# MEASUREMENTS of RF Voltage

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## 1. Introduction

National standard instruments for the direct measurement of rf voltage in coaxial transmission lines have in the past been developed by detecting and measuring the voltage developed across a resistor placed in the transverse plane of the TEM field. An early NBS standard used a thermistor as a resistor in a radial configuration in a coaxial line, but residual reactances and the imperfect equivalence of rf to dc resistance limited its application to below 1GHz. A split film radial resistance instrument, known as the Bolovac, overcame these shortcomings and acted as an NBS standard up to 8GHz and with development had a potential range up to 18GHz and beyond. However the development of these and other proposed instruments for direct voltage measurement has not progressed. One reason is that nowadays the characterisation of rf and microwave systems and associated instruments are usually considered to be more satisfactorily expressed in terms of rf power and rf impedance (or the scalar quantities VSWR or VRC when phase is not a consideration).

Although rf voltage is not as important a quantity as its proponents for its measurement once felt, nevertheless there is still a requirement for the calibration of instruments such as rf millivoltmeters, oscilloscopes and EMC receivers and other instruments in terms of rf voltage, up to a frequency of at least 1GHz.

## 2. RF voltmeters

There are many techniques in use for measuring rf voltage and these may be categorised as:

**a.) Thermal ac/dc transfer standard**: A heater wire mounted in an evacuated glass envelope with thermocouples attached to the centre of the heater. 20Hz to 1MHz, accuracy ±50 to ±100 ppm.

**b.) Micropotentiometer**: A series circuit comprising a coaxial resister, thermocouple heater and shunt resistor. 20Hz to 500MHz, accuracy ±1% to 100MHz, ±5% at 500MHz.

**c.) Wideband rf comparator bridge**: Uses matched diode detectors in a bridge circuit. A dc null detector at the summing point of the bridge will read zero if the peak amplitude of a standard low frequency or dc reference applied to one input port has the same peak value as an rf signal applied to the other. 20Hz to 1.5GHz, ±2% at 1GHz.

**d.) Sampling voltmeter**: Uses a switched diode bridge to sample input signals. Frequencies up to 100MHz, ±2%, ±1.5 degrees.

**e.) Solid state diode sensor**: This is the most common type of rf voltmeter, using a diode detector or bridge to convert the applied ac voltage to dc. It has a logarithmic response approximating a square law at voltages up to about 30mV but this gradually changes to a peak response at higher voltage inputs. Due to the diode capacitance, the impedance of the diode changes with input voltage level and hence the diode frequency response will also change. The minimum detectable level is a function of temperature. ±1.5% to 500MHz, ±5% to 3 GHz.

**f.)** **Solid state thermal sensor**: A small film resistor is fabricated on a substrate in close proximity to an open base transistor which is used as a temperature sensor. The ac/dc transfer approaches that of the best vacuum thermocouples but this device is small, giving a fast response, is less likely to burn out and has negligible reversal error. These devices are suitable as rms converters in digital multimeters.

## 3. Techniques for calibrating an rf voltmeter

In the absence of a standard rf voltage measuring instrument for a sine wave signal, the voltage at a reference place in a coaxial transmission line may be calculated from a knowledge of the incident rf power, that is the power which would be absorbed in a perfectly terminated line, and the rf impedance at the reference plane in accordance with the expression

$$V = (P \times Z)^{1/2}$$

The measurement of the power is straightforward and in the DMC laboratory a calibrated Rohde and Schwarz NRS power sensor, (dry calorimeter) or Hewlett Packard 8478B thermistor power sensor are used, due to their excellent match and low measurement uncertainty

The measurement of rf impedance is less easily realised. Where they are available, automatic network analysers (ANA) or vector voltmeters are ideally suited for the task and traceability of measurement is achievable. Instruments of an earlier generation, such as the General Radio 1602B Admittance Bridge, however, still have a role and are relatively simple and flexible instruments with a frequency range from 10MHz to 1.5GHz. Although the accuracy of the GR1602B is modest compared with present day standards it can be quite suitable as an adjunct to rf voltage measurements.

