effects of both shunt susceptance and series inductance increase with frequency at the same rate, and because the screw and the groove are placed at the same point in the transmission line, *the neutral setting is independent of frequency.* The neutral-setting feature was, in fact, fundamental to the design of the tuner; only with such provision could several screws be placed in the transmission line at different spacings to satisfy the odd-eighth-wavelength condition at many frequencies and to provide reasonably orthogonal tuning adjustments over a broad and continuous frequency range. In operation, two of the three screws are adjusted for match (which two depends on the frequency), while the unused screw is set to the neutral position. Each screw has a scale, with vernier, and can be locked at any setting.

The VSWR matching ranges of the TYPES 900-TUB and -TUA Tuners (see Figure 3), while they are high enough for most applications, have been kept sufficiently low that extremely fine

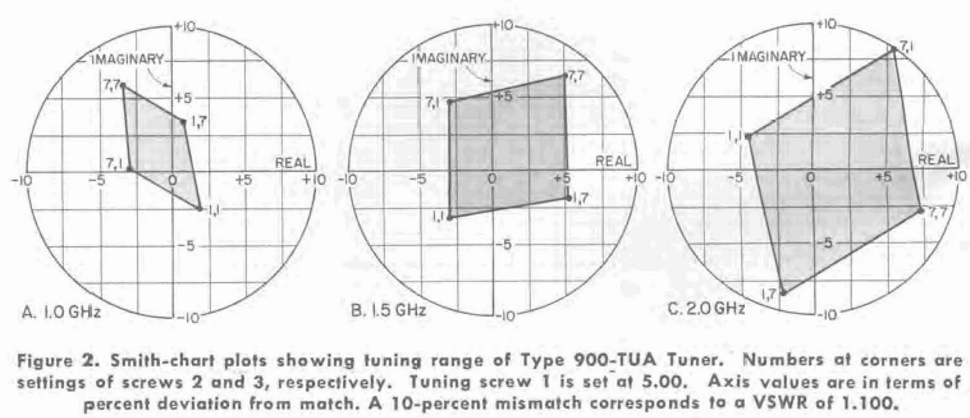


Figure 2. Smith-chart plots showing tuning range of Type 900-TUA Tuner. Numbers at corners are settings of screws 2 and 3, respectively. Tuning screw 1 is set at 5.00. Axis values are in terms of percent deviation from match. A 10-percent mismatch corresponds to a VSWR of 1.100.

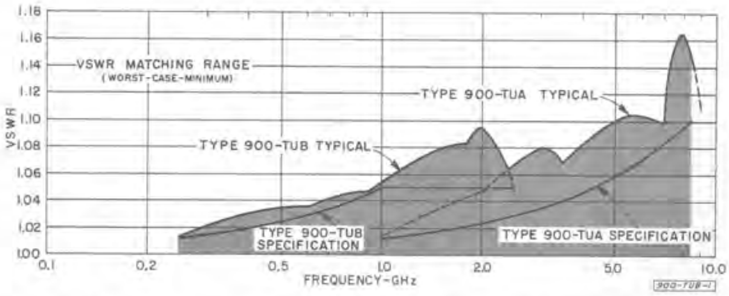


Figure 3. VSWR matching range of the Types 900-TUB and -TUA Tuners. Specifications and data shown are under the most restrictive phase conditions of the reflection to be matched out.

matches can be achieved with ease and speed.[1]

APPLICATIONS

Matching to a Standard of Impedance

With the GR900 Tuners one can reduce the residual reflections introduced into a coaxial system by terminations, measuring instruments (such as slotted lines, rf bridges and directional couplers), adaptors between line sizes, and connectors. These residual reflections must always be considered with respect to some standard of impedance. The standard may be part of a measuring instrument, it may be a termina-

Figure 4. Type 900-TUA Tuner, shown in place between reference air line and Type 900-W50 50-ohm Standard Termination.

tion, or it may be a section of precision air line. The tuner is used, therefore, to match the impedance of the device in question to that of the standard.

The Measuring Instrument as an Impedance Standard

The Type 900-LB Precision Slotted Line is an excellent impedance standard. It covers the 0.3- to 8.5-GHz frequency range, and, at 2 GHz, for example, the residual impedance error (expressed in VSWR) is less than 1.003. If a composite termination consisting of a Type 900-W50 Standard Termination and a Type 900-TUA or -TUB Tuner is assembled, as shown in Figure 4, and the tuner is adjusted so that the amplitude of the standing-wave pattern observed on the slotted line is reduced to zero, then the residual VSWR of the composite termination is made equal to the residual VSWR of the slotted line. The improvement in VSWR can be as much as five-fold over the direct residual VSWR of the termination alone.

Termination as an Impedance Standard

A well-matched termination, such as the Type 900-W50 Standard Termination or, even better, the composite termination described above, can also be used as an impedance standard. For example, if the measuring instrument is a directional coupler or a hybrid junction, the instrument residual may be much greater than that of an available standard termination. In these cases a composite measuring instrument, consisting of the basic measuring instrument and a Type 900-TUA or -TUB Tuner, can be formed, as shown in Figure 5, and the tuner adjusted so that a null is observed with the measuring instrument. The residual VSWR of the composite instrument is thus made equal to that of the standard termination.

Air Line as an Impedance Standard

The most accurate impedance standard is the characteristic impedance of a section of precision air-dielectric coaxial line, such as a Type 900-LZ Reference Air Line. The residual VSWR of these air lines at 2 GHz is less than 1.0009. Both a composite measuring instrument and a composite termination, as shown in Figure 6, can be independently and simultaneously matched to the characteristic impedance of the air-line standard, at frequencies where the air-line length is an odd multiple of a quarter wavelength[2]. The matching is accomplished by alternate adjustment of the tuners, I and II, until no reflection is observed by the measuring instrument (1) when the composite termination is connected through the air-line standard to the composite measuring instrument and (2) when the composite termination is connected directly to the composite measuring instrument (that is, with the air line out of the system).

Simplifying Substitution Measurements

Substitution techniques, such as those described by Sanderson[3] and Zorzy[4], are used to obtain accurate measurements of small reflections in the presence of comparable residual reflec-

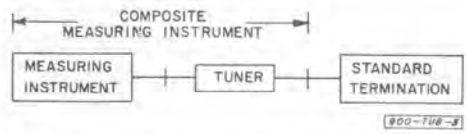


Figure 5. Standard termination attached to a composite measuring instrument.

tions in the measuring systems. In these techniques, two measurements are required, and the desired quantity is dependent on the vector difference of the two measured quantities.

When an impedance-matching tuner is used to make one of the measured reflection coefficients equal to zero, the second measurement alone provides the answer[2,5]. This means that it is not necessary for one to perform the vector subtraction or to plot measurements on a Smith Chart and to make tedious constructions. Also, if only the magni-

[1] See Reference 11.
[2] See Reference 13.
[3] See Reference 19.
[4] See Reference 32.
[5] See Reference 18.

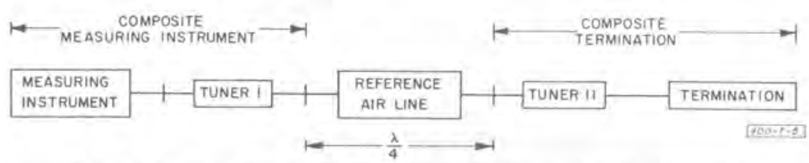


Figure 6. Setup for matching composite measuring instrument and composite termination to the characteristic impedance of an air-line standard.

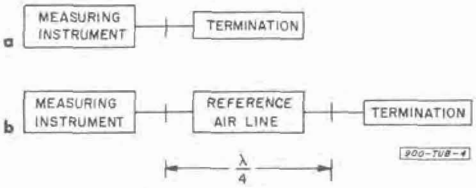


Figure 7. a) Setup to measure Γ_1. b) Setup to measure Γ_2.

tude of the answer is required, it can be obtained directly from just one magnitude measurement.

Quarter-Wavelength Substitution to Measure Termination

The simplification resulting from the use of the tuner is illustrated by the example of the substitution technique that employs a quarter-wavelength reference air line to determine the reflection of a termination in the presence of the residual reflection of the measuring instrument.

Without the tuner, two measurements are required, one with and one without the reference air line in the system, as illustrated in Figure 7. (It is assumed that the reference air line is reflectionless and lossless and that the reflection coefficients of interest are small.) Thus

$$\Gamma_1 = \Gamma_m + \Gamma_t \qquad (1)$$

$$\Gamma_2 = \Gamma_m + \Gamma_t e^{-j\pi} = \Gamma_m - \Gamma_t \qquad (2)$$

where

Γ_1 is the measured reflection coefficient without the reference air line inserted,

Γ_2 is the measured reflection coefficient with the reference air line inserted,

Γ_t is the reflection coefficient of the termination, and

Γ_m is the residual reflection coefficient of the measuring instrument. The termination reflection coefficient is given from the difference of equations (1) and (2) by the vector relation

$$\Gamma_t = \frac{\Gamma_1 - \Gamma_2}{2} \qquad (3)$$

The reflection coefficients Γ_1 and Γ_2 are plotted on the Smith Chart of Figure 8 with the construction required to obtain Γ_t.

