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AN INTERNATIONAL INTERCOMPARISON OF REFLECTION COEFFICIENT MAGNITUDES AT 10 GHz

Final Report
by
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Final Report of the Pilot Laboratory

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ABSTRACT

Five reduced-height-waveguide reflection coefficient travelling standards, equipped with sliding terminations, have been measured at 10 GHz by national standards laboratories in the UK, the USA, Australia, Japan, Italy and Canada. The travelling standards, the measuring equipments used by each participant and the measurement and analysis procedures are described. The results are then presented graphically and also in several tables. The travelling standards were designed to give voltage standing wave ratios of 1.02, 1.05, 1.1 and 1.2. The mean values obtained for these VSWRs by the 6 participants range from 1.01822 to 1.02124 on the lowest step and from 1.19758 to 1.20314 on the highest step. The theory of the reduced-height waveguide travelling standard is discussed in an appendix.

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1 INTRODUCTION

Under the auspices of the Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures (CIPM), an international intercomparison of reflection coefficient magnitudes in waveguide at 10 GHz has been completed by the 6 following laboratories:-

Royal Signals and Radar Establishment (RSRE), UK;
National Bureau of Standards (NBS), USA;
National Measurement Laboratory (NML), Australia;
Electrotechnical Laboratory (ETL), Japan;
Istituto Elettrotecnico Nazionale (IEN), Italy
National Research Council (NRC), Canada.

This international intercomparison was started in 1978 and completed in 1982, with RSRE acting as the pilot laboratory. Rectangular waveguide with internal dimensions of 22.860 mm x 10.160 mm (0.9000" x 0.4000"), designated WG16 in the UK and WR90 in the USA, was specified for use at the reference plane on each measuring equipment. Six reduced height waveguide travelling standards, equipped with sliding terminations, were prepared for this exercise: four by RSRE and two by NBS. The RSRE travelling standards were designed to give voltage standing wave ratios close to 1.02, 1.05, 1.1 and 1.2. These four standards were designated "RSRE 1.02", "RSRE 1.05", etc. The NBS travelling standards give VSWR's close to 1.04 and 1.19 and were designated "NBS A" and "NBS B" respectively.

The original aim was to send all 6 travelling standards around the world together; but various set-backs caused some deviations from this plan. The four RSRE standards travelled around the following route:-

RSRE → NRC → NBS → NML → ETL → IEN → RSRE → NRC → RSRE

Unfortunately, travelling standard "NBS A" had to be withdrawn from this intercomparison at an early stage due to corrosion and the route followed by "NBS B" was:-

NBS → NML → ETL → IEN → RSRE → NBS → RSRE → NRC → NBS

Measuring equipment problems necessitated a return of the RSRE standards to NRC and "NBS B" was sent back to its parent laboratory in July, 1980 for the removal of some corrosion.

The CIPM reference number for this intercomparison is 75-A12.

2 TRAVELLING STANDARDS

The four RSRE travelling standards consist of 0.3m lengths of reduced-height, normal-width, gold-flashed rectangular waveguide, produced by electro-deposition of copper on to stainless steel mandrels. They contain micrometer-driven Eccosorb MF 117 sliding terminations, which are tapered linearly in each case to a point that is midway between the two broad faces and midway between the centre and one of the narrow faces. This configuration gave the best match out of several different ones that were tried. These RSRE travelling standards have electrolytically grown round flanges. This manufacturing technique completely eliminated the need for solder or an adhesive between the waveguides and their associated flanges. These round flanges are compatible with the standard UG-39/U square flanges. They contain, in stainless steel inserts, two 3.175 mm (0.1250") dowel holes that are spaced symmetrically 45.720 mm (1.8000") apart on the centre line perpendicular to the broad faces. Dowel holes to this specification are widely used at RSRE but not elsewhere; so use of them in this intercomparison was not obligatory. The 4 standard holes in each flange were also positioned with extreme care. The mating surfaces on these flanges were lapped initially to a surface roughness of about 0.1 micron; but, at the end of this intercomparison, minor imperfections caused by normal use were clearly visible on all of them. The internal heights of the four RSRE standards (in order of increasing VSWR) are: 0.3922", 0.3810", 0.3636" and 0.3333" respectively, with a tolerance of ± 0.0001" in each case.

The two NBS travelling standards are basically similar to those provided by RSRE. They consist of 0.25m lengths of reduced-height, normal-width, unplated electroformed copper waveguide and they contain micrometer-driven pyramid shaped sliding terminations. Copper flanges have been attached with solder and the four standard fixing holes in them are in stainless steel inserts.

Appendix 1 gives the theory underlying the type of reflection coefficient travelling standard described above.

To a first approximation, the voltage standing wave ratio produced by the reduction in waveguide height is given by h_n/h_r, where h_n is the internal height of the normal waveguide on the measuring equipment and h_r is the internal height of the waveguide in the travelling standard. Second order effects are caused by:-

(a) the discontinuity capacitance at the step;
(b) loss in the waveguide connector;
(c) misalignment and twisting in the waveguide connector;
(d) roundness in the corners of the waveguides;
(e) a width change at the interface.

All of these second order effects are discussed in the Appendix. The effect of imperfect matching in the sliding termination is eliminated during the measurement procedure. Movement of this termination produces a circular movement of the input reflection coefficient on a Smith chart and the centre of this circle represents the reflection that would be obtained with a perfect reflectionless termination.

3 MEASURING EQUIPMENTS USED

3.1 RSRE

At RSRE, two different measurement techniques were employed. Firstly, a tuned reflectometer was used in the sub-carrier channel of the RSRE X-band modulated sub-carrier system [1]. A zero setting switch was incorporated in the reflectometer [1] and a low noise superheterodyne receiver provided improved sensitivity during the reflectometer tuning procedure. Secondly, a precision slotted line was used. Its microwave source was well filtered and highly stabilized in both amplitude and frequency. The input end of the slotted line was carefully matched. Detector non-linearity was eliminated by using a precision calibrated rotary vane attenuator to equalize the outputs at the maximum and minimum positions. The loss in the slotted line was determined by connecting a short circuit to the reference plane and measuring the resulting very high VSWR by the Roberts - von Hippel method [2]. Reflections from the end of the slot and probe coupling variations were eliminated by making measurements without and with a precision quarter wave section [3].

3.2 NBS

The measurement technique employed by NBS was a modified reflectometer [4], using a precision rotary vane attenuator [5] in an rf series substitution bridge system [6] as a detector/receiver. The travelling standards were connected to a precision section of standard-dimension (IEC: R-100) waveguide made to a tolerance of ± 0.0001" with negligible corner radii. The frequency of the microwave source was stabilized and held within ± 2 KHz of 10 GHz.

3.3 NML

Two different measurement techniques were employed by NML and these are described below:-

The first method employed a tuned reflectometer.

A 10 dB directional coupler plus source combination was tuned for the simultaneous conditions of source match and near zero leakage. The coupled, reflected signal was down-converted to 30 MHz and the level changes between the conditions of connecting a short-circuit and the unknowns were measured at 30 MHz with a waveguide below cut-off attenuation standard [7, 8]. Possible effects of level drifts during the interchanges of the short circuit and the unknowns, and during the repeated disconnections of the unknowns, were minimized using a 'reference path' to which the signal was switched during flange disconnections, and constancy of level was monitored in this condition [9].

