

**Recent improvements to the traceability of
APC-7 impedance measurements at lower RF in the UK.**

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Abstract

This paper reports on a measurement service introduced recently by NPL at Malvern to provide traceability for impedance, and other complex reflection parameters, for coaxial line terminations fitted with APC-7 connectors at frequencies below 50 MHz. The new service is a result of several improvements made to an existing generalised measurement system. These improvements are discussed and typical results produced by the system are presented.

1 Introduction

Over recent years, a generalised measurement technique^[1] has been developed by NPL at Malvern to provide traceability for the reflection characteristics of terminations at RF. The technique has been applied to six-port reflectometers^[2] and vector automatic network analysers (ANAs)^[3,4]. The resulting measurement system uses external algorithms to implement calibration routines, calculate measurement results, and assess the uncertainties in the measurements.

Implementations of this technique in 50 ohm coaxial line have been reported in the 14 mm line size down to 300 kHz^[5,6], and in the 7 mm line size, for devices fitted with APC-7 connectors, down to 50 MHz^[7,8].

The current paper reports on the latest developments in this work program which have; (i) extended the frequency down to 100 kHz for APC-7 devices, and (ii) introduced robust statistical procedures to aid in the assessment of the uncertainties. Some results are presented, using the improved measurement capability, for an APC-7 mismatched termination over the frequency range 100 kHz to 50 MHz. An HP 8751 ANA was used to provide the vector indications, processed by the system's algorithms, for both calibration and measurement artefacts.

2 Low frequency calibration

The NPL measurement system requires three "known" standards to achieve calibration at each frequency of operation. Commercial ANA calibration routines usually employ the Short-Open-Load technique at low frequencies, with a conventional short-circuit, an open-circuit containing a dielectric rod to compress the test-port collet and a well-matched load assumed to provide zero reflection.

Below 50 MHz, the calibration artefacts for the NPL measurement system comprise a short-circuit, a calculable open (described below) and a characterised load, with a predicted value of reflection derived from measurement data.

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2.1 Open-circuit standard.

The 7 mm calculable open-circuit standard has previously been used by NPL for measurements above 50 MHz^[7]. However, its characteristics become easier to predict at lower frequencies so it also makes a useful standard for lower frequency systems. Fabrication and modelling details for the open circuit have been given elsewhere^[9].

2.2 Load standard.

The characteristics of high quality APC-7 loads at frequencies below 50 MHz can be predicted, to a fair degree of accuracy, from knowledge of the impedance of the load at DC ($Z_{DC} = R_{DC} + jX_{DC}$). The DC resistance, R_{DC} , of the load can be measured using a digital ohmmeter, while the DC reactance, X_{DC} , is equal to zero by definition.

The impedance of the load at 50 MHz ($Z_{50} = R_{50} + jX_{50}$) can be measured, with respect to offset open- and short-circuit standards, and is used to gauge how closely the DC impedance of the load predicts its impedance at intermediate frequencies ($Z = R + jX$). The 50 MHz measurement is also used to assess the uncertainty associated with the predicted values R and X . Symmetric uncertainties are ascribed to R and X so that the ranges of values engulf the uncertainties of R_{50} and X_{50} respectively. *ie*:

$$R = R_{DC} \pm [|R_{50} - R_{DC}| + \text{unc}(R_{50})], \quad X = 0 \pm [|X_{50}| + \text{unc}(X_{50})]$$

where $\text{unc}()$ indicates the uncertainty for the parameter. (Uncertainties are treated at a 95% level of confidence.)

3 Robust statistics

Part of the uncertainty assessment for the measuring system involves evaluating the size of the effects of random errors on the measurement results. National and international guidelines on the subject^[10,11] have traditionally recommended methods based on Gaussian (normal) statistics, *ie* using the arithmetic mean and the standard deviation. However such methods are adversely affected by data which is either non-normal or contaminated by outliers. Under these circumstances, Gaussian statistics produce skewed average values and unrealistically large uncertainty intervals.

