Application Note

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Using the 2309 FFT Analyzer for mm-wave attenuation measurements

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This application note describes the benefits of using a 2309 FFT analyzer in a precision attenuation measurement system at millimetric wave frequencies, with the instrument as the receiver in the down-converter.
The general principles can be applied at any RF or microwave frequency, using suitable mixers.

Section 1: Introduction

The National Physical Laboratory in Teddington, UK has for many years provided a comprehensive RF and Microwave attenuation measurement facility, covering the frequency range of 10 kHz to 110 GHz. (Reference 1). The WG 25 (50 - 75 GHz) and WG 27 (75 -110 GHz) modulated sub-carrier systems have recently been replaced with more modern systems based around synthesized millimetric sources, harmonic mixers and a receiver as a final detector / attenuation reference. Such systems are generally not used at primary standards level due to the high performance demanded of the receiver. Instead it is generally preferred to incorporate a low frequency standard such as an Inductive Voltage Divider or a Waveguide Beyond Cut-Off attenuator directly in the measurement system.

Section 2: Receiver / mixer attenuation systems

By definition attenuation is 'the ratio of the power delivered to a (impedance) matched load by a matched generator which is connected directly to it, to the power delivered to the same load by the same generator when the 2-port device is inserted between them'. Attenuation is commonly expressed in decibels.

Clearly power sensors can be used to measure attenuation directly. For wide dynamic range and lower uncertainties it is more common to use a frequency conversion system, with an attenuation standard operating at a low frequency. Such systems are commonly used at NPL to perform measurements up to 50 GHz. In these systems the RF or Microwave signal, having passed through the device under test (DUT), is down converted using a conventional local oscillator / mixer combination to a low or Audio Frequency (AF), typically 10 kHz or 50 kHz, where it is detected. Using an AC detector, the change in low frequency signal level can be measured as the DUT is alternated between the datum and attenuation states. Assuming the mixer is linear, the change (in power) in AF signal level is the attenuation, for an impedance matched system. The attenuation standard, usually, but not necessarily an Inductive Voltage Divider (IVD), is placed before the AF detector and the IVD is adjusted to restore the detected signal level as the RF attenuator is varied. This is the classic AF substitution technique (Reference 2), and places no demand on the detector performance other than sufficient resolution and repeatability. For greater convenience this system can be adapted to become a Voltage Ratio system. Here the detector is replaced by an AC voltmeter, which is calibrated before use with precise voltage step changes using the IVD and a stable AF source.

As the microwave frequency increases it becomes increasingly difficult to maintain the frequency difference between the signal source and the local oscillator to deliver a highly stable low frequency (AF) signal. One solution to this is to use a higher IF, usually in the 10 - 100 MHz region and detect the signal with a suitable measurement receiver. Receivers usually have narrow, but variable bandwidths which can be adjusted to suit the application. Modern receivers usually have a wide input frequency range and an internal mixer to convert the incoming signal to the internal detector frequency. For primary standards work it is often more convenient to use an external mixer and convert to the (usually low) detector frequency. The advantage of this is that the properties of the mixer can be fully evaluated separately from the receiver and its performance optimized, for example, by adjusting the LO power or DC bias.

The millimetric attenuation systems at NPL for waveguide bands WG25 and WG27 (50-75 and 75-110 GHz) have been built around synthesized microwave sources driving solid state millimetric multipliers and harmonic mixers. The IF signal, at 10.71 MHz, is measured using a 2309 100 MHz to 2.4 GHz FFT Analyzer[1] receiver which, partly due to the digital sigma-delta analog to digital converter, has highly suitable characteristics for use as a precision measurement receiver.