Now, with the tuner forming a composite measuring instrument as shown in Figure 9, Γ_1 can be tuned to zero.

$$\Gamma_1 = \Gamma'_m + \Gamma_t = 0 \qquad (4)$$

where Γ'_m is the residual reflection coefficient of the composite measuring instrument under the condition of (4). With

$$\Gamma_2 = \Gamma'_m - \Gamma_t, \qquad (5)$$

the termination reflection coefficient is given directly by

$$\Gamma_t = -\frac{\Gamma_2}{2}. \qquad (6)$$

No vector subtraction, and therefore

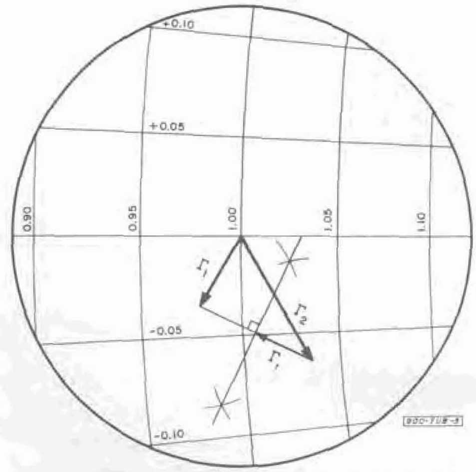


Figure 8. Smith Chart construction to determine Γ_t.

no constructions on the Smith Chart, is required.

Similar simplifications can be realized in other substitution techniques through the application of the Types 900-TUA and -TUB Tuners.

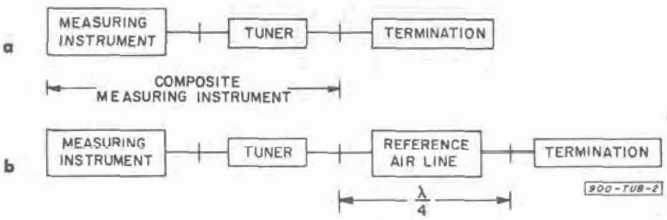


Figure 9. a) Setup to adjust Γ_1 to zero. b) Setup to measure Γ_2 and to determine Γ_t directly.

SPECIFICATIONS

	900-TUA	900-TUB
Frequency Range	1 to 8.5 GHz	0.25 to 2.5 GHz
Characteristic Impedance	50 Ω	50 Ω
VSWR Matching Range (worst-case minimum)*	$1.00 + 0.012 f_{GHz}$	$1.00 + 0.05 f_{GHz}$ to 1 GHz 1.05 from 1 to 2.5 GHz
VSWR Resettability	$<1.0005 + 0.0003 f_{GHz}$	$<1.0005 + 0.0003 f_{GHz}$
Residual VSWR (all controls at neutral)	<1.03 to 5 GHz <1.05 from 5 to 7 GHz	<1.03 to 1.5 GHz
Insertion Loss	<0.1 dB to 4 GHz <0.3 dB to 8.5 GHz	<0.1 dB
Repeatability of Connection	0.05%	0.05%
Electrical Length	12.0 cm	18.5 cm
Dimensions	4½ × 3½ × 1 in (115, 88, 25 mm)	6½ × 4¾ × 1 in (165, 120, 25 mm)
Net Weight	1 lb (0.5 kg)	1¼ lb (0.6 kg)
Shipping Weight	3 lb (1.4 kg)	4 lb (1.9 kg)

* Range is wider under most conditions

TYPE 900-LB PRECISION SLOTTED LINE

The slotted line is the basic immittance- and VSWR-measuring instrument for the uhf and shf ranges. It has yet to be surpassed in absolute accuracy, versatility, and bandwidth. Its accuracy is absolute because its built-in impedance standard is the characteristic impedance of its coaxial line, which is directly dependent upon mechanical dimensions.

Imperfections in the slotted coaxial-line system and the discontinuities at slot end, transitions, and connectors are the principal sources of error. Such imperfections and discontinuities in the coaxial-line section have been virtually eliminated in the Type 900-LB Precision Slotted Line. New manufacturing methods and further development in the conventional methods have made this possible. Furthermore, there is no transition problem because there is no transition; the connection between the slotted section and the connector is a continuous, uniform, coaxial transmission line with very close control of diameters, as in the slotted section. And Type

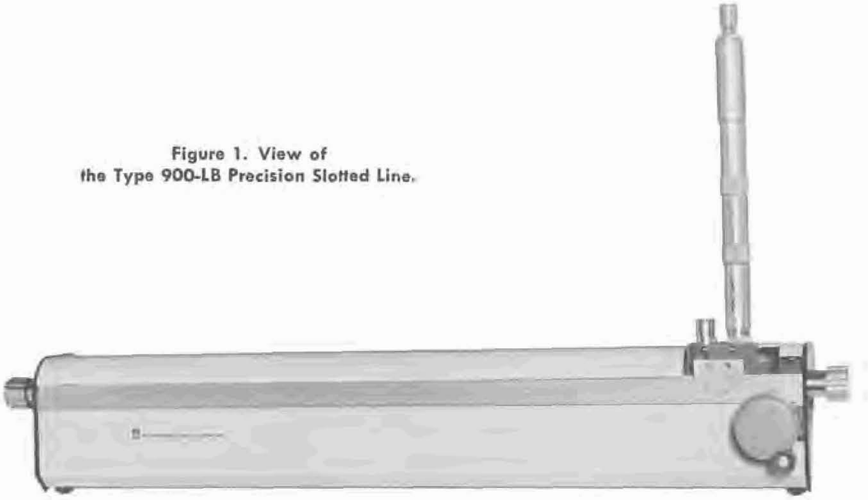


Figure 1. View of the Type 900-LB Precision Slotted Line.

900-BT Connector has effectively eliminated connector errors.

The new precision slotted line is similar in general construction to the TYPE 874-LBB, which has in recent years been constantly improved and ruggedized, and whose accuracy is comparable with that of other commercially available types. Many of its design features have been embodied in the 900 model, along with a number of refinements and improvements.*

The precision slotted line uses an air-dielectric coaxial line, with an outer conductor ID of 0.5625 inch, made to extremely close dimensional tolerances. Connectors are a TYPE 900-BT at the unknown terminals, a GR900 Connector at the input side and a nonlocking GR874 at the demodulated detector output terminals.

The following new features have been incorporated:

A new probe assembly, comprised of an externally adjustable probe, with calibrated penetration depth, and a probe tuner with micrometer-type drive, calibrated in centimeters, and having excellent tuning stability.

A vernier scale and, in addition, a micrometer drive for fine resolution.

Provision for direct rf connection to the probe; the tuner is replaced with an rf probe assembly.

A protective cover, which can be closed to prevent dust accumulation and damage. The cover reinforces the basic assembly and adds very little extra weight.

* The Type 900-LB Slotted Line does not supersede the Type 874-LBB, which is still available.

The 900-LB can be quickly converted, by means of low-VSWR adaptors, into a precision type N, BNC, TNC, C, SC, OSM/BRM, 7-mm Amphenol APC-7, 7-mm Rohde and Schwarz Precifix and Dezifix A connectors, or TYPE 874 Slotted Line.

The slotted line can be calibrated absolutely with the TYPE 900-BT Connectors to a much higher degree of accuracy than with other connector types. The TYPE 900-LZ Reference Air Lines and the TYPE 900-W50 Termination are excellent calibration devices for this purpose.

The most important feature, however, is performance:

Residual VSWR is extremely small (Figure 2), $1.001 + 0.001 \times f_{GHz}$. With a TYPE 900-QNJ or -QNP Adaptor to type N installed, over-all VSWR is $1.005 + 0.005 f_{GHz}$.

Constancy of probe coupling, a most important characteristic, is ±0.5%.

Frequency range is 300 MHz to 8500 MHz; probe carriage travel is 50 cm.

With the precision air lines the length can be extended to permit operation down to 150 MHz.

Applications

The TYPE 900-LB Slotted Line is well suited to all the well-known slotted line measurements, such as immittance, VSWR, and reflection coefficients of distributed and lumped elements and antennas. More importantly, it is recommended for the absolute calibration of standards.

[1] See Reference 19.
[2] See Reference 17.

Additional applications include:

(1) Measurement of connectors and elements by the substitution method.[1,2]

(2) Determination of small-signal characteristics of diodes and transistors. For these measurements, the slotted line is driven through the probe with the special connector provided, and the detector then connects to what is normally the generator end of the line. By this means, adequate sensitivity is maintained at low voltage levels.

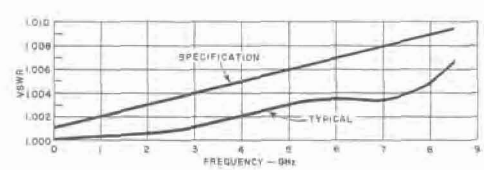
(3) Measurement of dielectric constant and loss tangent of dielectric materials.

(4) Precision phase shifter. The slotted line can be terminated with the TYPE 900-W50 Termination and variable phase signal taken from the probe. Phase shift is accurately calibrated in terms of probe travel.

(5) Sliding short-circuit measurements of scattering coefficients of distributed and lumped elements.[3,4]

Those engaged in the development of coaxial devices will find this slotted line an invaluable aid to the design of equipment with truly low standing-wave ratio.