The usual method of calibrating a voltmeter against a standard power sensor is to connect the instruments to two arms of a coaxial line T-junction. Normally the T-junction is selected to have connectors appropriate for the unknown voltmeter and is either supplied by the customer with the voltmeter to be calibrated or a suitable T-junction is specified by the calibration laboratory. If necessary an adaptor is used to connect the standard power sensor. The rf signal is fed into the third arm of the T-junction and the unknown voltmeter is calibrated in terms of the voltage established at the reference plane of the T-junction by the standard power sensor (Figure 1).

At low frequencies, the unknown voltmeter and standard power sensor can be considered as electrically connected in parallel at the reference plane of the T-junction. However, although T-junctions are chosen to be as compact as possible, the electrical path lengths between the ports to which the instruments are connected and the reference plane become increasingly important above 10MHz, particularly when the unknown voltmeter presents a high input impedance. The device to be calibrated may not be an actual indicating rf voltmeter but, for example, an oscilloscope with a high input impedance of 1 megohm in parallel with 15 picofarad, whose frequency response is to be determined, or a thermal transfer standard having an impedance of 200 ohm/volt.

In these circumstances of higher frequencies and instruments that are not matched to the coaxial transmission line system, impedance transformations are necessary if it is required to relate the rf voltage at the reference plane of the T-junction to that at the point to which the instrument is connected. Although transmission line impedance transformations can be readily made using a Smith chart, or more accurately and quickly with a computer program, a difficulty is an imperfect knowledge of the equivalent circuits of commercially available T-junctions. The availability of specially designed compact T-junctions for such measurements can be very desirable. Failing this, one approach is to assume that the T-junction is completely filled with dielectric and allow for the deviation from the true equivalent circuit as an uncorrected error treated as an uncertainty contribution.

Another approximation is that a measurement of the modulus of the voltage reflection coefficient, rather than the actual complex impedance may be acceptable when electrical path lengths, although not negligible, are a lot less than a quarter of a wavelength.

However, because of these difficulties in calibrating an instrument in terms of the voltage developed at the plane of the input connector of the instrument, two simpler calibration methods have been devised and are the subject of this paper.

The two calibration methods which are widely used to meet present rf voltage calibration requirements are:

### a.) A comparator reference plane voltage calibration

By referring all rf voltage measurements to the central reference plane of a T-junction (Figure 1), there is no longer a need to measure the impedance of the unknown voltmeter. As far as the standard instrument is concerned, provided it presents a good match to the transmission line system it can be considered that the modulus of the voltage reflection coefficient may be of any phase at frequencies where electrical path lengths are possibly significant. The upper frequency for insignificance in path length depends on VRC magnitude. For the Rohde and Schwarz NRS power sensor used in the laboratory, the frequency will be taken as 10MHz.

### b.) An incident voltage calibration

A calibration in terms of the rf voltage which would be developed in a perfectly matched 50 ohm coaxial transmission line system is referred to as an incident voltage calibration. It is required for the calibration of the output of signal generators or for the calibration of voltmeters in terms of incident voltage. Although the impedance Z in the expression for voltage may be taken as 50 Ohms, deviations of source impedance or voltmeter impedance from 50 Ohms may contribute to uncertainty due to voltage wave reflections.

## 4. Contributions to voltmeter calibration measurement uncertainty

### General

In the Dowding & Mills Laboratory the instrument used for rf voltage measurement for comparator reference plane and incident voltage calibrations is a Rohde & Schwarz URV5 millivoltmeter and 10V insertion unit. The 10V insertion unit is a short length of coaxial transmission line with 2 full wave diode rectifiers capacitively coupled to the inner conductor centre. The rectified output voltage is processed to correct for frequency response, dynamic linearity and temperature effects.

In addition to providing a much larger dynamic range of voltage measurements, it is more convenient to use as a standard voltmeter than the NRS power meter and probe. Figures 1 and 2 show the equipment configurations for the two kinds of voltage calibrations. The URV5 millivoltmeter and 10V insertion unit is calibrated against the traceable NRS power meter.