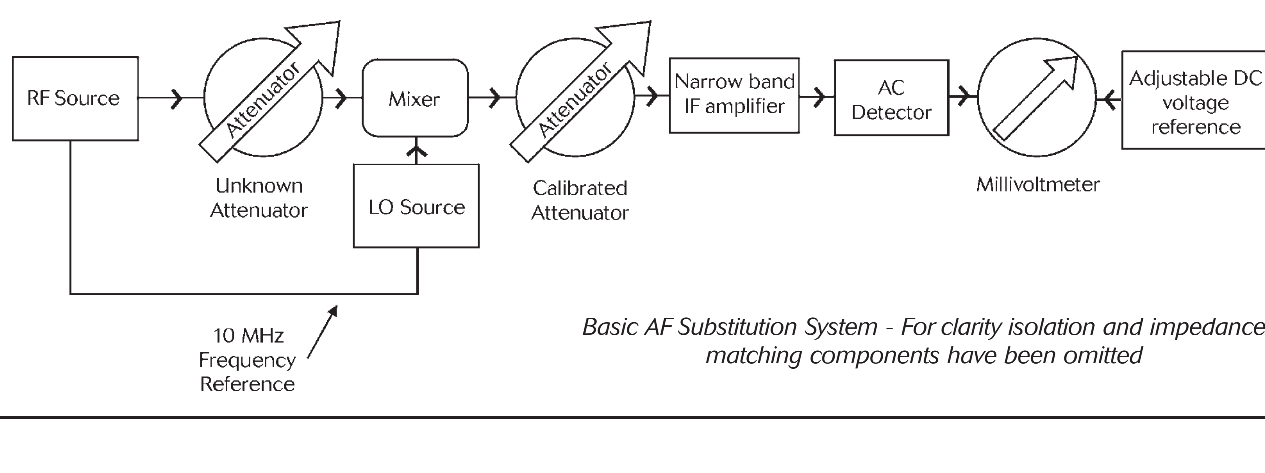
Section 3: Receiver Requirements

For the highest primary laboratory level measurements the requirements placed on the receiver are stringent. It must possess sufficient signal level resolution (0.0001 dB in this context), be highly stable and ideally highly linear - but the latter is less important if the receiver can be calibrated, and then hold the calibration. Linearity in this context is the invariance of reported signal level change as identical input signal level step changes are made at different mean power levels. Additionally the input power range (and signal to noise ratio) of the unit must be compatible with the expected output level and dynamic range of the mixer.

Where the receiver contains selectable internal attenuators or amplifiers to optimize the detector performance, the insertion and removal of these 'gain blocks' must be repeatable, or be capable of being externally controlled.

Ease of use and full remote control of all functions, display, etc. is also highly desirable if full use is to be made of the performance of the instrument.

[1] From Aeroflex



Basic AF Substitution System - For clarity isolation and impedance matching components have been omitted

It should be noted that in this application the receiver is used as a power meter with a wide dynamic range. It is not used to measure the absolute power but only relative (ratio) changes in signal level. However, measurement of absolute power is needed for estimation of the dynamic range.

Section 4: Traceability

Traceability is the direct link of a measurement, through a series of measurements or calibrations, back to the realization of the SI Base Units. In our millimetric systems the traceability route is through the calibration of a highly repeatable 10 dB switched resistive attenuator. This attenuator is fitted with a pair of 10 dB fixed attenuators, one on each port, which improves the isolation, and hence repeatability of the attenuation step. This step attenuator is measured at 10.71 MHz using the NPL low frequency Voltage Ratio system which is traceable, through an Inductive Voltage Divider (the local low frequency attenuation standard), to the NPL National Standard for AC voltage ratio.

The traceability for impedance (attenuation cannot be stated without reference to the transmission line impedance) comes through a calibrated mismatch, which has been measured on the NPL Primary Impedance Standard System.

Section 5: Receiver evaluation - typical results

As explained in Section 3, the receiver is used as a stable power meter, which must be capable of measuring power ratios for a large range of input power. It does not need to be able to measure absolute power. If the power input to the receiver is approaching its maximum, it is likely that it will under-read, as mixers and amplifiers approach saturation. If the power is close to the minimum detectable, noise and leakage signals within the measurement system may be comparable to or larger than the signal being measured, causing significant errors. Between these extremes, a good receiver will be very linear.

The linearity of a receiver may be evaluated using a source of variable power in series with a stable matched attenuator which may be switched in and out using very repeatable switches - the 'repeatable step' technique. In practice, the source power is varied using an adjustable attenuator (which may be referred to as a level set attenuator). The measurement procedure is:

(1) Set the level set attenuator (typically values between 0 and 100 dB in steps of 10 dB are used, though the range must be chosen to suit the working range of the receiver).

(2) Measure the power with the stable attenuator switched in.

(3) Measure the power with a through connection in place of the stable attenuator.

(4) Take the ratio of these two measurements (or if working in decibels, the difference).