The second NML measurement technique employed a computer assisted slotted line. A precision reference guide was connected to a slotted line having a computer driven probe. First, a short circuit was connected to this guide to establish the plane of the measurement.

Then, a sliding load was moved inside the precision reference guide and, for each position, a VSWR pattern was recorded and, via Fourier analysis, the value of the reflection coefficient was computed. Using four positions of the sliding load, a circle was fitted by least squares to these points and its centre was established. In subsequent measurements of the unknowns, the vector defined by the centre of this circle, which represents the residual reflections, was subtracted from the calculated reflection coefficients.

The departure of the power law from quadratic, of the crystal detector used, was established at the operating level and was taken into account in the calculation of the results.

3.4 ETL

At ETL, a tuned reflectometer measurement technique was used but the waveguide circuit employed a symmetrical hybrid tee junction instead of the more usual multi-hole directional coupler. For measuring the reflected signal level, a specially designed heterodyne system and a Weinschel VM-3 were used. The heterodyne system converted the reflected 10 GHz signal to a stable IF signal at 30 MHz. The VM-3 was calibrated against the Japanese attenuation standard whose accuracy is ± 0.002 dB/10 dB.

3.5 IEN

The measurements at IEN were made using a modified reflectometer technique [4]. The receiver was a Weinschel VM-1D that employs parallel substitution at 30 MHz and uses a waveguide-below-cut-off attenuator as the reference standard. A klystron provided the local oscillator signal and an external waveguide mixer, containing a single 1N23D diode, was employed.

3.6 NRC

At NRC, the measurements were carried out on a tuned waveguide reflectometer. The source and receiver used with this reflectometer were the same as are employed in the NRC 10 KHz IF attenuation measurement system[10]. The receiver was operated in the asynchronous mode. The reflectometer was tuned with the help of a sliding load and a sliding short. The reflectometer was then used to compare the voltage reflection coefficient of the travelling standards to that of a $\lambda g/4$ offset short circuit having an experimentally determined reflection coefficient modulus of 0.99950. The residual reflection error of the tuned reflectometer was measured with the help of a reference waveguide which was constructed as an assembly of four rectangular bars similar to a standard described by Ellerbruch[11].

4 MEASUREMENT PROCEDURE

Before the commencement of this intercomparison, the laboratories that provided the travelling standards determined the micrometer settings L1 and L2 that give minimum and maximum reflection coefficients. These micrometer settings are given in Table 1.

Travelling standard	Micrometer setting L1 where the reflection coefficient is minimum	Micrometer setting L2 where the reflection coefficient is maximum
RSRE 1.02	4.0 mm	14.0 mm
RSRE 1.05	3.4 mm	13.4 mm
RSRE 1.1	0.0 mm	10.0 mm
RSRE 1.2	2.5 mm	12.5 mm
NBS B	0.575 in	0.965 in

TABLE 1

The values for L1 and L2 were given to the participants.* The specified measurement procedure was as follows:-

"Connect each travelling standard to the measuring equipment and then remove it again 4 times. After each connection, measure the modulus of the reflection coefficient 4 times with the micrometer set at L1 and 4 times with it set at L2".

Thus, 32 reflection coefficient measurements were requested on each travelling standard and all of the measured values were sent to the Pilot Laboratory arranged in a specified manner.

The participating laboratories were also asked to provide the following information:

(a) the frequency limits of the microwave source used;

(b) the mean temperature of the laboratory in which the measurements were performed;

(c) the internal dimensions and corner radii of the waveguide on the measuring equipment to which the travelling standards were connected;

(d) the estimated systematic component of the uncertainty for a confidence level of 95%.

All of this information is presented in Table 2.

*Due to an oversight, the values of L1 and L2 for "NBS B" were not sent to NRC; so the workers there determined their own values for these two settings.

<table>
<tr><th>Laboratory</th><th>Frequency limits of source</th><th>Mean laboratory temperature</th><th>Internal dimensions of waveguide on measuring equipment at reference plane</th><th>Corner radii</th><th colspan="3">Estimated systematic component of reflection coefficient uncertainty for 95% confidence level</th></tr>
<tr><td>RSRE</td><td>± 100 Hz</td><td>21°C</td><td>0.9000" ± 0.0001"
0.4000" ± 0.0001"</td><td>< 0.004"</td><td colspan="3">± 0.0003 with reflectometer
± 0.0004 with slotted line</td></tr>
<tr><td>NBS</td><td>± 2 KHz</td><td>23°C</td><td>0.9000" ± 0.0001"
0.4000" ± 0.0001"</td><td>negligible</td><td colspan="3">± 0.0002</td></tr>
<tr><td rowspan="6">NML</td><td rowspan="6">± 10 KHz</td><td rowspan="6">22°C</td><td rowspan="6">0.9007" ± 0.0001"
0.4000" ± 0.0001"</td><td rowspan="6">0.002"</td><td>Travelling standard</td><td>Reflectometer</td><td>Slotted line</td></tr>
<tr><td>RSRE 1.02</td><td>± 0.00024</td><td>± 0.001</td></tr>
<tr><td>RSRE 1.05</td><td>± 0.00029</td><td>± 0.001</td></tr>
<tr><td>RSRE 1.1</td><td>± 0.00035</td><td>± 0.001</td></tr>
<tr><td>RSRE 1.2</td><td>± 0.00035</td><td>± 0.001</td></tr>
<tr><td>NBS B</td><td>± 0.00022</td><td>± 0.001</td></tr>
<tr><td>ETL</td><td>± 10 KHz</td><td>21°C</td><td>0.9000" ± 0.0002"
0.4000" ± 0.0002"</td><td>negligible</td><td colspan="3">± (0.0005 + 0.0014$|\Gamma|$)</td></tr>
<tr><td>IEN</td><td>± 100 KHz</td><td>23°C</td><td>0.8999" ± 0.00006"
0.4004" ± 0.00006"</td><td>not reported</td><td colspan="3">± 0.00014 for VSWR of 1.02
± 0.00017 for VSWR of 1.05
± 0.00028 for VSWR of 1.1
± 0.00044 for VSWR of 1.2</td></tr>
<tr><td>NRC</td><td>± 100 KHz</td><td>23°C</td><td>not reported</td><td>negligible</td><td colspan="3">± 0.0005</td></tr>
</table>

TABLE 2

5 ANALYSIS OF THE RESULTS

The primary objective of the analysis was to determine, for each travelling standard, the mean value for the voltage standing wave ratio of the step obtained by each standards laboratory, together with the associated total uncertainty for a confidence level of 95%.