[3] See Reference 2.
[4] See Reference 22.



SPECIFICATIONS

Characteristic Impedance: 50.0 ohms ± 0.1%.
Probe Travel: 50 cm. Scale calibrated in centimeters from the reference plane. Attached vernier scale can be read to 0.1 mm.
Scale Accuracy: ± (0.1 mm + 0.05%).
Frequency Range: 300 MHz to 8.5 GHz. At 300 MHz, covers a half wavelength. Operates below 300 MHz with TYPE 900 Precision Air Line.
Constancy of Probe Pickup: ±0.5%.
Residual VSWR: Less than $1.001 + 0.001 \times f_{GHz}$ (e.g., 1.002 at 1 GHz), unknown connector side.
Accessories Supplied: TYPE 874-R22A Patch Cord; TYPE 900-WN Precision Short-Circuit; TYPE 900-WO Precision Open-Circuit; 874-Q900L Adaptor; tuning stub-probe assembly (including 1N21C and 1N23C diodes); rf-probe assembly (with TYPE 874-BBL Connector); micrometer carriage drive (accurate to 0.01 mm); spare drive cable; storage box; Smith charts.
Accessories Required: Generator and detector.
Dimensions: Width 27½, height 10, depth 4¾ inches (700 by 255 by 125 mm).
Net Weight: 10¾ pounds (4.9 kg).
Shipping Weight: 27 pounds (12.5 kg).

A SLOTTED LINE RECORDER SYSTEM

As the basic tool in coaxial impedance measurements, the slotted line remains unsurpassed; its accuracy is absolute, since its standard impedance is the characteristic impedance of a coaxial line. The inherent accuracy of the slotted line, as well as its stability and broad bandwidth, led to the investigation of the limitations of this instrument for low VSWR measurements. As might be expected, we found the limiting factors to be not in the slotted line itself but in the noise level and limited scale expansion of commercial standing-wave indicators. This conclusion led to the development of the TYPE 1640-A Slotted Line Recorder System.

The combination of a slotted line and a graphic recorder produces a recording of the slotted-line probe output as a function of probe position that far exceeds, in resolution and usefulness, the conventional meter readout. The noise figure of the transistorized TYPE 1640-A System is held to less than 5 dB, and the high signal-to-noise ratio at the crystal detector (normally over 80 dB) is preserved through the amplifier chain and the recording process. The recording of VSWR's as low as 1.001 with excellent signal-to-noise ratio is entirely practical.

The use of a slotted line recorder system not only overcomes the traditional scale-factor and noise problems but also offers the many advantages of a permanent recording. The chart record, for example, can be analyzed graphically for the most accurate measurement of VSWR, position of minimum, and other waveform characteristics. The minima of low-VSWR patterns are particularly difficult to locate by traditional techniques, because of their shallowness and because of the apparent shift of position if tilt exists in the flatness curve. On a chart record, the positions of minima are strikingly easier to locate, not only because the pattern is greatly expanded, but also because the VSWR pattern and the flatness curve are easily disentangled when both are visible together.

Several plots can be made on the same chart so that, for example, the positions of minima with short-circuit termination and with unknown at the reference plane can be intercompared directly. Wherever the *difference* between two measurement conditions is important, any irregularities in the slotted line (in constancy of probe penetration, for instance) effectively cancel out in a multiple plot, and the difference shows up clearly as a sinusoidal wobble of one trace about the other (see Figure 1). Because of the effective elimination of slotted line imperfections from the measurement, the substitution method by graphic recording yields the most accurate, repeatable measurements of low VSWR — with the TYPE 1640-A, down to 1.001.

Repeatability and comparison measurements are also facilitated by the multiple-recording technique. A series of measurements, for instance, can be plotted on the same section of chart paper as a rapid method of comparison-checking components against a standard. The graphic record also quickly reveals whether the measurement is a true one or whether it is being distorted by a noisy signal generator, a connector that doesn't repeat, or some other unforeseen factor. Finally, as a continuous monitor on equipment operation, the recording far surpasses the usual VSWR meter in convenience.

THE TYPE 1640-A SLOTTED LINE RECORDER SYSTEM

The new Slotted Line Recorder System, shown in Figure 2, comprises a standard TYPE 900-LB Precision Slotted Line and a modified version of the TYPE 1521 Graphic Level Recorder (TYPE 1521-SL), along with the necessary interconnecting linkage and mounting hardware. The slotted line is mounted in its usual bench-top position, and the recorder is beneath the bench, either on a shelf or suspended from the bench top with the bolts provided. The metal mounting plate on which the slotted line rests has four studs, which engage the rubber feet of the slotted line, and a projecting shaft. A gear on one end of this shaft is coupled to the probe-carriage drive, and a sprocket on the front end engages the external chain-link drive of the recorder. The motor that powers the chart drive thus also drives the probe carriage of the slotted line, and the chart paper is automatically given the correct horizontal axis for the desired VSWR plot. The vertical axis of the plot is supplied by the audio output of the crystal detector, which is connected by a coaxial cable from the probe carriage to the recorder input connector. The recorder suppresses the zero level and applies the resulting greatly expanded VSWR pattern to the vertical axis of the strip chart. The degree of scale expansion is remarkable: On a typical VSWR meter a VSWR of 1.10 takes up two inches of scale, whereas a VSWR of *1.008* can be expanded to the full 4-inch width of the chart paper!

THE SLOTTED LINE

The TYPE 900-LB Precision Slotted Line is the most precise coaxial impedance-measuring instrument available commercially, with a residual VSWR of $1.001 + 0.001 f_{GHz}$ from 300 MHz to 8.5 GHz; it is, moreover, an extremely rugged, reliable instrument whose calibration can be expected to stay within

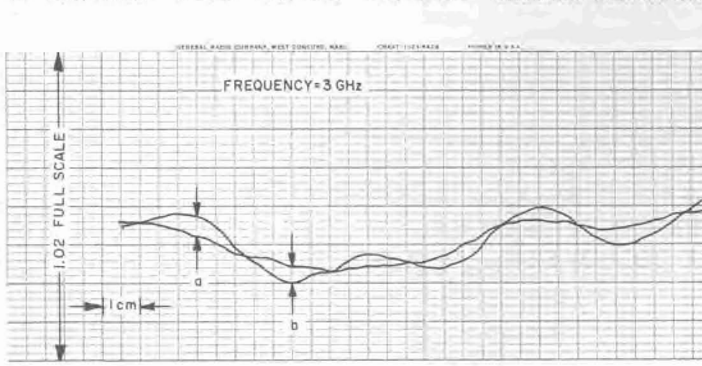


Figure 1. Multiple plot used to measure difference between two measurement conditions. Note that the difference in the recording (a + b) is a sine wave corresponding to a VSWR of 1.002!

specification indefinitely. The forged outer conductor joins its connectors smoothly, without the reflection-causing steps and discontinuities found in noncylindrical coaxial slotted lines.

The chrome-plated outer conductor of the line is a 26-inch, precision-forged, brass tube, lined with a 0.0005-inch layer of pure silver for low loss. The finished inner diameter is 0.5625 inch ± 100 microinches. The inner conductor is steel with a 0.0005-inch layer of silver and is centerless-ground to a tolerance of ± 50 microinches. Both inner and outer conductors are stress-relieved to resist diameter changes due to machining.

Two interchangeable electrostatic probe assemblies are supplied: a tunable probe for use with the built-in detector for modulated signals and an rf probe to couple an unmodulated signal to an external detector. Either mounts in the carriage that transports the probe through the entire 50-cm length of the slot. This cast brass carriage, with its honed sleeve bearing, rides smoothly on the finely ground surface of the outer conductor.

Probe position along the 50-cm slot, relative to the reference plane of the GR900 connector, is indicated to within 0.1 millimeter by a calibrated millimeter scale with attached vernier.

Depth of penetration of the tunable probe is controlled and indicated by a micrometer adjustment. The scale is preset to indicate directly the distance between the probe tip and the center conductor (smallest marked interval: 0.001 inch). A positive stop prevents the probe from striking the center conductor.

The probe is tuned to resonance (at any frequency from 300 MHz to 8.5 GHz) with a built-in short-circuited stub, whose length is adjusted by means of a rotating barrel drive. One turn of the barrel moves the short circuit 1 cm. A logging scale indicates position of the short circuit within the barrel.

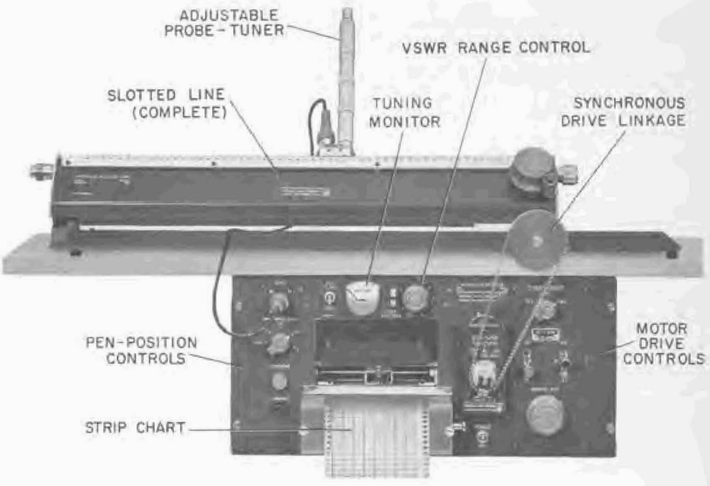


Figure 2. Type 1640-A Slotted Line Recorder System. Owners of Type 900-LB Slotted Lines can easily add recorder and connecting linkage.