It is often necessary to repeat steps 2 and 3 (as a pair) a number of times to obtain low uncertainties on account of measurement noise. These repeat measurements also ensure that effects of drift of the source power and of the switch non-repeatability are represented in the estimated uncertainties. To minimize the rate of drift, this measurement must be performed in a temperature-controlled laboratory, and equipment must be allowed typically 24 hours warm-up time. Effective shielding to minimize leakage signals is required in order to achieve good linearity at low signal levels. Copper tape is commonly wound round the coaxial or waveguide connections for this purpose.

The 2309 FFT Analyzer uses an intermediate frequency (IF) of 10.71 MHz. For many applications this is obtained using an internal mixer, however, for mm-wave measurements this does not have the required frequency range and an external mixer must be used. To obtain best system performance it is usually best to mix down to 10.71 MHz in one step, and use the rear-panel IF input of the instrument. This bypasses the internal mixer and connects directly to the 'IF strip' and Digital Signal Processor.

Measurements of the linearity of two 2309 receivers using the 10.71 MHz input are given in Tables 1a and 1b. These were obtained using an Adret 730A VHF signal generator[2] (which is a very stable source with built-in level-set attenuator) and a nominal 10 dB switched coaxial attenuator. Isolation attenuators (often referred to as pads) with an attenuation of 10 dB were placed at both input and output of the switched attenuator. These have the effect of minimizing the change of mismatch when the attenuator is switched in and out. This experiment can be fully automated if the switched coaxial attenuator is used in conjunction with a GPIB-controlled driver. The maximum input level for the 2309 FFT Analyzer rear panel connector is -14 dBm, and this corresponds to signal generator setting of +6 dBm, since there are two 10 dB pads in the circuit. Measurements are made at the peak shown on the 2309's display. As can be seen from the table, the dynamic range of the instrument is very wide, exceeding 70 dB.

[2] This obsolete signal generator could be replaced by an Aeroflex IFR 2040 series signal generator

Nominal Input Power	N	Mean Step	Sample Std. Dev.	Std. Dev. of Mean	Measured peak (without 10 dB atten)
dBm		dB	±	±	dBm
6	10	10.0274	0.00011	0.000038	-13.4165
0	10	10.0284	0.00008	0.000025	-19.4775
-10	10	10.0288	0.00012	0.000037	-29.2830
-20	10	10.0288	0.00013	0.000040	-39.3472
-30	10	10.0281	0.00045	0.00014	-49.4568
-40	10	10.0287	0.00099	0.00031	-59.3943
-50	10	10.0289	0.0029	0.00092	-69.2968
-60	10	10.0272	0.0098	0.0031	-79.4839
-70	15	10.0290	0.025	0.0064	-89.1470
-80	20	10.021	0.078	0.018	-99.066
-90	25	10.03	0.31	0.062	-108.332
-100	30	9.761	0.54	0.099	-117.108
-110	60	9.05	0.88	0.11	-121.85

Table 1a: Linearity of 2309 FFT Analyzer Receiver '1' using rear panel 10.71 MHz input.

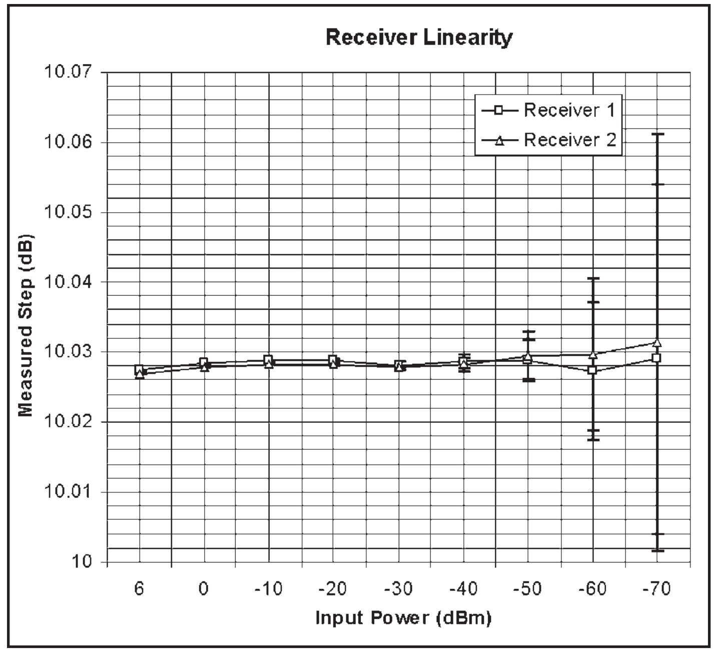
The 2309 bandwidth was 2 kHz and internal averaging was 10. N refers to the number of measurements of the attenuation step which were made.