The elementary equations used in this analysis were as follows:-

For the first mating of a given travelling standard, let the four measured values for the reflection coefficient modulus at micrometer setting L1 be denoted by: A1, A2, A3 and A4; and let the four measured values for the reflection coefficient modulus at micrometer setting L2 be denoted by E1, E2, E3 and E4. Then

Mean value for reflection coefficient modulus at setting L1

$$= A = \frac{A1 + A2 + A3 + A4}{4} \tag{1}$$

Standard deviation of measured values A1 to A4

$$= \sigma_A = \left\{ \frac{\sum_{i=1}^{i=4} (A_i - A)^2}{3} \right\}^{\frac{1}{2}} \tag{2}$$

Similarly, let E and σ_E denote respectively the mean value and standard deviation of E1, E2, E3 and E4.

From equation (A9), in the Appendix, it is seen that:

Modulus of reflection coefficient of step derived from first mating

$$= |\Gamma_{s1}| = \frac{A + E}{2} \tag{3}$$

From elementary microwave theory it then follows that:-

VSWR of step derived from first mating

$$= S1 = \frac{1 + |\Gamma_{s1}|}{1 - |\Gamma_{s1}|} \tag{4}$$

In a similar manner, the second, third and fourth matings of this travelling standard yield values of S2, S3 and S4 for the VSWR of the step. Thus:

Mean value for VSWR of step

$$= S = \frac{S1 + S2 + S3 + S4}{4} \tag{5}$$

Standard deviation of the four VSWR values

$$= \sigma_s = \left\{ \frac{\sum_{i=1}^{i=4} (S_i - S)^2}{3} \right\}^{\frac{1}{2}} \tag{6}$$

The random component of the uncertainty, for a confidence level (CL) of 95%, associated with the above value for S is given by [12]:-

$$U_r = \frac{t\,\sigma_s}{\sqrt{n}} \tag{7}$$

where n is the number of calculated values of VSWR (= 4) and t is the Student's - t factor for 4 values and a confidence level of 95% (= 3.18245).

The systematic component of the uncertainty, for a confidence level of 95%, associated with S, is:-

$$U_s = \frac{(S + 1)^2}{2} \quad \Delta\Gamma \tag{8}$$

where $\Delta\Gamma$ is the estimated systematic uncertainty of the related reflection coefficient measurement (for CL = 95%). The values for $\Delta\Gamma$ are given in column 6 of Table 2. Equation (8) stems from differentiation of the simple relationship between VSWR and reflection coefficient.

The total uncertainty, for a confidence level of 95%, associated with S is:-

$$U_t = \sqrt{U_r^2 + U_s^2} \tag{9}$$

Table 3 gives all the values for $S \pm U_t$ obtained in this international intercomparison.

Since a large amount of data had to be handled, a simple computer program was written in BASIC to perform all of the above calculations and it was used on an HP 85 desktop computer.

The results in Table 3 are shown graphically in Figs. 1 to 4. The uncertainty bars extend from $S - U_t$ to $S + U_t$.

The values for σ_A and σ_E give an indication of the repeatability of the measuring equipment when the travelling standard remains connected to it.

For matings 2, 3 and 4, let the mean values for the reflection coefficient modulus at micrometer setting L1 be denoted by B, C and D; and let the mean values for the reflection coefficient modulus at micrometer setting L2 be given by F, G and H.

Let σ_x = the standard deviation of A, B, C and D

and let σ_y = the standard deviation of E, F, G and H

The values for σ_x and σ_y are in general much larger than the values for σ_A and σ_E. Thus σ_x and σ_y give an indication of the repeatability of the waveguide coupling between the travelling standard and the measuring equipment.

The values for σ_A and σ_E tend to be very similar in all cases. Likewise, the values for σ_x and σ_y tend to be very similar in all cases. Tables 4 and 5 give the values yielded for σ_A and σ_x by all 5 travelling standards in each standards laboratory.

Lastly, equation (A15) in Appendix 1 shows how the reflection coefficient modulus, $|\Gamma_t|$, for the sliding termination can be derived from the measured reflection coefficient values. Tables 6 gives the values for $|\Gamma_t|$ derived in this way for each travelling standard in every standards laboratory.

MEAN MEASURED VALUE FOR VSWR OF STEP

AND TOTAL UNCERTAINTY FOR 95% CONFIDENCE LEVEL

LABORATORY	MEASUREMENT TECHNIQUE	DATE	TRAVELLING STANDARD				
			RSRE 1.02	RSRE 1.05	RSRE 1.1	RSRE 1.2	NBS B
RSRE	reflectometer	Apl 78	1.02049 ± 0.00099	1.04981 ± 0.00074	1.10083 ± 0.00078	1.20202 ± 0.00091	
RSRE	slotted line	Apl 78	1.02124 ± 0.00083	1.05018 ± 0.00088	1.10141 ± 0.00090	1.20228 ± 0.00098	
NBS	reflectometer	July 78	1.01972 ± 0.00041	1.04876 ± 0.00042	1.10009 ± 0.00047	1.20151 ± 0.00049	1.19117 ± 0.00053
NML	reflectometer	Nov 78	1.01934 ± 0.00051	1.04839 ± 0.00062	1.09938 ± 0.00081	1.20012 ± 0.00091	1.19051 ± 0.00070
NML	slotted line	Nov 78	1.01822 ± 0.00206	1.04712 ± 0.00215	1.09688 ± 0.00237	1.19758 ± 0.00289	1.18967 ± 0.00308
ETL	reflectometer	Feb 79	1.02035 ± 0.00103	1.04909 ± 0.00121	1.10108 ± 0.00126	1.20165 ± 0.00158	1.19558 ± 0.00165
IEN	reflectometer	Sept 80	1.02106 ± 0.00038	1.05011 ± 0.00038	1.10159 ± 0.00063	1.20314 ± 0.00116	1.19279 ± 0.00360
RSRE	reflectometer	May 81	1.02083 ± 0.00073	1.04965 ± 0.00077	1.10085 ± 0.00077	1.20213 ± 0.00073	1.19054 ± 0.00118
NRC	reflectometer	Oct 81	1.02026 ± 0.00102	1.04917 ± 0.00105	1.10019 ± 0.00110	1.20152 ± 0.00121	1.19228 ± 0.00120
World averages			1.02017	1.04914	1.10026	1.20133	1.19179
Theoretical values			1.0199	1.0499	1.1005	1.2020	

TABLE 3

VALUES FOR THE STANDARD DEVIATION, σ_A, WHICH EXCLUDES WAVEGUIDE CONNECTOR REPEATABILITY

LABORATORY	MEASUREMENT TECHNIQUE	DATE	TRAVELLING STANDARD				
			RSRE 1.02	RSRE 1.05	RSRE 1.1	RSRE 1.2	NBS B
RSRE	reflectometer	Apl 78	0.0000029	0.0000048	0.0000025	0.0000025	
RSRE	slotted line	Apl 78	0.0000404	0.0000749	0.0000706	0.0001244	
NBS	reflectometer	July 78	0.0000080	0.0000045	0.0000043	0.0000067	0.0000194
NML	reflectometer	Nov 78	0.0000026	0.0000041	0.0000048	0.0000000	0.0000058
NML	slotted line	Nov 78	0.0001258	0.0001708	0.0003304	0.0003096	0.0001708
ETL	reflectometer	Feb 79	0.0000049	0.0000070	0.0000090	0.0000217	0.0000330
IEN	reflectometer	Sept 80	0.0000046	0.0000052	0.0000171	0.0000181	0.0000642
RSRE	reflectometer	May 81	0.0000082	0.0000096	0.0000082	0.0000050	0.0000082
NRC	reflectometer	Oct 81	0.0000008	0.0000010	0.0000013	0.0000010	0.0000055
AVERAGE VALUE FOR REFLECTOMETER MEASUREMENTS			0.0000046	0.0000052	0.0000067	0.0000079	0.0000227