SLOTTED LINE RECORDER

The Type 1521-SL Slotted Line Recorder is a transistorized, single-frequency, servo-type instrument (see block diagram, Figure 3), which produces, on white chart paper, an ink record of the standing-wave pattern of the slotted line. Scale expansion is continuously adjustable, with the control calibrated in VSWR, % FULL SCALE (a VSWR of 1.01 is defined as equivalent to 1%). Standing-wave patterns of 1.2 to 1.008 in VSWR can be expanded to occupy full scale.

The VSWR accuracy of the strip-chart recording depends only on three stable, wire-wound potentiometers in the servo loop. These are custom-calibrated in each instrument. The accuracy is within one minor division of the chart paper (1/40th of full scale) for all positions of the VSWR, % FULL SCALE control.

Sensitivity (the minimum signal level for an on-scale indication) is continuously adjustable from 50 microvolts to 2 millivolts. The 2-millivolt upper limit is set by the square-law characteristic of the crystal detector, the 50-microvolt lower limit by the degradation in signal-to-noise-ratio (which also determines the minimum detectable VSWR).

The amplifier is fixed-tuned to 990 Hz (avoiding harmonics of 60 Hz and 50 Hz) and has a 35-cycle bandwidth. The 5-dB noise figure at this bandwidth results in a VSWR-equivalent noise level of 1.0001 (0.01%) at an audio input signal level of 1.0 millivolt.

Chart Drive

The chart drive has four speeds, since two sprockets of 2:1 different sizes are supplied, there are eight possible slotted-line carriage drive

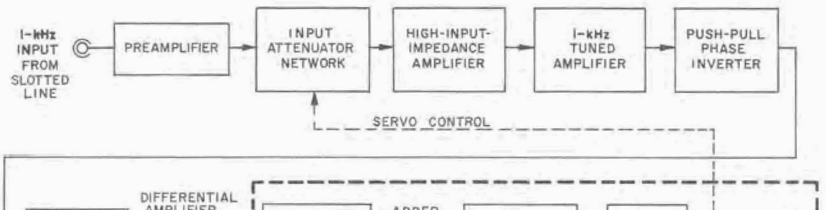


Figure 3. Block diagram of Type 1521-SL Slotted Line Recorder.

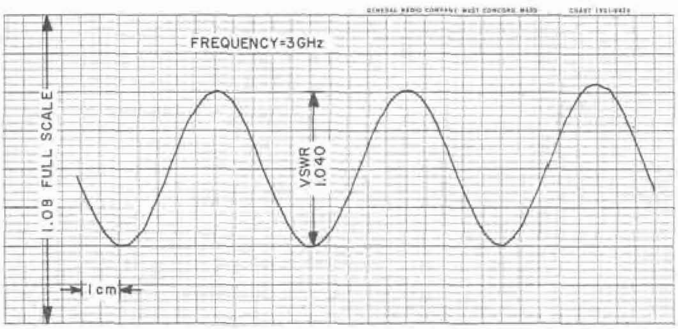


Figure 4. Typical direct recording of VSWR.

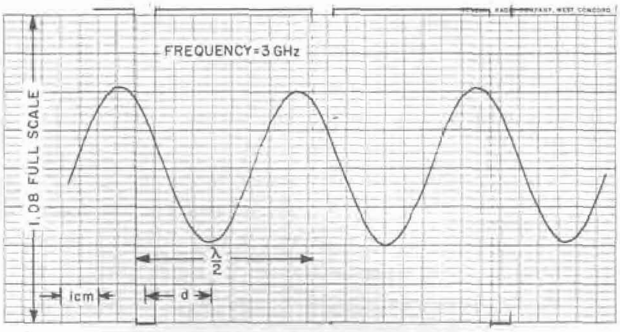


Figure 5. Multiple recording used in direct measurement of VSWR and phase.

speeds, from 5 to 0.08 centimeters per second. One horizontal division on the chart paper corresponds to either 1 or 0.5 centimeter on the slotted-line scale, depending on which sprocket is used. Fast chart speeds and the 1-cm/division sprocket are used at lower frequencies, while the slower speeds and the 0.5-cm/division sprocket expand the horizontal scale for better precision at the high end of the band. *At any frequency from 0.6 to 8.5 GHz, two full cycles of the standing-wave pattern can be scanned in five seconds, without perceptible distortion of the standing-wave pattern.*

APPLICATIONS

Direct VSWR Measurement

The primary application of the Slotted Line Recorder System is, of course, the measurement of the VSWR of an unknown one-port component by the direct method. If VSWR alone is desired, the recorder motor drive is engaged for at least one cycle of the standing-wave pattern, to produce a record similar to that shown in Figure 4. If the phase of the VSWR pattern is also important, then a TYPE 900-WN Short-Circuit Termination (supplied with the system) is connected in place of the unknown, and a second curve is superimposed on the first (see Figure 5). The distance between positions of minima is then measured directly on the chart paper, as is wavelength, and the value of d/λ, thus determined, is transferred to the Smith chart as wavelengths-toward-load. The ease with which the positions of minima can be located graphically ensures excellent phase measurements, even for VSWR's as low as 1.01.

Direct VSWR measurements can be made on connector systems other than GR900 by means of GR900 precision, low-VSWR adaptors. These are now available to types BNC, C, N, TNC, SC, OSM/BRM, Amphenol 7-mm APC-7, Rohde and Schwarz Precifix and Dezifix A, and GR874 connectors.

Substitution VSWR Measurement

For even greater accuracy, a substitution technique can be used,[1] with a TYPE 900-LZ Reference Air Line acting as an impedance standard. Accuracy of measurement is increased by a factor of from 2 to 5, depending on frequency, and the position of minimum can be located accurately for a VSWR as low as 1.001.

In the substitution method, a multiple plot is recorded, showing (1) the VSWR of the unknown connected directly to the slotted line and (2) the VSWR with the reference air line inserted between the unknown and the slotted line. (See Figure 6.) With the impedance transformation of a quarter-wave air-line section, the difference between the two curves represents twice the VSWR of the unknown impedance with respect to the reference air line. The residual VSWR of the slotted line effectively cancels out.

To determine phase, a curve is run with a short circuit at the reference plane, as before (see Figure 7). The position of minimum of the unknown is halfway between two adjacent intersections on the multiple VSWR plot and can thus be located with pinpoint accuracy, no matter how low the VSWR may be. As before, d and λ are both on the chart paper, and their quotient becomes the "wavelengths-toward-load" reading on the Smith chart.

Insertion VSWR

Many of the most common design problems can be cast in the form of two-port unknowns, and the insertion VSWR of a two-port unknown can be measured very accurately on the slotted-line recorder system by a substitution method.[1,2] Examples of design problems centering on the insertion VSWR are the design of coaxial connectors, of isolated bead supports, or of transitions between coaxial lines of different diameters. Separating the reflections of the two-port unknown from those of the

[1] See Reference 17.
[2] See Reference 18.

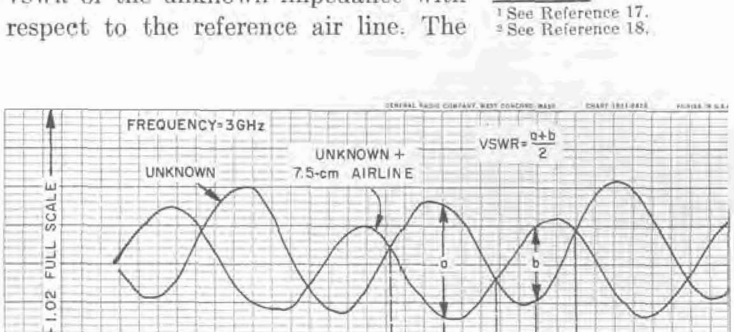


Figure 6. Multiple recording used in substitution-method VSWR measurement.

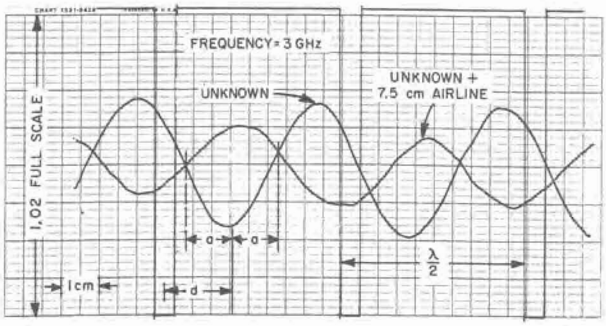


Figure 7. Multiple recording used in substitution-method VSWR and phase measurement.

slotted line and termination has always been difficult in such design problems. In the substitution method with the recorder system, separation is easily achieved, since the undesired reflections cancel out, while the desired reflections do not. The insertion VSWR of the two-port is the difference between two curves recorded on the same section of chart paper, just as in the one-port substitution method described above. The short-circuit reference plane marks can also be recorded on the chart paper

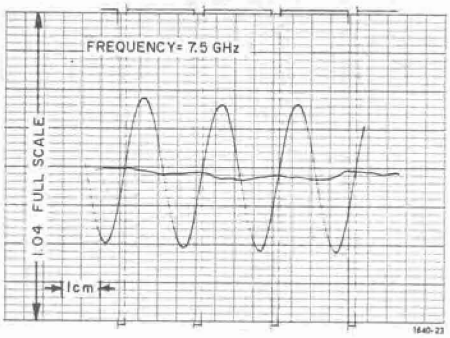


Figure 8. Recording showing insertion VSWR of a mated pair of GR900 adaptors (Types 900-QNJ and -QNP) at 7.5 GHz.

for Smith-chart plots of the measurement (see Figure 8).