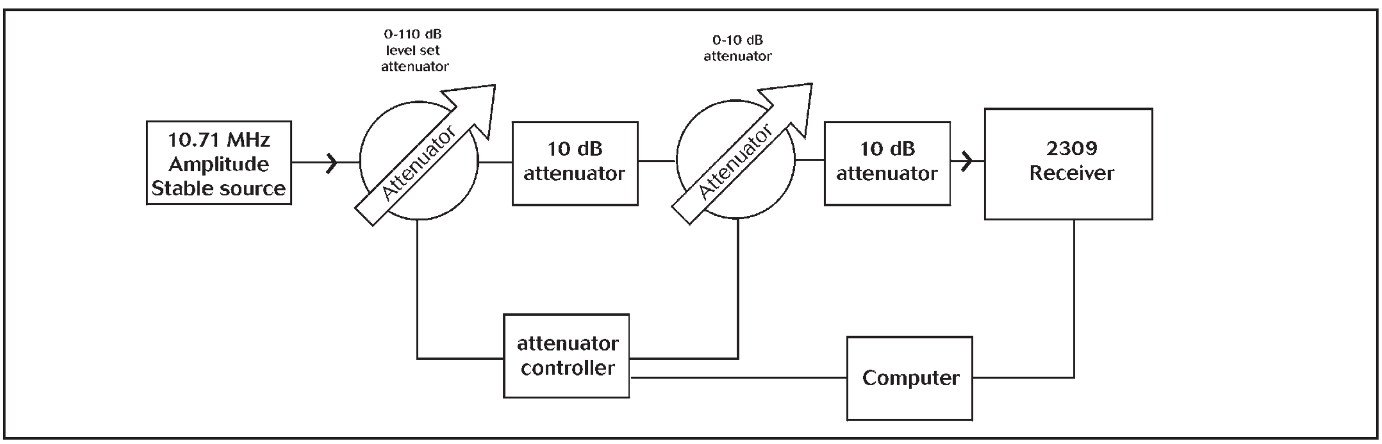
Nominal Input Power	N	Mean Step	Sample std. dev.	Std. dev. of mean	Measured peak (without 10 dB atten).
dBm		dB	±	±	dBm
6	10	10.0269	0.000114	0.000036	-13.3824
0	10	10.0279	0.000087	0.000028	-19.4409
-10	10	10.0283	0.000090	0.000028	-29.2463
-20	10	10.0282	0.000173	0.000055	-39.3085
-30	10	10.0278	0.000316	0.000100	-49.4056
-40	10	10.0282	0.000961	0.000304	-59.3399
-50	10	10.0294	0.003513	0.001111	-69.2413
-60	10	10.0297	0.010856	0.003433	-79.4348
-70	15	10.0314	0.029869	0.007712	-89.1136
-80	20	10.0169	0.129556	0.028970	-99.0353
-90	25	9.96448	0.349022	0.069804	-108.359
-100	30	9.55147	0.626718	0.114422	-117.093
-110	60	8.06865	0.865307	0.111711	-121.947

Table 1b: Linearity of 2309 FFT Analyzer Receiver '2' using rear panel 10.71 MHz input.

The 2309 bandwidth was 2 kHz and internal averaging was 10. N refers to the number of measurements of the attenuation step which were made.

As can be seen the performance of both receivers is very comparable, the slight difference in actual measured values of the transfer can be attributed to the temperature coefficient of the calibrated attenuator (typically 0.001 dB / ºC).