### a) Rohde & Schwarz NRS Power Meter and Probe

The laboratory reference instrument for the measurement of rf power is a Rohde & schwarz NRS power meter and probe fitted with a type N connector. This instrument is a dry calorimeter, where the input signal is absorbed by a 50 ohm resistor attached to a thermopile. A second identical 50 ohm resistor and thermopile are energised using dc. The output of the thermopiles is connected to a bridge and servo feed back circuit and the bridge is driven to equalise the thermopile outputs. The energising dc voltage is then proportional to the applied rf voltage. The instrument measures true rms and measures power from 0.1mW to 300mW, dc to 18GHz.

The NRS probe is calibrated for calibration factor and VRC at SESC Aquila, Bromley. As it will be considered that the NRS probe VRC can have any phase at the comparator reference plane above 10MHz, it is important that the modulus of the VRC be as small as possible. In undertaking the calibration, SESC was therefore asked to minimise the measurement uncertainties by using a dual admittance bridge for measurements up to 300MHz. The results of an SESC calibration Table 1. illustrates the variation of VSWR with frequency up to 1GHz.

Up to 10MHz, the NRS probe can be considered as effectively directly connected to the reference plane of the T-junction comparator (Figure 1). Knowledge of the impedance of the probe would then allow a correction to be applied for any deviation from 50 Ohms

The NRS power meter and probe is restricted in its use as a standard voltmeter to the range 0.5V (5mW) to 1V (20mW). Measurements below 0.5V result in increased random uncertainty and the upper limit of 1V is to ensure that any additional heating effect does not result in a change in the VRC of the probe that may be significant in voltage measurement

At the connector plane of the NRS probe, the uncertainty in rf voltage is derived from the differentiation of the expression :

$$V = (P \times Z)^{1/2}$$

or $$\frac{dV}{V} = \frac{1}{2} \times \frac{dP}{P} + \frac{1}{2} \times \frac{dZ}{Z}$$

**b.) Rohde & Schwarz URV5 Millivoltmeter and 10V Insertion Unit**

For comparator reference plane voltage calibrations, the URV5 millivoltmeter and terminated 10V insertion unit are calibrated against the NRS power meter and probe as the UUT in Figure 1. The calibration should be undertaken using the T-junction and adaptors appropriate for subsequent customer calibration. Such a calibration of the terminated 10V insertion unit can only be used with a different type T-junction when there is experimental confirmation that, at the highest frequency, the calibration is not affected by the change in the T-junction.

For incident voltage calibration, URV5 millivoltmeter and terminated 10V insertion unit are calibrated as the UUT in the configuration of Figure 2.

Measurements of a number of URV5/Z2 millivoltmeter probes show the overall accuracy of the frequency response to be far better than that claimed by Rohde & Schwarz. Up to 300MHz the response is flat to +/- 0.15% whereas the manufacturer's claim is at least an order greater than this above 30MHz. Although there are marked variations in response above 300MHz, they do not appear to exceed +/- 1%. To provide some safety margin it is considered that the response of the insertion unit is flat within the following limits:

10kHz to 300MHz : +/- 0.3%
300MHz to 1GHz : +/- 2%

The URV5 10V insertion unit is used over the range 1mV to 10V and measurements have been made at both 10kHz and 100kHz on the linearity of the instrument, against an inductive divider and AC calibrator standards. The results show that the insertion unit is linear within the following limits:

1mV to 100mV : +/- 0.1%
100mV to 10V : +/- 0.3%

The Rohde & Schwarz specification indicates some dependence of reading on ambient temperature. This dependence was checked at nominal levels of 1mV, 10mV, 100mV and 1V over a wide range of temperatures. For the laboratory environmental control range of 23 deg C +/-2 deg C, the variation did not exceed +/- 0.3%.

### c.) Signal Generators

The signal generators used in the calibration configuration of Figures 1 and 2 are required to produce signals that are as near sinusoidal in waveform as possible. This is more important in voltage measurements than in power measurements as a harmonic level of -40dBc can change signal level by as much as +/- 1% under in-phase or anti-phase conditions.
To reduce the harmonic and spurious levels to well below -40dBc, a tuner or filter must be used.