Repeatability

In the process of any VSWR measurement it is important to check periodically that the measurement is repeatable, that is, that it can be duplicated several times in succession with a variation no greater than the rated repeatability of the connector (for the GR900, 0.05%). The TYPE 1640-A system is well suited for such checks, because several successive curves can be plotted on the chart for direct intercomparison, as shown in Figure 9. For this check, it is desirable to match the slotted line to its load by means of the TYPE 900-TUA Tuner (see page 22) for maximum recorder scale expansion (1.008 full-scale). The successive curves are spaced with the recorder CENTERING control and should agree within 0.05%, or 1.0005.

System Noise Check

The equivalent noise level of the system, all-important in precision VSWR measurements, can be checked easily with the TYPE 1640-A Slotted Line Recorder System. Contributing about equally to the system noise are three sources: the signal sources, the crystal detector, and the recorder itself. To measure the VSWR equivalent of system noise, the probe carriage drive is declutched, the recorder set for maximum resolution, and the chart drive activated. Since the probe is not moving, the sole cause of any wiggles on the chart is system noise. The peak-to-valley noise excursions can then be translated into an approximately equivalent VSWR. In the example of Figure 10, the peak-to-valley ratio is 0.02%, for a VSWR equivalent of 1.0002. This amounts to a basic figure of merit for the system, since the VSWR of the unknown must be comfortably above that of the noise level in order to give accurate results.

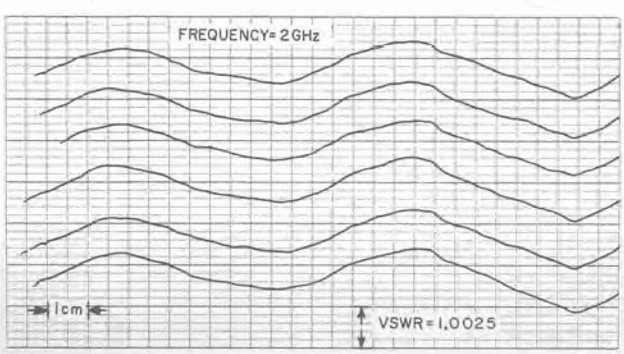


Figure 9. Multiple recording showing excellent repeatability of GR900 connection at six different orientations, in a very low VSWR measurement.

SUMMARY

The use of a graphic level recorder greatly enhances the usefulness of the precision slotted line. Among the benefits derived from this synergistic alliance are:

— a scale expansion that makes the recorder the equivalent of a VSWR meter with a 10-foot-long scale,

— a signal-to-noise ratio of over 80 dB,

— the pinpoint location of positions of minima,

— the many advantages of multiple recording (in substitution measurements, for example),

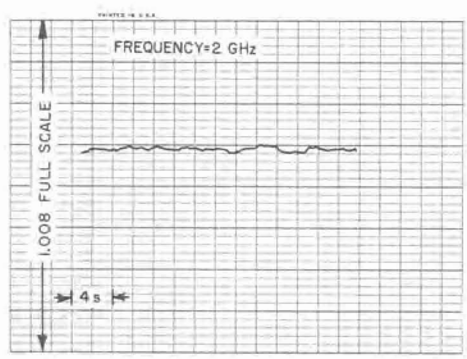


Figure 10. Typical recording of system noise at 2 GHz, with Type 1360-B Microwave Oscillator used as signal source. Chart speed was 30 div/min. Note that total excursion over entire 25-second recording is equivalent to VSWR of only 1.0002.

— the possibilities of graphical analysis of recordings,

— the availability of permanent recording for reference and later study.

For engineers working on coaxial design problems, for instructors wishing to demonstrate standing-wave phenomena most effectively, for anyone concerned with slotted-line measurements, the TYPE 1640-A Slotted Line Recorder System merits very serious appraisal.

SPECIFICATIONS

SLOTTED LINE (TYPE 900-LB)

Characteristic Impedance: 50.0 ohms ±0.1%.

Probe Travel: 50 cm. Scale calibrated in centimeters from reference plane. Attached vernier can be read to 0.1 mm.

Scale Accuracy: ±(0.1 mm + 0.05%).

Frequency Range: 0.3 to 8.5 GHz. At 300 MHz, covers a half wavelength. Operates below 300 MHz with TYPE 900 Precision Air Line.

Constancy of Probe Pickup: ±0.5%.

Residual VSWR: Less than $1.001 + 0.001\, f_{GHz}$ (e.g., 1.002 at 1 GHz).

Accessories Required: Generator and detector.

Dimensions: Width 27½, height 10, depth 4¾ inches (700, 255, 125 mm).

RECORDER (TYPE 1521-SL)

Sensitivity: Continuously adjustable from 0.05 to 2.0 mV (on-scale).

Frequency: 990 Hz ±2%.

Bandwidth: 35 Hz ± 7 Hz (at 3 dB).

VSWR Range: Continuously adjustable from 1.008 (0.8%) to 1.20 (20%) full-scale; accurate to within one minor division.

Noise Level (referred to input): Short-circuit, less than 0.1 µV; open-circuit, less than 3.0 pA. Noise figure less than 5 dB at the optimum source resistance (about 30 kilohms).

Power Required: 105 to 125 or 210 to 250 V, 60 Hz, 35 W. TYPE 1521-SLQ1 Recorder, used with TYPE 1640-AQ1 System, 50 Hz.

Chart Paper: 4-inch recording on 5-inch paper; 40 minor and 8 major divisions vertically. Horizontal scale ruling, ¼ inch.

Paper Speeds: Adjustable, 2.5 to 75 inches per minute; plots correspond to 5- to 300-cm/min carriage travel on slotted line. Two interchangeable sprockets advance paper 1 or 2 horizontal divisions per cm probe travel.

Servo Bandwidth of Pen Drive: More than 4 Hz.

Input Connector: GR874 Coaxial Connector, locking, recessed.

SYSTEM

Accessories Supplied: TYPE 874-R22A Patch Cord; TYPE 900-WN Precision Short Circuit; TYPE 900-WO Precision Open Circuit; tuning stub — probe assembly (including 1N21C and 1N23C crystals); rf-probe assembly (with TYPE 874-BBL Connector); micrometer carriage drive (accurate to 0.01 mm); spare drive cable; storage box; Smith charts; 1 set of *fastrak* recorder markers of assorted colors; ten 100-foot rolls of chart paper; power cord; spare fuses.

Bench Space Required: Width 48, depth 14 in (1220 by 355 mm); height above bench, 12 in, depth below bench, 9 in (315 and 230 mm).

Net Weight: 67 lb (37 kg).

Shipping Weight: 120 lb (55 kg).

Measurements of Dielectric Materials with the Precision Slotted Line

The slotted line has long been recognized as a fundamental tool for measuring the dielectric properties of materials at high frequencies. In principle, the measuring technique is simple: fill a section of coaxial line with dielectric material, determine the propagation constant of the filled section of line from the phase and magnitude of the reflection introduced, as determined by measurement of standing-wave ratio on the slotted line, and calculate the dielectric constant and loss tangent from the propagation constant.

For valid measurements, there are needed (1) an accurate slotted line, (2) sections of air line usable as sample holders, and (3) low-reflection, low-loss, coaxial connectors. These are all now available in the GR900 series, and the accompanying article tells how to use them.

The low and repeatable VSWR and the low loss of the GR900 Precision Coaxial Connector make possible the use of GR900 equipment for the accurate determination of dielectric constant and loss tangent. No specialized dielectric measuring apparatus is necessary.

The measuring device is the TYPE 900-LB Precision Slotted Line. The combination of a TYPE 900-LZ Reference Air Line and a TYPE 900-WNC Short Circuit makes a convenient sample holder for solid dielectrics. The error introduced by the inclusion of the GR900 Connector between the sample and the point of measurement is negligible for most purposes.

The dimensions for a cylindrical sample of solid dielectric are shown in Figure 1. The total length of the sample may be made up of a number of pieces and may be equal to or less than the length of the sample holder. There should be no gaps between the individual pieces. The accuracy of the measurements will depend upon the precision with which the diameters are machined. A light press fit of the sample against the inner and outer conductors is desirable, but too tight a fit may damage the TYPE 900-LZ Reference Air Line. For accurate loss-tangent measurements of a very low-loss material, the length of the sample should be selected by the procedure described below under *Effect of Contact Resistance.*

Standard lengths of TYPE 900-LZ Reference Air Lines (5 cm, 6 cm, 7.5 cm, 10 cm, 15 cm, 30 cm) will meet most needs. If other lengths are needed, they can be constructed from TYPE 0900-9507 rod, TYPE 0900-9509 tube, and TYPE 900-AP Connector Kits.