10.71 MHz Receiver Linearity Measurement System

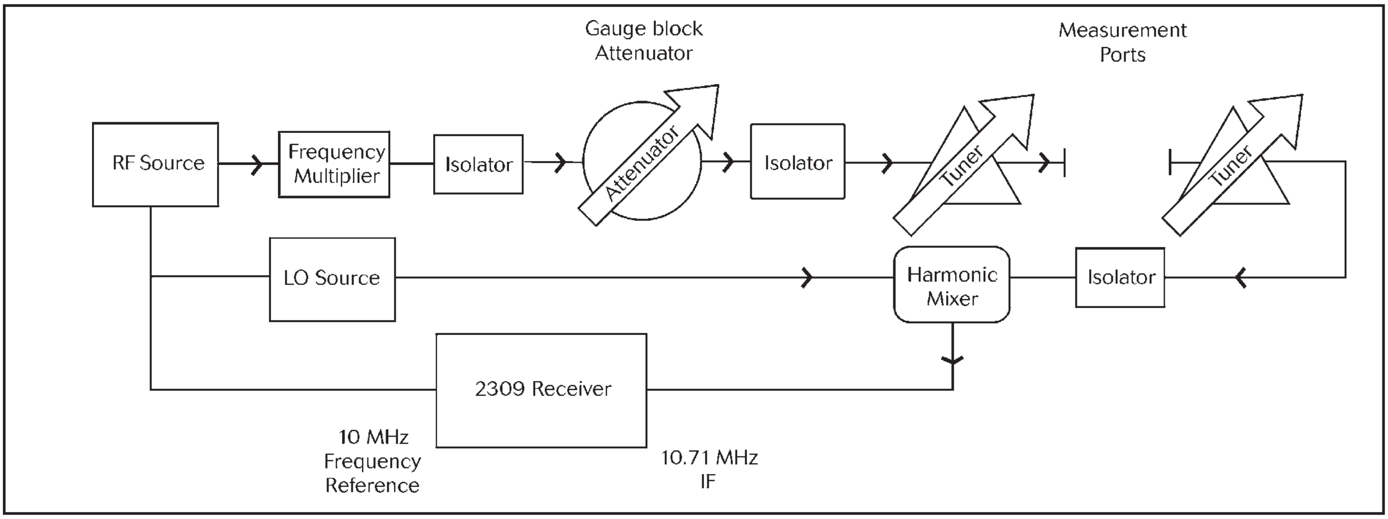
Section 6: NPL WG25/27 attenuation measurement system

Systems for measuring attenuation in WG25 (50-75 GHz) and WG27 (75-110GHz) are described in this section. Both use a 2309 FFT Analyzer as a receiver, in combination with a waveguide mixer and a synthesizer as local oscillator. Third harmonic mixers are used. For example, to achieve the required 10.71 MHz IF at 75 GHz requires the local oscillator synthesizer to operate at (75000-10.71)/3 = 24996.43333 MHz. Mixers often require a low voltage bias supply for optimum performance.

The WG25 source was formed from a microwave synthesizer and a doubler, and the WG27 source from a microwave synthesizer, a power amplifier and a quadrupler.

The synthesizer settings are left constant during an experiment, as this promotes greater stability. Normally the power output is set to the highest level and rotary-vane waveguide attenuators are used to set the actual source power level. It is important to allow the system to warm up fully before commencing measurements. Isolators are placed at the input and output of the RVA, and at the waveguide input to the mixer. This reduces unwanted level changes due to mismatch changes and results in a measurement of attenuation, rather than insertion loss.

Attenuation measurements of the device require the source and detector to be impedance matched at the measurement planes. This is achieved using waveguide tuners at the measurement ports. These are set by attaching the source and detector sections to a calibrated mm-wave Vector Network Analyzer (VNA) and adjusting for minimum reflection coefficient (i.e. perfect match). Uncertainties in the match of the system (due to VNA calibration uncertainties and connector non-repeatability) and the device under test itself contribute to the overall attenuation measurement uncertainty.



mm-wave Attenuator System general schematic

Section 7: System performance - mixer linearity

The 'repeatable step' technique can also be used to establish the linearity of the external mixer as well as that of the receiver. The step attenuator in this instance operates at the microwave frequency, rather than the IF. The measurement of linearity / dynamic range allows the optimum setting of input power level for best performance of the mixer to be ascertained. In practice, the linearity of the mixer and 2309 FFT Analyzer combined is measured, although the mixer linearity is dominant. Very repeatable waveguide switches are used to allow a stable reference attenuator and a waveguide section to be interchanged to make the input level changes. It is possible to optimize the mixer performance by adjusting its bias supply or LO power level. Experience suggests that operating at the best conversion loss point is the same as the best signal / noise point. As a general rule the LO power of an unbiased mixer should be at least 30 dB above the input power for best linear operation.

Table 2 shows results for a WG25 mixer at 60GHz. Note that the switched attenuator has attenuation of approximately 11 dB at this frequency.