### d.) T-Junctions

For voltage calibrations referred to the centre line reference plane of a T-junction (Figure 1), it is preferable for the customer to supply the T-junction used with the voltmeter. Figure 3 shows the outline dimensions of three commonly used coaxial line T-junctions.
The type N and BNC T-junctions shown at A and B of Figure 3 incorporate dielectric support structures for the inner of the coaxial line. An appreciation of the significance of the electrical path lengths can be obtained by assuming that these T-junctions are uniformly filled with dielectric. If the dielectric constant of the material is taken to be 2.2, then the frequencies corresponding to the fractional wavelength separation between the reference plane to which a voltmeter would be attached are shown in Table 2. Also included in this table, as C, is the larger hermaphrodite GR874 T-junction which has a relatively small support structure for the inner of the coaxial line. For this T-junction, air-filled lines are assumed.

From Table 2, it is seen that a frequency of 10MHz corresponds to an electrical path length separation between connector and reference planes for any of the T-junctions, A, B, or C, of less than 1/500 of a wavelength. It is thus considered that, at least for the connection of the standard instruments (the NRS probe and the URV5 terminated 10V insertion unit), and following an acceptable determination of the complex impedances, it should be possible to establish that these instruments are effectively directly connected to the reference planes of the comparators up to a frequency of at least 50MHz although with perhaps some additional uncertainty contributions to cover any uncorrected impedance errors.

### e.) Adaptors

Where coaxial line adaptors have to be used to connect either the NRS probe or the URV5 10V insertion unit in the calibration configurations of Figures 1 and 2, then a correction has to be made to the reading of the

NRS power meter or the URV5 millivoltmeter to allow for the attenuation of the adaptor. In addition any adaptor will modify the VRC of the sensor with which it is used.

### f.) RF Mismatch

In incident voltage calibrations when the voltmeter that is to be calibrated is not a good match to 50 Ohms, the reflected voltage wave may be of sufficient magnitude that when further reflected by the generator, the vector addition of the voltage to the initial incident voltage may contribute a significant error to the magnitude of the incident voltage.

The error in the incident voltage due to multiple reflections can be illustrated by the following example:

Signal generator output return loss = 14dB (0.2 VRC)

Generator return loss as seen through 6dB pad = 26dB (0.05 VRC)

Return loss from 6dB pad = 40dB (0.01 VRC)

Maximum VRC at source pad output = 0.06

VRC for UUT (1.15 VSWR) = 0.07

Maximum error in incident voltage: = 0.06 x 0.07 x 100% = **0.42%**

### g.) Connector Repeatability

The uncertainty in connector loss when making the connection of the NRS probe or the URV5 10V insertion unit in the calibration configurations of Figures 1 and 2 are reflected in the calibration uncertainties for these sensors. Bearing in mind that the upper frequency of interest is 1GHz, these uncertainty contributions are in any case very small. In voltage terms for type N and GR874 connector pairs, the repeatability due to connector loss variation is likely to be better than 0.1%. This will not make a significant contribution to overall uncertainties.

The repeatability of BNC connectors is much poorer than N or GR874 connectors and has to be evaluated for the connector pair in use by repeating measurements at least four times. If the repeatability is poorer than ±1% it may contribute significantly to the total uncertainty.

## 5. Calculating the measurement uncertainty (NRS power meter and probe)

**Considering the above contribution:**

| **Name** | | **Distribution** | **Divisor** |
|---|---|---|---|
| Us | Calibration factor of standard | normal | 2 |
| Ug | Signal generator purity | limit | $(3)^{1/2}$ |
| Ut | T-junction correction | limit | $(3)^{1/2}$ |
| Um | Mismatch | cosine | $(2)^{1/2}$ |
| Ur | Random (type A, UKAS M3003) | standard | 1 |

Combining the uncertainties for an expanded uncertainty *k* = 2 (approximately 95% confidence probability)

$U = 2 \times [ (Us/2)^2 + ((Ug^2+Ut^2)/3) + (Um^2/2) + Ur]^{1/2}$

When using the URV5 millivoltmeter and 10 volt insertion probe, further contributions due to Temperature dependence, linearity from 1mV to 10V and frequency response must also be considered. Table 3 and 4 show the uncertainty of standard voltage provided by the NRS power meter and probe and the URV5 millivoltmeter and 10V insertion unit.