TABLE 4

VALUES FOR THE STANDARD DEVIATION, σ_x, WHICH INCLUDES WAVEGUIDE CONNECTOR REPEATABILITY

LABORATORY	MEASUREMENT TECHNIQUE	DATE	TRAVELLING STANDARD				
			RSRE 1.02	RSRE 1.05	RSRE 1.1	RSRE 1.2	NBS B
RSRE	reflectometer	Apl 78	0.000235	0.000113	0.000115	0.000152	
RSRE	slotted line	Apl 78	0.000055	0.000094	0.000089	0.000023	
NBS	reflectometer	July 78	0.000022	0.000005	0.000044	0.000024	0.000061
NML	reflectometer	Nov 78	0.000041	0.000035	0.000067	0.000078	0.000123
NML	slotted line	Nov 78	0.000066	0.000175	0.000202	0.000402	0.000515
ETL	reflectometer	Feb 79	0.000043	0.000050	0.000022	0.000080	0.000157
IEN	reflectometer	Sept 80	0.000076	0.000035	0.000025	0.000108	0.000858
RSRE	reflectometer	May 81	0.000088	0.000144	0.000102	0.000021	0.000234
NRC	reflectometer	Oct 81	0.000016	0.000011	0.000003	0.000009	0.000008
AVERAGE VALUE			0.000071	0.000074	0.000074	0.000100	0.000279

TABLE 5

MEAN VALUES FOR THE REFLECTION COEFFICIENT MODULI OF THE SLIDING TERMINATIONS

LABORATORY	MEASUREMENT TECHNIQUE	DATE	TRAVELLING STANDARD				
			RSRE 1.02	RSRE 1.05	RSRE 1.1	RSRE 1.2	NBS B
RSRE	reflectometer	Apl 78	0.000443	0.000636	0.000452	0.000670	
RSRE	slotted line	Apl 78	0.000431	0.000621	0.000477	0.000622	
NBS	reflectometer	July 78	0.000447	0.000636	0.000447	0.000669	0.001852
NML	reflectometer	Nov 78	0.000448	0.000637	0.000442	0.000656	0.001849
NML	slotted line	Nov 78	0.000416	0.000603	0.000395	0.000722	0.001831
ETL	reflectometer	Feb 79	0.000450	0.000639	0.000456	0.000635	0.001866
IEN	reflectometer	Sept 80	0.000452	0.000629	0.000452	0.000672	0.001858
RSRE	reflectometer	May 81	0.000429	0.000622	0.000444	0.000662	0.001831
NRC	reflectometer	Oct 81	0.000448	0.000633	0.000438	0.000657	0.001895

TABLE 6

6 REFERENCE FLANGE CONSIDERATIONS

A major contribution to this international intercomparison was made by P I Somlo in 1979 (13). He showed that the ever-present loss in the flange coupling between the measuring equipment and a reduced height travelling standard can significantly lower the reflection coefficient. The theory of this effect is given in the paper cited above and it is also briefly discussed in the Appendix. The importance of this effect became very apparent when the NML results were sent to the pilot laboratory. Thus, at this stage, the author asked each participant to supply details about the reference flange on his measuring equipment. The received data is presented in Table 7 and discussed in Section 7. From his work on this topic, Somlo concluded that reflection coefficient standards superior to those used in the present exercise could be constructed by stepping the waveguide height a quarter guide wavelength, or odd multiples of this, away from the flange. This would cause the flange loss to be in quadrature with the theoretically calculable reflection coefficient; so the effect of the loss would be reduced.

CHARACTERISTICS OF THE REFERENCE FLANGES ON THE VARIOUS MEASURING EQUIPMENTS

Laboratory	Metal used for reference flange	Plating on reference flange	Flatness of reference flange	Were torque spanners used?	Torque value used	Were dowel pins used?
RSRE	copper	gold	2.5 μ	no	-	yes
NBS						
NML	aluminium alloy	none	< 3 μ	no	-	no
ETL	oxygen free copper	none	< 3 μ	no	NBS B was screwed up loosely to avoid damage to the reference flange by corrosion on the NBS flange.	no
IEN	anodized aluminium	none	2 μ	no	-	yes
NRC	Brush Wellman copper alloy 3	none		yes	10 in lbs	yes

TABLE 7

7 CONCLUSIONS

The highest and lowest mean values for the VSWR of each step can be readily found from either Table 3 or Figs 1 to 4. For the convenience of readers, these values are gathered together in Table 8.

Travelling standard	Highest mean value	Lowest mean value	Total spread of mean value
RSRE 1.02	1.02124 (RSRE)	1.01822 (NML)	0.00302
RSRE 1.05	1.05018 (RSRE)	1.04712 (NML)	0.00306
RSRE 1.1	1.10159 (IEN)	1.09688 (NML)	0.00471
RSRE 1.2	1.20314 (IEN)	1.19758 (NML)	0.00556
NBS B	1.19558 (ETL)	1.18967 (NML)	0.00591

TABLE 8. STEP VSWRs (NML results included)

In each case, the lowest mean values were yielded by the NML slotted line technique and, as mentioned earlier, P I Somlo [13] attributes this to loss in the flange coupling between their measuring equipment and the travelling standards. NML used an aluminium alloy reference flange and their results are consistently lower than those obtained at RSRE, for example, where a gold-plated copper reference flange was used. A further factor may have contributed to the rather low NML results. From Table 2, it is seen that the internal broad dimension of the NML reference waveguide is 0.0007" above the correct value. This small deviation makes the characteristic impedance of their reference waveguide 0.14% lower than the correct value resulting in a slightly lower value for the modulus of the reflection coefficient.

If the NML results are excluded, the total spreads of the mean values are distinctly lower as shown in Table 9.

Travelling standard	Highest mean value	Lowest mean value	Total spread of mean value
RSRE 1.02	1.02124 (RSRE)	1.01972 (NBS)	0.00152
RSRE 1.05	1.05018 (RSRE)	1.04876 (NBS)	0.00142
RSRE 1.1	1.10159 (IEN)	1.10009 (NBS)	0.00150
RSRE 1.2	1.20314 (IEN)	1.20151 (NBS)	0.00163
NBS B	1.19558 (ETL)	1.19054 (RSRE)	0.00504

TABLE 9. STEP VSWRs (NML results excluded)

In Table 9, the total spreads of the mean values on the 4 RSRE travelling standards are remarkably low and can almost be accounted for by the mechanical tolerances on the waveguides (see the Appendix). The larger total spread of the mean values on NBS B may have been caused by the varying amounts of corrosion on its flange as it travelled around the world. Also, no provision was made for using dowel pins with NBS B; whereas RSRE, IEN and NRC all used dowel pins in their measurements on the four UK travelling standards. The differences between the initial and final RSRE mean values on the four UK travelling standards are very small; so the reflection co-efficients of these standards do not appear to have changed to any significant extent during their 4 year journey around the world.