RVA setting dB	N	Mean step dB	Sample Std. Dev. ±
95	30	10.73	0.77
90	20	10.98	0.43
80	10	11.08	0.15
70	10	11.140	0.045
60	10	11.088	0.026
55	10	11.105	0.009
50	10	11.094	0.005
45	10	11.105	0.004
40	10	11.117	0.007
35	10	11.102	0.001
30	10	11.0991	0.0006
25	10	11.0980	0.0005
20	10	11.0980	0.0003
15	10	11.0900	0.0005
10	10	11.0756	0.0005
5	10	11.0118	0.0003
0	10	10.5549	0.0004

Table 2: Linearity in WG25 measured at 60 GHz by repeatable attenuator technique (N is number of measurements of step).

As can be seen there is an optimal operating region for the system, avoiding noise problems at low signal levels and mixer compression at high levels, both these effects compressing the reported attenuation value.

Section 8: Overall system performance

Table 3 gives some typical uncertainties of measurements on attenuators made at 60 GHz in WG25. Using a level-set attenuator, the power input to the mixer was set to keep it within the linear region established prior to the measurements. Note that the 40 and 50 dB measurements were made using an "offset" or "gauge-blocking" technique to reduce uncertainties. This entailed first measuring the step of an adjustable rotary vane attenuator, in this instance between 0 and 25 dB settings. When the 40 and 50 dB attenuators were measured the size of the measured step was reduced by using the rotary vane attenuator, i.e. removing the 25 dB when the attenuator under test was in circuit.

Nom. atten. dB	Estimated uncertainty (at k=2)
10	0.0034
20	0.0068
30	0.020
40	0.016
50	0.016

Table 3: Example uncertainties of measurements in a WG25 system at 60 GHz

These values compare very favorably with the estimated uncertainties of other mm-wave measurement techniques, such as the Modulated Subcarrier System previously used at NPL and are considerably lower than those obtained from commercial automated network analyzers.

Section 9: Comparison with alternative measurements

In order to verify the operation of the new systems a comparison was conducted with a commercial mm-wave automated network analyzer. The devices were also measured on the NPL Primary IMpedance Measurement System (PIMMS). Additionally some historical values of the transfer attenuators were available from measurements made on the NPL (Malvern) Modulated Sub-Carrier System.

These values are tabulated below. (All uncertainties are reported at the 95% confidence level)

Frequency: 60 GHz

Nominal Value (dB)	mm-wave receiver system (dB)	MSCS system (dB)	mm-wave ANA (dB)	mm-wave ANA (PIMMS) (dB)
10	11.098 ± 0.003	11.092 ± 0.010	11.100	11.062
20	21.130 ± 0.007	21.138 ± 0.010	21.142	21.120
20*	21.693 ± 0.007	-	21.694	21.670
30	33.307 ± 0.020	33.304 ± 0.012	33.290	33.293
40	42.820 ± 0.016	-	42.806	42.793
50	55.012 ± 0.016	-	54.823	54.952

Frequency: 94 GHz

Nominal Value (dB)	mm-wave receiver system (dB)	MSCS system (dB)	mm-wave ANA (PIMMS) (dB)
10	9.720 ± 0.015	9.755 ± 0.010	9.681
20	20.45 ± 0.12	20.53 ± 0.011	20.453
30	33.02 ± 0.14	33.00 ± 0.013	32.985

As can be seen from the measured attenuation values the different techniques are in good agreement with one another, giving confidence in all of the systems.

Section 10: Summary

Two receiver based waveguide attenuation measurement systems have been assembled covering the frequency range 50 to 110 GHz. The dynamic range is typically in excess of 50 dB over the full bands. Transfer attenuation standards have been measured by several different techniques and there is good agreement of the reported attenuation values. Generally the performance of the receiver based system is comparable with the original Modulated Sub-carrier System but it has considerable advantages in convenience and speed of use. The outstanding linearity and stability performance of the receiver considerably simplifies data processing and contributes to the overall system capability.

While this particular application is for millimetric wave attenuation measurements the general principles can be applied at any RF or microwave frequency, providing that suitable mixers and sources can be procured.

Section 11: Acknowledgements

This work was supported by the Department of Trade and Industry National Measurement System Directorate.

We would like to thank David Gentle and Matt Maddock (NPL) for the ANA and PIMMS measurements.

We would also like to thank Aeroflex Test Solutions for their assistance and help by providing firmware enhancement of the 2309 FFT Analyzer for this application.

Section 12: References

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Part No. 46891/925, Issue1, 02/04