As both non-normality *and* outlier contamination occasionally occur with this measurement system, robust statistical techniques have been introduced to provide more resilient average values and efficient uncertainty intervals. One of the most reliable robust estimates of an average value and its uncertainty interval has been shown^[12] to be the biweight and its associated asymptotic variance as described below.

3.1 Average values.

The biweight estimate of an average value $\hat{y}$, for a series of observations y_i ($i = 1, \dots, n$), is an iteratively calculated weighted mean:

$$\hat{y} = \frac{\sum w_i y_i}{\sum w_i}$$

where the weights are given by:

$$w_i = \begin{cases} (1 - u_i^2)^2 & \text{when } u_i^2 < 1, \\ 0 & \text{otherwise,} \end{cases}$$

where $u_i = \frac{y_i - \hat{y}}{c (MAD)}$

and $MAD = \text{Median Absolute Deviation} = \text{median} \{ |y_i - \hat{y}| \}$

(Note, setting $w_i = 1$, ie $u_i = 0$, for all y_i gives: $\hat{y}$ = arithmetic mean.)

c is a tuning constant affecting the biweight's robustness to outliers. (Experience has shown that setting $c = 9$ works well for data distributions produced by the measurement system.) The arithmetic mean is taken as an initial estimate of $\hat{y}$ and the biweight is calculated iteratively until convergence is achieved. The number of iterations required indicates the amount of adjustment made by the biweight estimator to establish an average value. This provides a useful indicator of the departure from normality of the measurement data.

3.2 Confidence intervals.

The confidence interval is derived from the asymptotic variance, $\hat{v}ar$, for the biweight:

$$\hat{v}ar \hat{y} = \frac{\sum^* (y_i - \hat{y})^2 (1 - u_i^2)^4}{\left[\sum^* (1 - u_i^2)(1 - 5u_i^2) \right] \left[-1 + \sum^* (1 - u_i^2)(1 - 5u_i^2) \right]}$$

where $\sum^*$ indicates summation for $u_i^2 < 1$ only.

(Note, setting $u_i = 0$ for all y_i gives: $\hat{v}ar \hat{y}$ = variance of the mean.)

It has been shown empirically^[12] that a confidence interval can be derived from the asymptotic variance using Student's t with 0.7 times the usual number of degrees of freedom, ie:

$$95\% \text{ confidence interval} = \left[\hat{y} - t_{0.7(n-1)} \sqrt{\hat{v}ar \hat{y}}, \hat{y} + t_{0.7(n-1)} \sqrt{\hat{v}ar \hat{y}} \right]$$

4 Typical results

The table below presents results obtained using the new capability for a mismatched load providing a nominal linear reflection coefficient magnitude of 0.33. The results are presented as complex voltage reflection coefficient linear magnitude and phase. The uncertainties are quoted at a 95% level of confidence.

Frequency	Magnitude	Uncertainty	Phase	Uncertainty
100 kHz	0.3356	± 0.0037	+180.00°	$\pm 0.62^\circ$
300 kHz	0.3355	± 0.0037	+179.97°	$\pm 0.62^\circ$
1 MHz	0.3355	± 0.0037	+179.92°	$\pm 0.62^\circ$
3 MHz	0.3355	± 0.0037	+179.77°	$\pm 0.62^\circ$
10 MHz	0.3354	± 0.0037	+179.25°	$\pm 0.62^\circ$
50 MHz	0.3351	± 0.0037	+176.29°	$\pm 0.62^\circ$

5 Summary

This paper has presented some new developments resulting in extended frequency coverage for NPL's RF impedance measurement system. The improvements to low frequency calibrations have been discussed — specifically, the use of a calculable open-circuit standard and a characterised load. Robust statistical techniques have been used during the measurement uncertainty assessment producing resilient average values and efficient confidence intervals in the presence of abnormal, and outlier contaminated, measurement data.

Results have been presented indicating typical uncertainties of less than ± 0.004 in linear reflection coefficient, although uncertainties will vary as a function of the reflected signal from the device being measured.

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7 References

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