THEORY

The measurements that will be considered here are those of nonmagnetic materials in a short-circuited sample holder. Other types of measurements are described in various references.[1]

If a coaxial line containing a dielectric sample is short-circuited at its far end, the relationship between the propagation constant, γ, of the dielectric-filled line and the standing-wave ratio, S, and wavelength, λ_o, in an attached air-filled section of the line is:

$$\frac{\tanh \gamma d}{\gamma d} = \frac{\dfrac{1}{S} - j \tan \dfrac{2\pi X_o}{\lambda_o}}{1 - j\dfrac{1}{S}\tan\dfrac{2\pi X_o}{\lambda_o}} \; \frac{(-j)\,\lambda_o}{2\pi d} \qquad (1)^2$$

where X_o = the distance from the face of the dielectric sample to the first voltage minimum in the air-filled line,

d = the length of the sample,

λ_o = the wavelength in the air-filled line,

S = the standing-wave ratio in the air-filled line.

This equation can be separated into its real and imaginary parts and, if $\tan \delta$ (the loss tangent) is less than 0.1, simplified with results accurate within ±1%. The simplified equations are:

$$\frac{\tan \beta d}{\beta d} = \frac{-\lambda_o \tan \dfrac{2\pi X_o}{\lambda_o}}{2\pi d} \qquad (2)^2$$

[1] See References 26 and 28.
[2] See Reference 1.

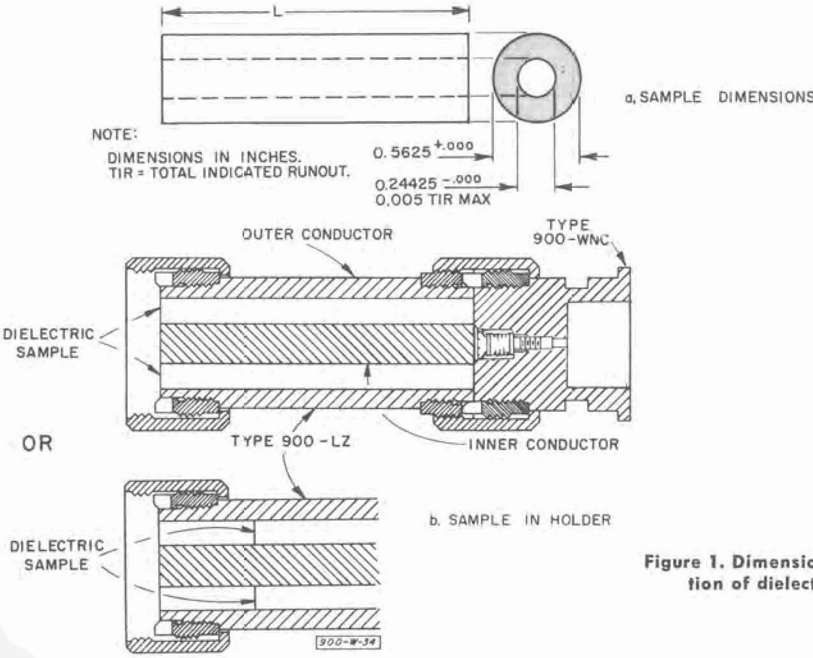


Figure 1. Dimensions and installation of dielectric sample.

where β = phase constant, and

$$\alpha d = \frac{\beta^2 d^2 \lambda_o}{2\pi d}\,\frac{1}{S}\,\frac{1+\tan^2 \dfrac{2\pi X_o}{\lambda_o}}{\beta d\,(1+\tan^2 \beta d) - \tan \beta d} \qquad (3)^2$$

where α = attenuation constant.

If the frequency and sample length are chosen so that $X_o = 0$, then $\tan \beta d = 0$ and $\beta d = N_s \pi$, where N_s is the number of half wavelengths in the sample. The equation for αd then becomes:

$$\alpha d = \frac{N_s \lambda_o}{2d}\,\frac{1}{S}. \qquad (4)$$

From a knowledge of α and β in the dielectric-filled line, the relative dielectric constant, ϵ_r, and the loss tangent, $\tan \delta$, can be calculated. For the TEM mode in a coaxial line:

$$\epsilon_r = \frac{\lambda_o^2}{4\pi^2}\,(\beta^2 - \alpha^2), \qquad (5)$$

$$\text{and} \quad \tan \delta = \frac{2\alpha\beta}{\beta^2 - \alpha^2}. \qquad (6)$$

If α^2 is small compared with β^2, as is the case when $\tan \delta$ is less than 0.1, equations (5) and (6) simplify, for samples that are an integral number of half-wavelengths long, to

$$\epsilon_r = \frac{\lambda_o^2 \beta^2}{4\pi^2} = \left(\frac{N_s\,\lambda_o}{2d}\right)^2, \qquad (7)$$

$$\text{and} \quad \tan \delta = \frac{2\alpha}{\beta} = \frac{\lambda_o}{\pi d}\,\frac{1}{S}. \qquad (8)$$

For small values of $\frac{1}{S}$ (high standing-wave ratio) it is more accurate to determine $\frac{1}{S}$ by a width-of-minimum method rather than by direct measurement. $\frac{1}{S}$ is related to the voltage at point X, a distance $\frac{\Delta X}{2}$ from the minimum by:

$$\frac{1}{S} = \frac{\sin \theta}{\left[\left(\dfrac{E_x}{E_{min}}\right)^2 - \cos^2\theta\right]^{1/2}} \qquad (9)$$

where $\theta = \frac{\pi \Delta X}{\lambda_o}$.

If ΔX is the distance between points where the power is twice that at the minimum (3.01-dB points), then:

$$\frac{1}{S} = \frac{\sin \theta}{(2 - \cos^2\theta)^{1/2}} \qquad (10)$$

For small values of θ, (<0.075 radian), $\sin \theta = \theta$ and $\cos \theta = 1$ are close approximations. Then:

$$\frac{1}{S} = \theta = \frac{\pi \Delta X}{\lambda_o}, \qquad (11)$$

$$\text{and} \quad \tan \delta = \frac{\Delta X}{d}. \qquad (12)$$

If the minimum is very narrow it may be desirable to use points more widely separated, such as the 10-dB points. In that case, for small θ

$$\frac{1}{S} = \frac{\pi \Delta X}{3\lambda_o}, \qquad (13)$$

$$\text{and} \quad \tan \delta = \frac{\Delta X}{3d} \qquad (14)$$

MEASURING PROCEDURE

(1) Insert the sample into the reference air line flush with one end and with no spaces between the pieces in the sample.

(2) Attach the Type 900-WNC Short Circuit so that it is in contact with the sample, as shown in Figure 1b.

(3) Connect the sample holder to the measuring setup (Figure 2), consisting of the Type 900-LB Slotted Line, a Type DNT-3 or DNT-4 Heterodyne Detector, and an appropriate generator, such as a GR Unit oscillator. A Type 874-G Fixed Attenuator or an isolator should be used between the generator and the slotted line. An amplitude-modulated source and a standing-wave indicator can be used if the frequency modulation of the source is kept very small.

(4) Adjust the frequency so that a voltage minimum occurs at the face of the dielectric sample, whether or not the sample completely fills the length of the holder. To do this, compare the positions of the minima first with the sample holder (containing the sample) on the Type 900-LB Slotted Line and then with a Type 900-WN Short

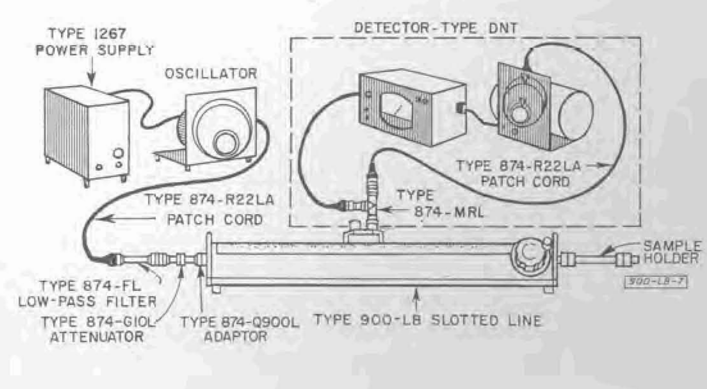


Figure 2. Setup for dielectric measurements.

Circuit on the slotted line. Then adjust the frequency until the proper relation exists between the minima. For example, if the sample completely fills the TYPE 900-LZ Reference Air Line, the minimum position with a TYPE 900-WN or -WNC Short Circuit connected to the slotted line should be the same as when the sample is connected to the slotted line. If measurements must be made at a certain frequency, then it is necessary either to adjust the length of the sample or to use equations (2) and (3) with X_o not equal to zero.[3]

(5) Once the frequency is properly adjusted, proceed as follows: Record the position and width of the minimum at two places along the slotted line (one of them near the load end), preferably separated by 20 centimeters or more. Measure the width of minimum with the micrometer carriage drive. Count the number of half wavelengths between the two minima (distance between adjacent minima is $\lambda_o/2$). Then remove the sample from the holder, attach the empty sample holder to the line, and record the position and width of a minimum near the load end of the slotted line.