The dotted lines in Figs 1, 2 and 3 indicate the theoretical values for the step VSWRs, obtained from the equations (A4), (A5), (A11) and (A13) in the Appendix, and the "tie up" between theory and practice is seen to be very satisfactory.

Table 4 gives the standard deviations on sets of four repeated reflection coefficient measurements when the connection between the measuring equipment and the specified travelling standard was untouched. The values in this table, denoted by σ_A, refer to the 4 measurements after the first mating with the sliding termination set at L1. Similar values were obtained for the four repeated measurements after all other matings. It is seen from Table 4 that the slotted line measurements at both RSRE and NML yielded higher values for σ_A than the reflectometer measurements. In most cases, the values for σ_A associated with reflectometer measurements are below 10^{-5}. These very low values are a remarkable tribute to the stabilities of the reflectometer systems used by all participants.

The standard deviations, denoted by σ_x, in Table 5 were derived from the 4 mean reflection coefficient values obtained from matings 1, 2, 3 and 4 with the sliding termination set at L1 in each case. The values for σ_x are seen to be roughly an order of magnitude higher than the values for σ_A. Thus, the values for σ_x give an indication of the repeatability of the waveguide coupling between the travelling standard and the measuring equipment. The average values of σ_x for the UK travelling standards are seen from Table 5 to lie in the range 0.00007 to 0.0001. The corresponding value for NBS B is 0.00028. These values for σ_x are surprisingly low and show that all of the reference waveguides, reference flanges and travelling standard flanges used in this intercomparison were manufactured with great care. The lowest values for σ_x were achieved by NRC. Referring to Table 7, it is seen that NRC used both dowel pins and torque spanners when connecting the travelling standards to their measuring equipment. No other participant used torque spanners. Thus, another conclusion is that waveguide connector repeatability really can be improved by using torque spanners.

The highest and lowest mean values obtained for the reflection coefficient moduli of the sliding terminations are presented in Table 10.

Travelling standard	Highest mean value	Lowest mean value	Total spread of mean values
RSRE 1.02	0.000452 (IEN)	0.000416 (NML)	0.000036
RSRE 1.05	0.000639 (ETL)	0.000603 (NML)	0.000036
RSRE 1.1	0.000477 (RSRE)	0.000395 (NML)	0.000082
RSRE 1.2	0.000722 (NML)	0.000622 (RSRE)	0.000100
NBS B	0.001895 (NRC)	0.001831 {NML, RSRE}	0.000064

TABLE 10. REFLECTION COEFFICIENT MODULI OF SLIDING TERMINATIONS.

To keep this report down to a reasonable length, the result sheets received from the participants and the computer program used to analyse the results have not been included. However, the author will gladly supply this extra information to any participant who requires it.

8 ACKNOWLEDGMENTS

The author extends his very grateful thanks to Mr R F Clark of NRC, Dr T Iwasaki of ETL, Dr G Rietto of IEN, Mr P I Somlo of NML and Mr B C Yates of NBS for their very good cooperation throughout this lengthy international intercomparison. Acknowledgment is also made to Messrs P Herman and J H Pace for very valuable help with the measurements at RSRE.

9 REFERENCES

(1) F L Warner: "Microwave attenuation measurement", (Peter Peregrinus, 1977). Chs. 8 and 9.

(2) S Roberts and A von Hippel: "A new method for measuring dielectric constant and loss in the range of centimetric waves", J Appl. Phys., 17, 610-616, 1946.

(3) P J Skilton: "Reflectometry and slotted lines", Lecture Notes for the 1976 IEE Vacation School on RF Electrical Measurements, pp 14/1 - 14/AIII/2.

(4) W J Anson: "A guide to the use of the modified reflectometer technique of VSWR measurement", J. Res. NBS, 65C, 217-223, 1961.

(5) W Larson: "The rotary-vane attenuator as an interlaboratory standard", NBS Monograph 144, November, 1975.

(6) W Larson and E Campbell: "Microwave attenuation measurement system (series substitution)", NBS Technical Note 647, February, 1974.

(7) D L Hollway and F P Kelly: "A standard attenuator and the precise measurement of attenuation", IEEE Trans., IM-13, 33-44, 1964.

(8) P I Somlo: "A voltage doubling circuit for the absolute calibration of 30 MHz attenuation measurement systems", IEEE Trans., IM-27, 76-79, 1978.

(9) D L Hollway and P I Somlo: "The reduction of errors in a precise microwave attenuator calibration system", IEEE Trans., IM-22, 268-270, 1973.

(10) R F Clark: "Superheterodyne measurement of microwave attenuation at a 10 KHz intermediate frequency", IEEE Trans. on Instrumentation, IM-18, 225-231, 1969.

(11) D A Ellerbruch: "Evaluation of a microwave phase measurement system", NBS Journal of Research, 69C, 55-65, 1965.

(12) I A Harris and F L Warner: "New expressions and some more precise values for Student's t-factor", Proc. IEE, 125, 902-904, 1978.

(13) P I Somlo: "The effect of flange loss on the reflection coefficient of reduced-height waveguide reflection standards", IEEE Trans., MTT-27, 795-797, 1979.

(14) S A Schelkunoff: "Electromagnetic waves", (Van Nostrand, 1943), p 319.

(15) N Marcuvitz: "Waveguide handbook", (McGraw Hill, 1951), pp 307-309.

(16) W B W Alison et al: "A handbook for the mechanical tolerancing of waveguide components", Sponsored by the RCRDC Technical Committee on Microwave Components and Techniques, Ministry of Defence (PE), 1972.

(17) P J Skilton: "A technique for determination of loss, reflection and repeatability in waveguide flanged couplings", IEEE Trans. on Instrumentation and Measurement, IM-23, 390-394, 1974.

10. APPENDIX

THEORY OF THE TRAVELLING STANDARDS

Using the definition based upon transmitted power and maximum voltage, the characteristic impedance of an H_{01} air-filled rectangular waveguide with perfectly square corners is given by [14]:

$$Z_o = 240\pi \frac{h}{a} \cdot \frac{1}{\{1 - (\frac{\lambda}{2a})^2\}^{\frac{1}{2}}} \quad \text{(A1)}$$

where a and h denote, respectively, the skin-depth-corrected broad and narrow internal dimensions of the waveguide and λ is the unbounded wavelength in air. Thus, when a and λ are kept constant, Z_o is directly proportional to h.