**References and further reading.**


Cook, J.D. "RF Voltage" IEE Microwave Measurements Training Course

Hinton, L. "RF Voltage Procedure"

Fantom, A. "Radio frequency and microwave power measurement", Peter Perigrinus

Somlo, P.I. "Microwave impedance measurement", Peter Perigrimus

UKAS "the expression of uncertainty and confidence in measurements", Publication M 3003 Edition 1 December 1997

# Tables

**Table 1. SESC calibration of Rohde and Schwarz NRS Probe**

| Frequency GHz | Calibration Factor % | Uncertainty ±% | VSWR | Uncertainty ± |
|---|---|---|---|---|
| 0.0001 | 100.0 | 0.5 | 1.003 | 0.003 |
| 0.01 | 99.9 | 0.5 | 1.004 | 0.003 |
| 0.03 | 99.9 | 0.5 | 1.005 | 0.003 |
| 0.1 | 99.8 | 0.5 | 1.006 | 0.003 |
| 0.2 | 99.7 | 0.5 | 1.008 | 0.003 |
| 0.3 | 99.7 | 0.5 | 1.011 | 0.003 |
| 1.0 | 99.5 | 0.5 | 1.019 | 0.022 |

**Table 2. Estimation of electrical path lengths between connectors and reference planes of T - junction**

| | | Frequencies for fractional w'length separation MHz | | | |
|---|---|---|---|---|---|
| **T - junction** | **Dielectric Constant** | **ë/500** | **ë/100** | **ë/20** | **ë/4** |
| **Type N** | 2.2 | 16 | 70 | 349 | 1747 |
| **Type BNC** | 2.2 | 25 | 125 | 623 | 3118 |
| **Type GR 874** | 1.0 | 16 | 70 | 349 | 1744 |

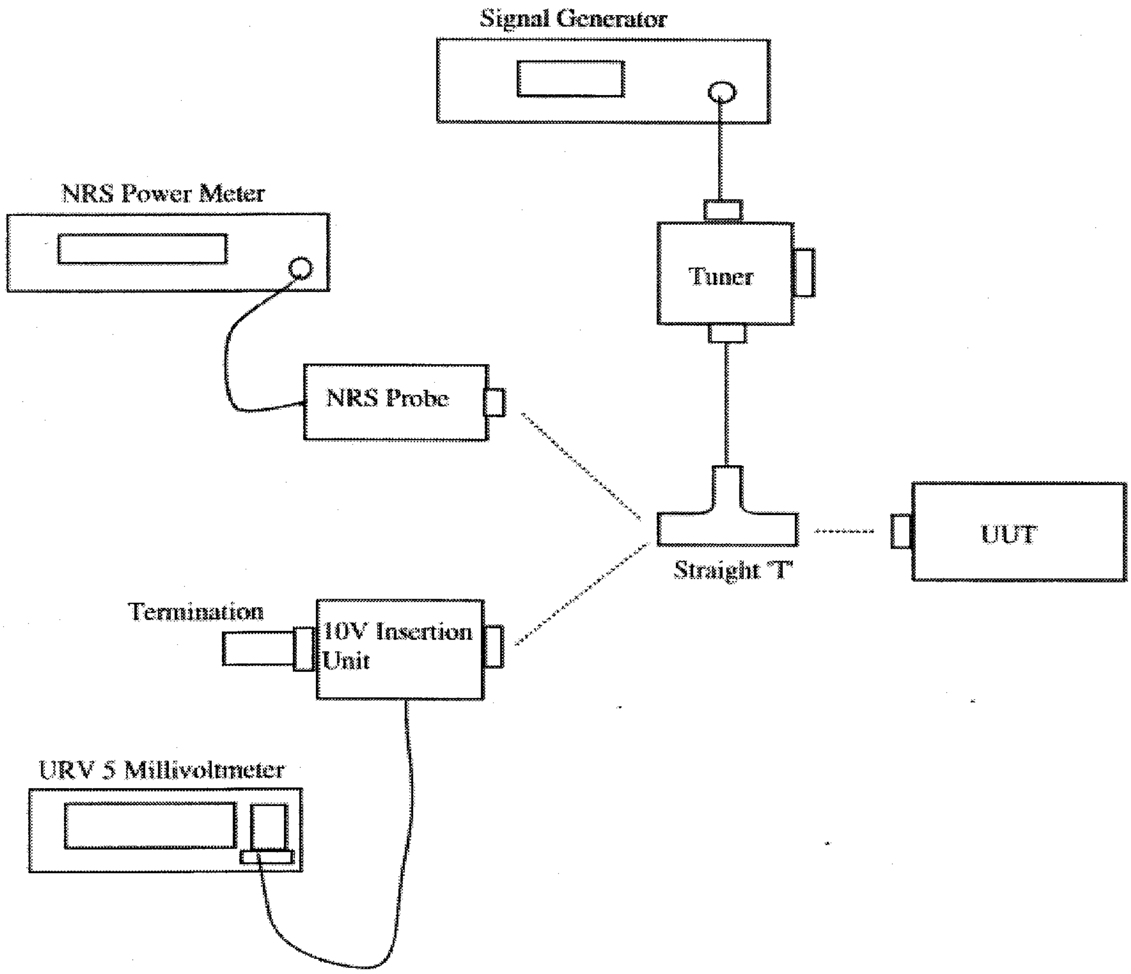
**Table 3. Calibration uncertainty of standard rf voltage, provided by the NRS power meter and probe.**