INTERPRETATION OF DATA

With the sample in place, the resulting width of minimum is determined by loss in the dielectric, loss in the sample holder, and loss in the slotted line up to the point of measurement. The width of minimum at a second point along the slotted line is increased by the loss in the slotted line between the two points. The width of minimum, with the sample holder empty, is determined by the losses in the sample holder and in the slotted line to the point of measurement. In order to determine the loss tangent of the dielectric, it is necessary to separate the dielectric loss from the other losses. Call ΔX_{1s} the width of minimum at position l_{1s} with the sample in place, ΔX_{2s} the width of minimum at position l_{2s}, and ΔX_{1e} the width of minimum at position l_{1e}, with the sample holder empty. Then the width of minimum due to loss in the dielectric is given by:

$$\Delta X_d = \Delta X_{1s} - \Delta X_{1e} - \frac{l_{1s} - l_{1e}}{l_{2s} - l_{1s}} \times (\Delta X_{2s} - \Delta X_{1s}). \qquad (15)$$

This width of minimum can be used in equation (12) or (14) to determine the loss tangent. The dielectric constant can be found from equation (7). If the approximate dielectric constant is unknown, then measurement at two frequencies will be necessary since N_s will not be known.

Example: A Teflon sample 15.00 centimeters long is measured. It is found that a voltage minimum occurs at the sample face when the frequency is adjusted so that $\lambda_o = 21.34$. Then from equation (7) $\epsilon_r = \left(\frac{N_s\lambda_o}{2d}\right)^2 = \left(\frac{N_s\, 21.34}{2(15.00)}\right)^2$. The dielectric constant is known to be approximately 2. Therefore, $N_s = 2$ and $\epsilon_r = \left(\frac{2(21.34)}{2(15.00)}\right)^2 = 2.024$. Since the minimum is very narrow, the 10-dB width-of-minimum points are used. The width of minimum at $l_{1s} = 21.34$ is 0.1004 cm. The width of minimum at $l_{2s} = 42.68$ is 0.1518 cm. With the sample holder empty, the width of minimum at $l_{1e} = 17.01$ is 0.0788 cm. Then the width due to losses in the sample is found from equation (15) as

$$\Delta X_d = 0.1004 - 0.0788 - \frac{(21.34 - 17.01)}{(42.68 - 21.34)} \times (0.1518 - 0.1004) = 0.0110.$$

From equation (14), $\tan\delta = \frac{0.0110}{3(15.00)} = 0.00024.$

Note that if a lossy material is measured ($\tan\delta > 0.1$), equations (2) and (3) are no longer valid and equation (1) must be solved.[2]

FREQUENCY RANGE OF MEASUREMENT

The lowest frequency at which measurements can be made is determined by the dielectric constant of the material being measured and by the necessity that at least one minimum occur along the slotted line so that its position and width can be measured. TYPE 900-L10, -L15, and -L30 Precision Air Lines can be used between the sample holder and the slotted line to position a minimum on the slotted line at low frequencies. If these additional air lines are used they should be externally supported. Sample holders up to 66 centimeters long can be constructed for low-frequency use. The sample can be made shorter than a half-wavelength and equations (2), (3), (5), and (6) used to determine the dielectric constant and loss tangent. With these methods, measurements can be made down to 50 MHz or even lower.

The upper frequency limit for the TYPE 900-LB Slotted Line is 8.5 GHz, but special precautions should be taken at frequencies higher than $\frac{9.5\text{ GHz}}{\sqrt{\epsilon_r}}$ as noted in the paragraph *Existence of Higher-Order Modes*.

ERRORS

Sample Fit

One of the most common sources of error in dielectric measurements by the coaxial method is the presence of air gaps between the sample and the inner and outer conductors. Correction formulas based upon a uniform distribution of the air gap can be used, but, since the actual air gap will usually not be uniformly distributed, the gaps should be avoided for maximum accuracy. The corrections for uniform air gaps for $\tan\delta < 0.1$ are

$$\epsilon_{r\,(correct)} = \epsilon_{r\,(measured)} \frac{L_2}{L_3 - \epsilon_{r\,(measured)}\, L_1} \qquad (16)^4$$

$$\tan\delta_{(correct)} = \tan\delta_{(measured)}\left(1 + \epsilon_{r\,(correct)}\frac{L_1}{L_2}\right) \qquad (17)^4$$

where $L_1 = \text{Log}\frac{D_2}{D_1} + \text{Log}\frac{D_4}{D_3}$,

$L_2 = \text{Log}\frac{D_3}{D_2}$,

$L_3 = \text{Log}\frac{D_4}{D_1}$,

$D_1 = 0.24425$,

D_2 = inside diameter of sample,

D_3 = outside diameter of sample, and

$D_4 = 0.5625$.

[3] A. von Hippel gives charts of $\frac{\tanh X}{X}$ and tables of $\frac{\tan X}{X}$ and suggests further references.

[2] *Ibid.*

[4] See Reference 28.

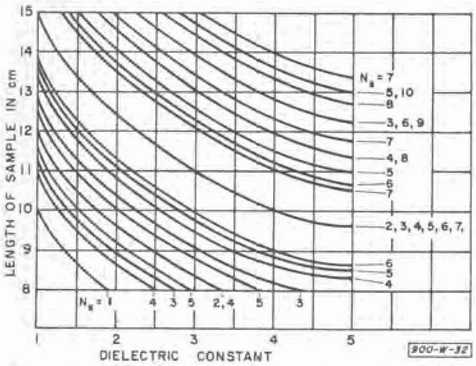


Figure 3. Lengths of samples for a Type 900-LZ15 Reference Air Line for minimum tan δ error in low-loss dielectric measurements. (See equations 18 and 19.)

Meter Errors

If a 3-dB width of minimum is used, meter indications on the GR TYPE 1216-A Unit I-F Amplifier will, in general, cause negligible error when the upper part of the scale is used and when care is taken to tune the local-oscillator frequency exactly for maximum output. A 10-dB width-of-minimum measurement may require that the i-f amplifier calibration be checked with a precision attenuator for greatest accuracy. As an example of the errors in loss-tangent measurements caused by poor i-f amplifier calibration, an error of 0.1 dB in a typical 3-dB width-of-minimum measurement will cause an error of 1.9% in tan δ. An error of 0.3 dB in a typical 10-dB width-of-minimum measurement will result in a 3.9% error in tan δ.

Effect of Contact Resistance

Although the connector contact resistance is typically less than half a milliohm, a small part of the measured loss is due to this resistance. The magnitude of the error caused by this loss depends upon the relative current through the contact for each measurement and is significant only when very low-loss dielectrics are measured. If the current is the same when the sample is measured as when the empty sample holder is measured, the contact loss will have no effect on the accuracy of the tan δ measurement. If the currents differ, there may be an error in tan δ as large as 0.0001. The amount of loss due to the finite contact resistance in a given measurement is

$$\text{Loss} \approx \frac{\cos 2\phi + 1}{2} \times \text{maximum loss}, \tag{18}$$

where $\phi = \frac{l}{\lambda} 360°$ and l is the distance from a voltage minimum to the contact. Maximum loss occurs when a voltage minimum occurs at the contact. It is difficult to evaluate the maximum loss exactly because of its small value. The condition that the current be the same for both measurements (with and without sample) may be met by appropriate choice of length and frequency for a sample with a given dielectric constant. If the dielectric constant is unknown, it may be necessary first to measure dielectric constant and then to trim the sample to the proper length for accurate determination of loss. This is necessary only for very accurate measurements of the loss tangent of low-loss dielectrics. For low-loss materials, the current through the contacts will be of approximately the same magnitude with and without the sample in the holder when the frequency and length are so chosen that sample

$$\text{length } d = \frac{2 N_s b}{(N+1)\sqrt{\epsilon} + N_s}, \tag{19}$$

$$\text{and } \lambda_o = \frac{2\sqrt{\epsilon}}{N_s} d, \tag{20}$$

where N_s and N are integers and b is the length of the sample holder. Lengths that satisfy the relationship and the corresponding values of N_s can be determined from Figure 3 for a 15-cm sample holder and from Figure 4 for a 30-cm sample holder. Figure 4 shows only the most useful curve of a very large family of curves. As an example of the use of these curves, suppose that the loss tangent of a low-loss material with a dielectric constant of 2 is to be measured. If a sample 12.43 cm long is used in a 15-cm sample holder, tan δ can be measured with maximum accuracy at λ_o = 17.60 cm, 11.73 cm, 8.80 cm, 7.05 cm, 5.87 cm, and 5.03 cm, corresponding to N_s = 2, 3, 4, 5, 6, 7. If, instead, a sample 13.54 cm long were chosen, tan δ could be measured with maximum accuracy only at λ_o = 5.48 cm, N_s = 7.