Many of the symbols used below are defined in Fig 5. The discontinuity susceptance, B, at the step must be taken into account. The step can be represented by a 2-port network. Let

$$\alpha = \frac{h_r}{h_n} = \frac{Z_r}{Z_n} = \frac{Y_n}{Y_r} \text{ and } b = \frac{B}{Y_n} \quad \text{(A2,A3)}$$

Then, the scattering parameters of this 2-port network are found to be given by the expressions shown on the signal flow graph in Fig 6. Marcuvitz[15] gives the following expression for the normalised discontinuity susceptance:

$$b \approx \frac{2h_n}{\lambda g}\left\{\frac{\alpha^2 + 1}{2\alpha}\log_e \frac{1+\alpha}{1-\alpha} + \log_e \frac{1-\alpha^2}{4\alpha} + \frac{2}{\Lambda}\right\} \quad \text{(A4)}$$

where

$$\Lambda = \left(\frac{1+\alpha}{1-\alpha}\right)^{2\alpha} \cdot \frac{1 + \{1 - (h_n/\lambda g)^2\}^{\frac{1}{2}}}{1 - \{1 - (h_n/\lambda g)^2\}^{\frac{1}{2}}} - \frac{1 + 3\alpha^2}{1 - \alpha^2} \quad \text{(A5)}$$

and λg is the guide wavelength.

Using the non-touching loop rule, the reflection coefficient, Γ, of the travelling standard is seen from Fig 6 to be:-

$$\Gamma = \frac{1 - \frac{1}{\alpha} - jb}{1 + \frac{1}{\alpha} + jb} + \frac{\frac{2}{1 + \frac{1}{\alpha} + jb} \cdot \frac{2/\alpha}{1 + \frac{1}{\alpha} + jb} \cdot |\Gamma_t| e^{j(\theta - 2\beta\ell)}}{1 - \left\{\frac{-1 + \frac{1}{\alpha} - jb}{1 + \frac{1}{\alpha} + jb}\right\} \cdot |\Gamma_t| e^{j(\theta - 2\beta\ell)}} \qquad (A6)$$

When the sliding termination is very well matched, as is the case for all 5 travelling standards used in this intercomparison, the product in the second denominator can be neglected and Γ is then the sum of the two vectors shown in Fig 7. Thus, by measuring the maximum value, $|\Gamma_{max}|$, and minimum value, $|\Gamma_{min}|$, of Γ as ℓ is varied, the reflection coefficient modulus, $|\Gamma_s|$, of the step and $|\Gamma_t|$ can be readily found. We have:

$$|\Gamma_{max}| = |\Gamma_s| + \frac{4|\Gamma_t|/\alpha}{(1 + \frac{1}{\alpha})^2 + b^2} \qquad (A7)$$

and

$$|\Gamma_{min}| = |\Gamma_s| - \frac{4|\Gamma_t|/\alpha}{(1 + \frac{1}{\alpha})^2 + b^2} \qquad (A8)$$

From equations (A7) and (A8), we get:-

$$|\Gamma_s| = \frac{|\Gamma_{max}| + |\Gamma_{min}|}{2} \qquad (A9)$$

and

$$|\Gamma_t| = \frac{|\Gamma_{max}| - |\Gamma_{min}|}{2} \cdot \left\{\frac{(1 + \frac{1}{\alpha})^2 + b^2}{4/\alpha}\right\} \qquad (A10)$$

The theoretical expression for $|\Gamma_s|$ is seen from (A6) and Fig 7 to be:-

$$|\Gamma_s| = \sqrt{\frac{(\frac{1}{\alpha} - 1)^2 + b^2}{(\frac{1}{\alpha} + 1)^2 + b^2}} \qquad (A11)$$

Fig 8 shows how $|\Gamma_s|$ varies with α and also the error caused by neglecting the discontinuity capacitance. Since the lowest value for α used in this intercomparison is 0.8333, the error in the reflection coefficient value caused by the neglect of b is seen to be always less than 0.001.

If b is neglected, equation (A11) simplifies to:-

$$|\Gamma_s| = \frac{1 - \alpha}{1 + \alpha} \qquad \text{(A12)}$$

The VSWR produced by the step is:-

$$S = \frac{1 + |\Gamma_s|}{1 - |\Gamma_s|} \qquad \text{(A13)}$$

If b is again neglected:-

$$S \approx \frac{1 + \frac{1-\alpha}{1+\alpha}}{1 - \frac{1-\alpha}{1+\alpha}} = \frac{1}{\alpha} = \frac{h_n}{h_r} \qquad \text{(A14)}$$

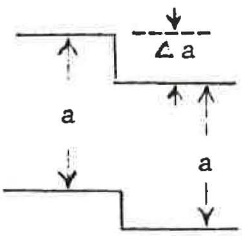
as stated in section 2.

Finally, with the above approximations, it follows from equation (A10) that:-

$$|\Gamma_t| \approx \frac{|\Gamma_{max}| - |\Gamma_{min}|}{2} \cdot \frac{(1 + S)^2}{4S} \qquad \text{(A15)}$$

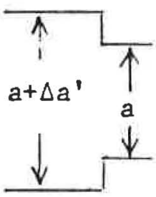
Six imperfections can affect the reflection coefficients of the travelling standards. These are shown below together with equations for the reflection coefficients produced solely by these imperfections.

H PLANE DISPLACEMENT (16)



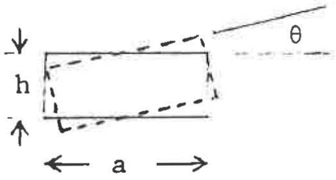
$$\Delta\Gamma_D = j \frac{\lambda g}{a} \left(\frac{\pi . \Delta a}{2a}\right)^2 \qquad \text{(A16)}$$

WIDTH ERROR IN REFERENCE WAVEGUIDE



$$\Delta\Gamma_W = \frac{\Delta a'}{2a} \left(\frac{\lambda g}{\lambda}\right)^2 \qquad \text{(A17)}$$

TWIST IN WAVEGUIDE CONNECTOR [16]

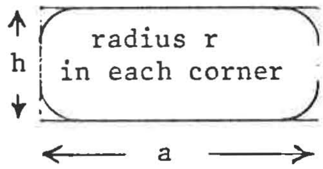


$$\Delta\Gamma_T = j\theta^2 \{0.0012-0.0024(\tfrac{a}{\lambda}) + 0.0013(\tfrac{a}{\lambda})^2\}$$

for $0 < \theta < 20^\circ$ and $0.6 < \frac{a}{\lambda} < 0.8$

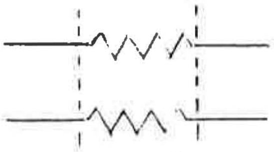
(A18)

CORNER ROUNDNESS IN REFERENCE WAVEGUIDE [16]



$$\Delta\Gamma_C = -0.1073 \frac{r^2}{ah} \cdot (\frac{\lambda g}{a})^2 \qquad \text{(A19)}$$

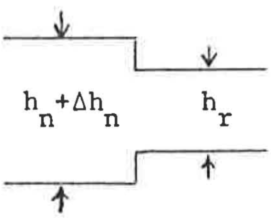
SERIES RESISTANCE IN WAVEGUIDE CONNECTOR [13]



series resistance
causing a loss of
A dB

$$\Delta\Gamma_R = \frac{A}{8.686} \qquad \text{(A20)}$$

HEIGHT ERROR IN REFERENCE WAVEGUIDE



$$\Delta\Gamma_H = -\frac{\Delta h_n}{h_n} \cdot \frac{2S}{(1+S)^2} \qquad \text{(A21)}$$

An attempt will now be made to estimate the upper limits for these various reflection coefficients. From Table 2, it is seen that the internal waveguide dimensions were all kept within 0.1% of the specified values and the largest reported corner radius is 0.1 mm. Thus, let us suppose that:-

$\Delta a = 0.02$ mm, $\Delta a' = 0.02$ mm, $\Delta h_n = 0.01$ mm and $r = 0.1$ mm.