| Frequency | 0.5V (5mW) ± | 0.7V to 1V (10mW to 20Mw) ± |
|---|---|---|
| 10kHz | 0.65% | 0.55% |
| 10M | 0.85% | 0.75% |
| 30M | 0.90% | 0.80% |
| 100M | 0.95% | 0.85% |
| 200M | 1.05% | 0.95% |
| 300M | 1.2% | 1.1% |
| 1000M | 2.6% | 2.5% |

**Table 4. Calibration uncertainty of rf voltage, provided by the URV5 millivoltmeter and 10V insertion unit.**

| **Frequency Band** | **1mV to 100mV ±** | **100mV to 10V ±** |
|---|---|---|
| 9kHz to 10MHz | 0.86% | 0.92% |
| 10MHz to 100MHz | 1.11% | 1.16% |
| 100MHz to 300MHz | 1.30% | 1.34% |
| 300MHz to 1000MHz | 3.47% | 3.48% |

## Figure 1. Comparitor Configuration




## Figure 2. Incident Voltage Configuration

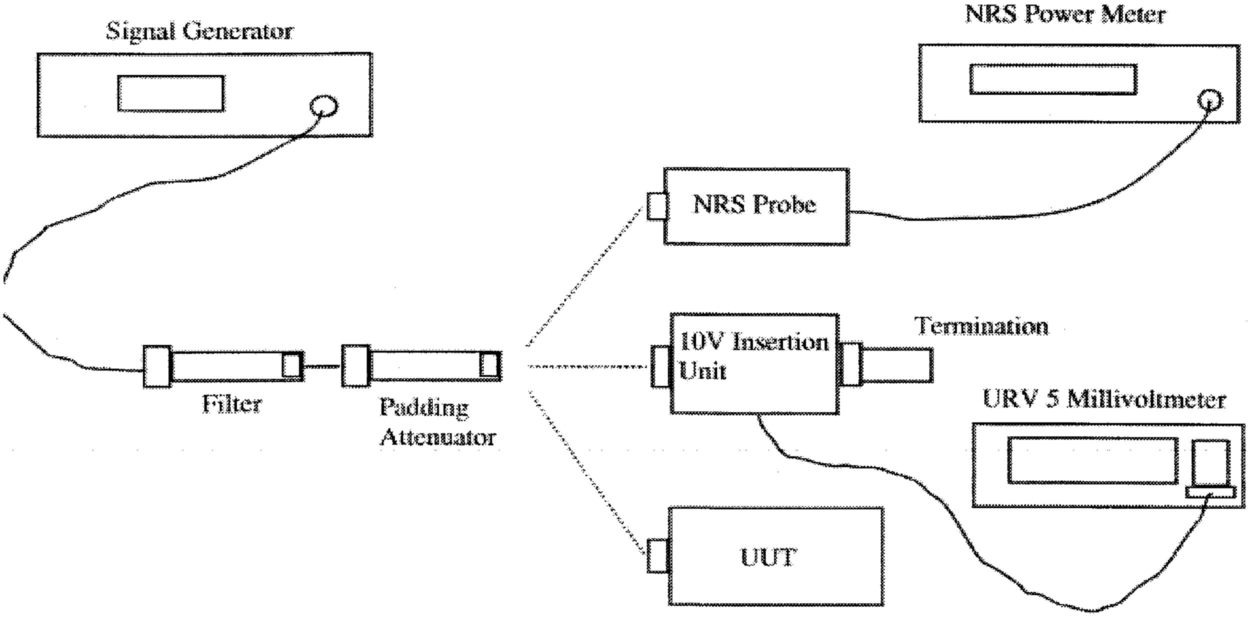
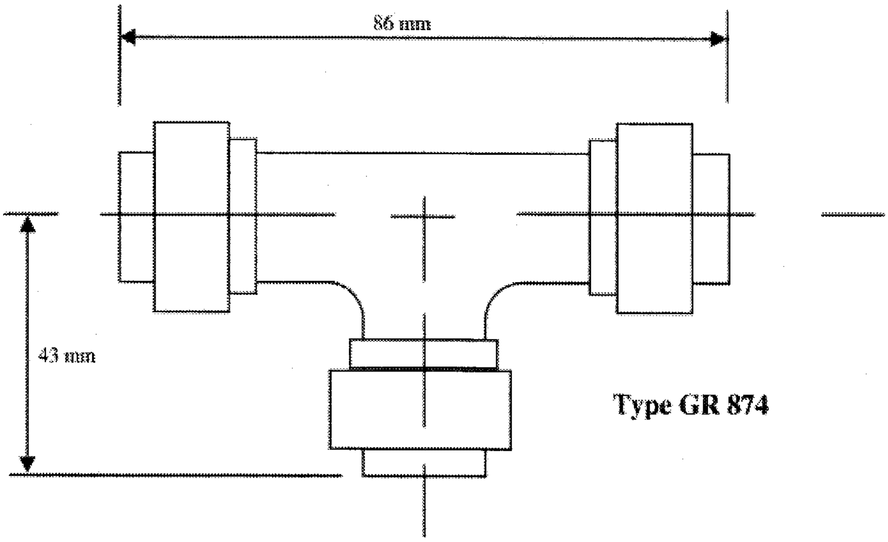
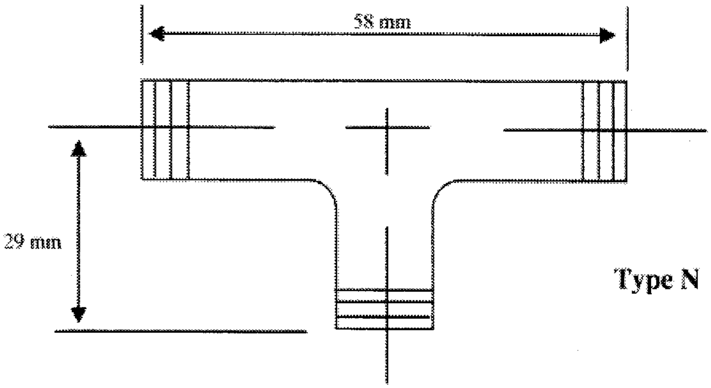


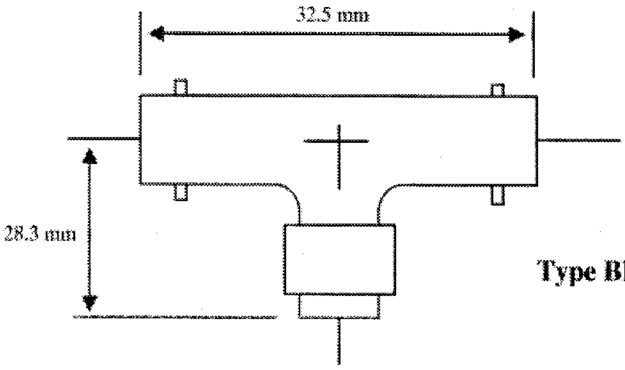
**Figure 3** **T – Junctions**




**Type GR 874**




**Type N**




**Type BNC**