Existence of Higher-Order Modes

At frequencies higher than $\frac{9.5}{\sqrt{\epsilon}}$ GHz, higher-order modes, particularly the TE_{11} mode, can be excited by axial dis-

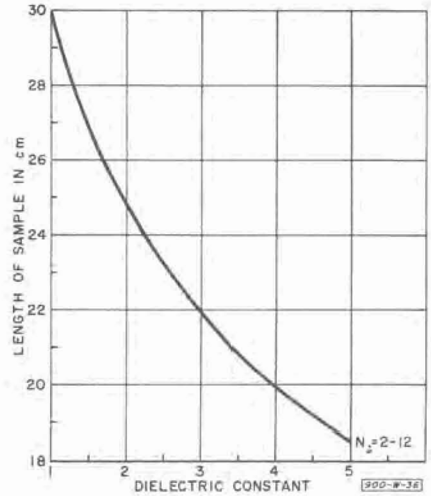


Figure 4. Lengths of samples for a Type 900-LZ30 Reference Air Line for minimum tan δ error in low-loss dielectric measurements.

symmetries in the dielectric material. While the air-filled section of line between the sample and the point of measurement acts as a filter for these higher-order modes, in some instances coupling between the TEM and TE modes may be great enough to produce an error in measurement. Measurements above this frequency, therefore, should be made at small (say 10%) frequency increments and compared with measurements below $\frac{9.5}{\sqrt{\epsilon}}$ GHz, in order that anomalous results can be detected.

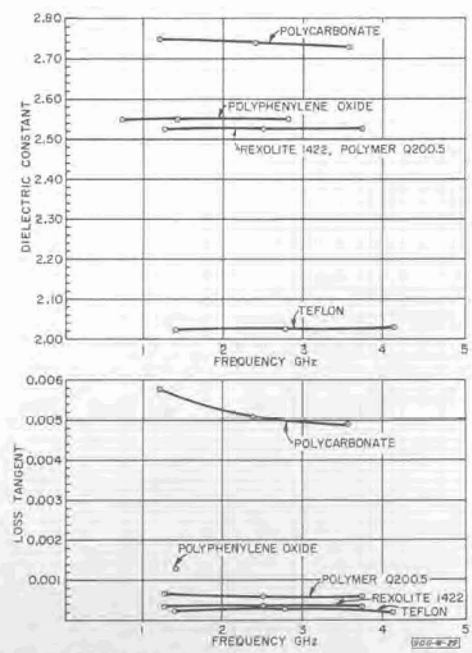


Figure 5. Dielectric constant and loss tangent of typical materials as measured on the Type 900-LB Precision Slotted Line.

REFERENCES

1. T. W. Dakin and C. N. Works, "Microwave Dielectric Measurements," *Journal of Applied Physics*, September 1947.
2. G. A. Deschamps, "A Simple Graphical Analysis of a Two-Port Waveguide Junction," *Proceedings of the IRE*, 42, May 1954.
3. M. Ebisch, "Coaxial Measurement-Line Inserts of High Precision For the Frequency Range 1–13 Gc," *Frequenz*, Vol 13, No. 2, February 1959.
4. D. E. Fossum, "Progress Report of the IEEE I-M Group Technical Subcommittee on Precision Coaxial Connectors," *IEEE Transactions on Instrumentation and Measurement*, Vol IM-13, December 1964.
5. J. W. E. Griemsmann, "Handbook of Design Data on Cable Connectors for Microwave Use," Polytechnic Institute of Brooklyn, Microwave Research Institute, *Report No. S-158-47, PIB 107*.
6. I. A. Harris, "The Theory and Design of Coaxial Resistor Mounts for the Frequency Band 0-4000 Mc/s," *Proceedings of the IEE (London)*, Vol 103, Part C, No. 3, March 1956.
7. I. A. Harris, and R. E. Spinney, "The Realization of High-Frequency Impedance Standards Using Air-Spaced Coaxial Lines," *IEEE Transactions on Instrumentation and Measurement*, Vol IM-13, December 1964.
8. C. W. Kennedy, *Inspection and Gaging*, 3rd ed. New York: Industrial Press, 1962.
9. A. P. Lagon and A. E. Sanderson, "Report on Early Development Work at General Radio on Precision Coaxial Connectors." Papers presented at the Meeting on Precision Coaxial Connectors at NBS Boulder Laboratories on June 29, 1961. (Available from General Radio as Reprint A127.)
10. F. A. Lowenheim, *Modern Electroplating*, 2nd ed. New York: Wiley, 1963.
11. T. E. MacKenzie, "Improve Convenience, Repeatability of Precision Coaxial-Line Impedance Measurements with Precision Impedance-Matching Tuners," *Electronic Instrument Digest*, March–April 1966.
12. T. E. MacKenzie, "Recent Advances in the Design of Precision Coaxial Standards and Components," *1965 IEEE International Convention Record*, Part 5, Session 67. (Available from General Radio as Reprint A115.)
13. T. E. MacKenzie, "Some Techniques and Their Limitations as Related to the Measurements of Small Reflections in Precision Coaxial Transmission Lines," *IEEE Transactions on Instrumentation and Measurement*, December 1966. (Available from General Radio as Reprint A133.)
14. T. E. MacKenzie and A. E. Sanderson, "Some Fundamental Design Principles for the Development of Precision Coaxial Standards and Components," *IEEE Transactions on Microwave Theory and Technique*, January 1966. (Available from General Radio as Reprint A121.)
15. C. G. Montgomery, *Technique of Microwave Measurements*, Vol 11, New York: McGraw-Hill, 1947.
16. "Recommended Practices for Precision Coaxial Connectors," *IEEE Precision Connector Subcommittee, Electronic and High Frequency Instruments Committee*, pts I and II, 1963.
17. A. E. Sanderson, "An Accurate Substitution Method of Measuring the VSWR of Coaxial Connectors," *The Microwave Journal*, Vol 5, No. 1, January 1962. (Available from General Radio as Reprint A95.)
18. A. E. Sanderson, "Calibration Techniques for One- and Two-Port Devices Using Coaxial Reference Air Lines as Absolute Impedance Standards," *19th Annual ISA Conference and Exhibit*, New York, NY, Preprint No 21.6-3-64, 1964. (Available from General Radio as Reprint B21.)
19. A. E. Sanderson, "A New High-Precision Method for the Measurement of the VSWR of Coaxial Connectors," *IRE Transactions On Microwave Theory and Techniques*, Vol MTT-9, No. 6, November 1961. (Available from General Radio as Reprint A92.)
20. A. E. Sanderson and F. T. Van Veen, "The Precise Measurement of Small Dimensions by a Capacitance Bridge," *General Radio Experimenter*, Vol 38, No. 2, February 1964.
21. R. A. Soderman, "Application of Precision Connectors to High-Frequency Measurements," *IEEE Transactions on Instrumentation and Measurement*, Vol IM-16, No. 1, March 1967. (Available from General Radio as Reprint A136.)
22. J. E. Storer, L. S. Sheingold, and S. Stein, "A Simple Graphical Analysis of a Two-Port Waveguide Junction," *Proceedings of the IRE*, 41, No. 8, August 1953.
23. L. Sweet and R. A. Lebowitz, "Measurement of VSWR in Coaxial Systems," *PRD Reports*, Vol 7, No. 3, July 1961.
24. "Test Report on General Radio Type 900 Precision Coaxial Connectors, Line Size III," General Radio Company, West Concord, Mass., July 30, 1963.
25. H. C. von Baeyer, "The Effect of Silver Plating on Attenuation at Microwave Frequencies," *The Microwave Journal*, Vol 3, No. 4, April 1960.
26. A. von Hippel, *Dielectric Materials and Applications*, Technology Press of MIT, 1954.
27. B. O. Weinschel, "Air-Filled Coaxial Lines as Absolute Impedance Standards," *The Microwave Journal*, Vol 7, No. 4, April 1964.
28. W. B. Westphal, "Techniques at Measuring the Permittivity and Permeability of Liquids and Solids in the Frequency Range 3 c/s to 50 kMc/s," *Technical Report No. 36*, Laboratory for Insulation Research, MIT, July 1950. (Out of Print)
29. J. R. Whinnery, H. W. Jamieson, and T. E. Robbins, "Coaxial-Line Discontinuities," *Proceedings of the IRE*, Vol 32, November 1944.
30. D. Woods, "A Coaxial Connector System for Precision R. F. Measuring Instruments and Standards," *Proceedings of the IEE (London)*, Vol 108, Part B, No. 38, March 1961.
31. J. Zorzy, "The Application of Precision Transmission Lines and Precision Connectors as Accurate Immittance Standards." This paper was presented at the 1967 Conference of EEMTIC, Ottawa, Canada. (Available from General Radio as Reprint IN-116.)
32. J. Zorzy, "Precise Impedance Measurements with Emphasis on Connector VSWR Measurements," *18th Annual ISA Conference and Exhibit*, Chicago, Ill., Preprint No. 47.4.63, 1963. (Available from General Radio as Reprint B20.)
33. J. Zorzy, "Skin-Effect Corrections in Immittance and Scattering Coefficient Standards Employing Precision Air-Dielectric Coaxial Lines," *IEEE Transactions on Instrumentation and Measurement*, Vol IM-15, No. 4, December 1966. (Available from General Radio as Reprint A134.)
34. J. Zorzy and R. F. Muehlberger, "RF Leakage Characteristics of Popular Coaxial Cables and Connectors, 500 Mc to 7.5 Gc," *The Microwave Journal*, November 1961. (Available from General Radio as Reprint A93.)

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