A few workers have measured the loss in waveguide flanged couplings; eg P J Skilton[17] obtained values at RSRE close to 0.0005 dB with copper flanges that were machine lapped to a mirror finish and used with precision dowel pins; while P I Somlo [13] obtained values near 0.006 dB, when connecting not-recently-lapped brass and aluminium flanges. Thus, for the present example, let A = 0.006 dB.

In this intercomparison extra care was taken over the drilling of the bolt holes in the flanges; so θ should not be greater than 0.05^{o}.

These values give the following upper limits for the various reflection coefficients:

H plane displacement, $\lvert\Delta\Gamma_D\rvert$	=	3.3×10^{-6}
Width error in reference waveguide $\lvert\Delta\Gamma_W\rvert$	=	7.7×10^{-4}
Twist in waveguide connector, $\lvert\Delta\Gamma_T\rvert$	=	3.1×10^{-7}
Corner roundness in reference waveguide, $\lvert\Delta\Gamma_C\rvert$	=	1.4×10^{-5}
Series resistance in waveguide connector, $\lvert\Delta\Gamma_R\rvert$	=	6.9×10^{-4}
Height error in reference waveguide, $\lvert\Delta\Gamma_H\rvert$	=	

4.4×10^{-4} for $S = 1.02$

4.4×10^{-4} for $S = 1.05$

4.4×10^{-4} for $S = 1.1$

4.3×10^{-4} for $S = 1.2$

Thus, the effects of H plane displacement, a twist in the waveguide connector and corner roundness are negligibly small. Errors in the inside dimensions of the waveguides are very important and a very significant error can be caused by series resistance in the waveguide connector, as pointed out by Somlo [13].

11 POSTSCRIPT

Some very interesting remarks on this report were received from R F Clark of NRC in January, 1983. With only a short time available before the next BIPM meeting in March, 1983, it is only possible at this stage to reproduce his remarks and make some brief comments on them.

He expressed the view that Schelkunoff's equation (A1) is not valid for calculation of characteristic impedance for reflection purposes and mentioned that Levy[18] refers to Riblet[19] and Marcuvitz[20] as support for:

$$Z_o \propto \lambda_g h \qquad \text{(P1)}$$

using the same nomenclature as before.

Starting with (P1) instead of (A1), the expression for the reflection coefficient due to a width error in the reference waveguide is found to be:

$$\Delta\Gamma_W = \frac{\Delta a'}{2a}\left(\frac{\lambda_g}{2a}\right)^2 \qquad \text{(P2)}$$

Also, R F Clark mentioned that an equation given by Levy[18] for the reflection coefficient caused by H plane displacement differs by a factor of 2 from the equation given by Alison et al[16]. Levy gives, in our nomenclature:

$$\Delta\Gamma_D = j\ 2\ \frac{\lambda_g}{a}\left(\frac{\pi \cdot \Delta a}{2a}\right)^2 \qquad \text{(P3)}$$

Equation (P3) represents experimental results obtained by Kienlein and Kurzl[21] whereas equation (A16) stems from work carried out by R B Nicholls[22]. Additional experimental evidence for equation (P3) has been given by Beatty et al[23].

If the calculations given on page A5 are repeated using equation (P2) instead of (A17) and (P3) instead of (A16), we get:

upper limit for reflection coefficient, $|\Delta\Gamma_D|$, caused by H plane displacement = 6.6×10^{-6}

and upper limit for reflection coefficient $|\Delta\Gamma_W|$ due to a width error in the reference waveguide = 3.3×10^{-4}

Furthermore, if equation (P1) is differentiated with respect to the width, we get:

$$\frac{\Delta Z_o}{Z_o} = -\frac{\Delta a}{a}\left(\frac{\lambda_g}{2a}\right)^2 \qquad \text{(P4)}$$

According to (P4), the error of 0.0007" in the width of the NML reference guide makes the characteristic impedance of this waveguide 0.06% lower than the correct value, instead of 0.14% lower as stated on page 18. Thus, replacement of Schelkunoff's expression (A1) by expression (P1) reduces the values for $|\Delta\Gamma_W|$ and $\Delta Z_o/Z_o$ to less than half of the values given in the main text.

Expression (A1) has been used by many workers in the last 40 years and some microwave experts in the UK were quite surprised by the assertion that it is not valid for calculation of characteristic impedance for reflection purposes. Thus, this matter will require further discussion and possibly further experimental work in the future.

ADDITIONAL REFERENCES

(18) R Levy: "Reflection coefficient of unequal displaced rectangular waveguides", IEEE Trans., MTT-24, 480-483, 1976.

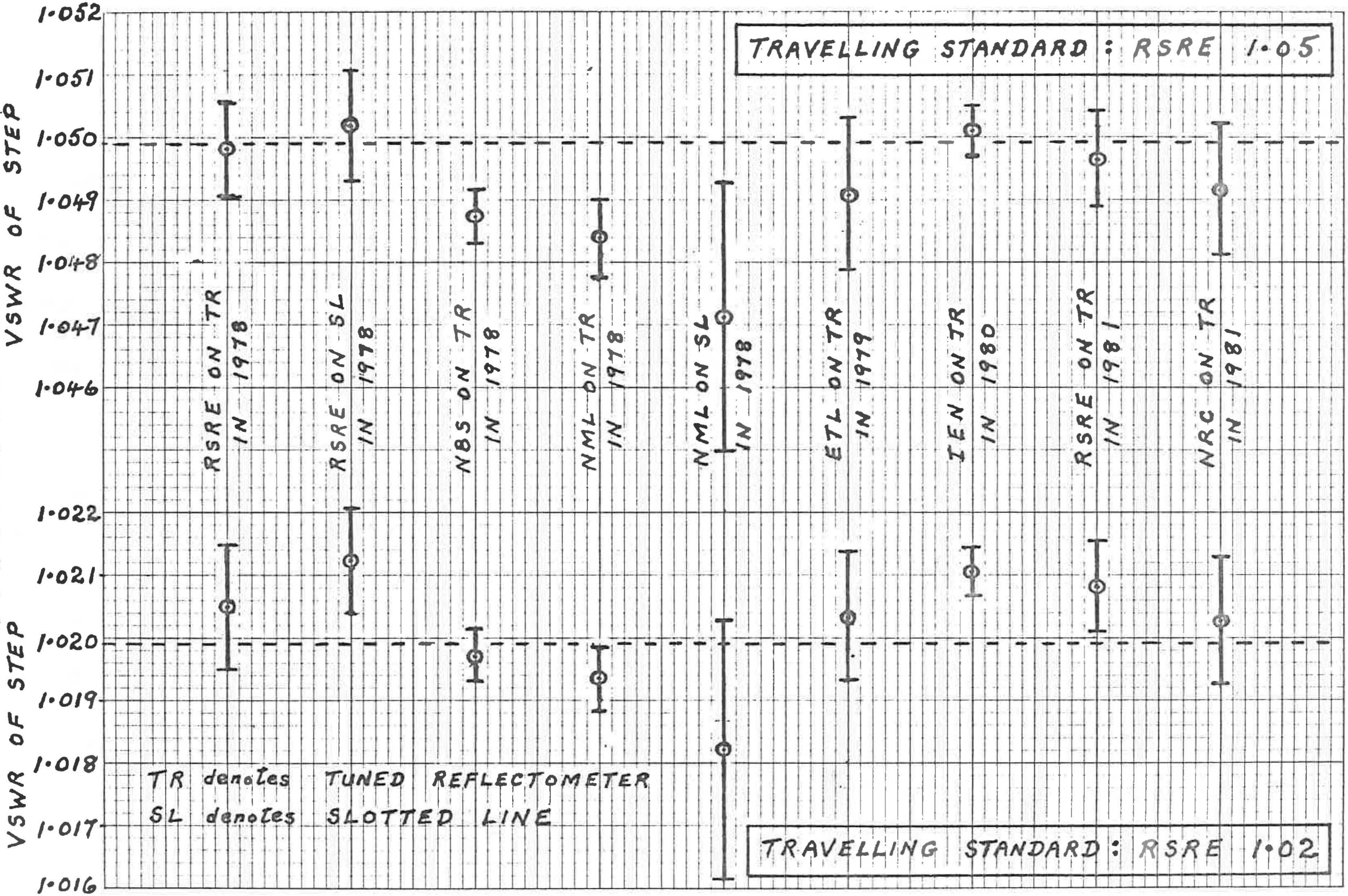
(19) H J Riblet: "A general design procedure for quarter-wavelength inhomogeneous transformers having approximately equal ripple performance", IEEE Trans., MTT-13, 622-629, 1965.

(20) N Marcuvitz: "Waveguide handbook", (McGraw-Hill, 1951), p 296.

(21) U Von Kienlein and A Kurzl: "Reflectionen an hollheiter flanschverbindungen", Nachtrichtentechnische Zeitschrift, 11, 561-564, 1958.

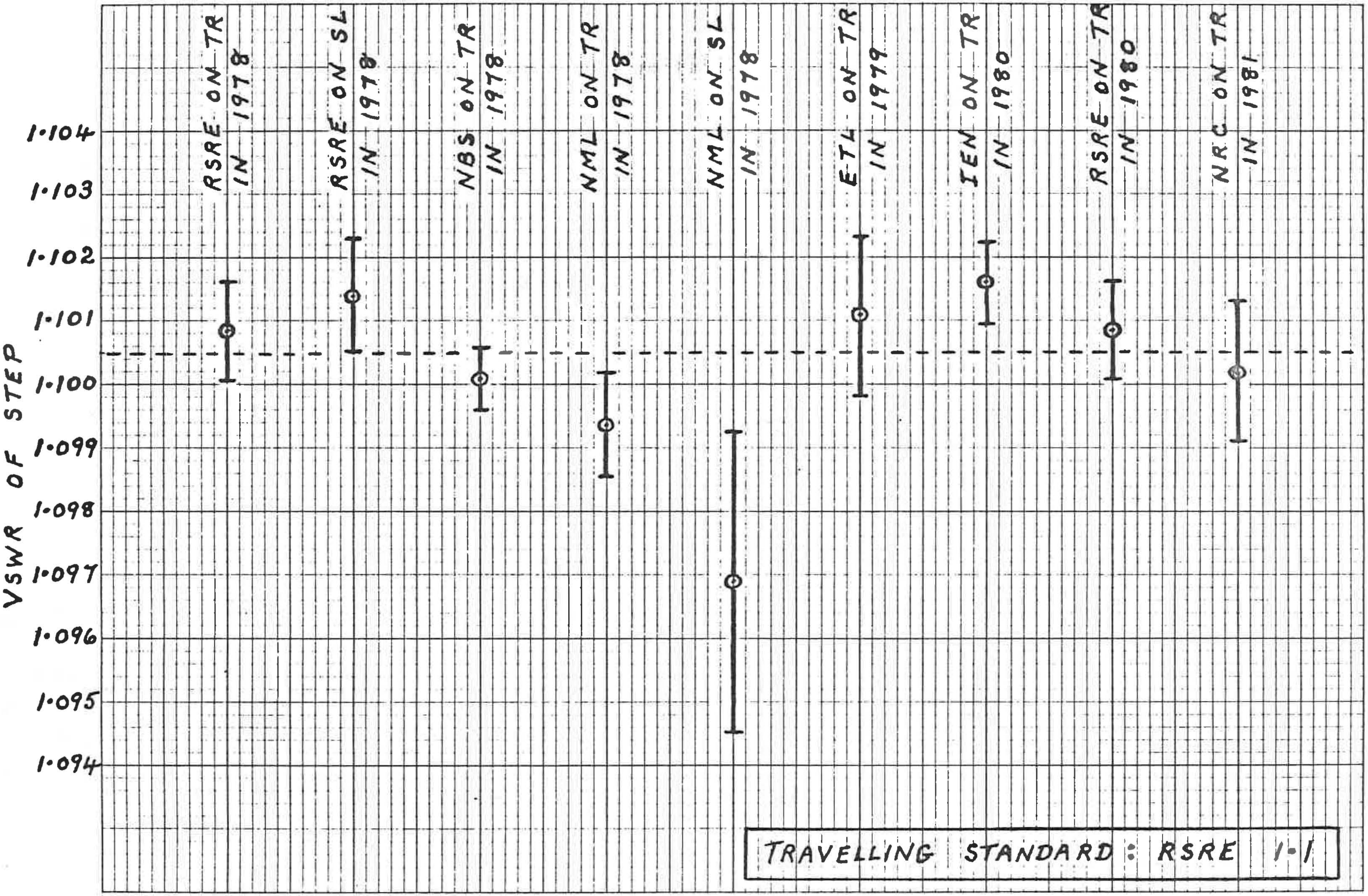
(22) R B Nicholls: "An estimation of the discontinuities introduced by flange couplings in rectangular waveguides", Elliott J., 2, 141, 1954.

(23) R W Beatty, G F Engen and W J Anson: "Measurement of reflections and losses of waveguide joints and connectors using microwave reflectometer techniques", IRE Trans., I-9, 219-226, 1960.



TRAVELLING STANDARD : RSRE 1·05
TRAVELLING STANDARD : RSRE 1·02
VSWR OF STEP
VSWR OF STEP
1·052
1·051
1·050
1·049
1·048
1·047
1·046
1·022
1·021
1·020
1·019
1·018
1·017
1·016
RSRE ON TR IN 1978
RSRE ON SL IN 1978
NBS ON TR IN 1978
NML ON TR IN 1978
NML ON SL IN 1978
ETL ON TR IN 1979
IEN ON TR IN 1980
RSRE ON TR IN 1981
NRC ON TR IN 1981
TR denotes TUNED REFLECTOMETER
SL denotes SLOTTED LINE

FIG. 1



VSWR OF STEP
1·104
1·103
1·102
1·101
1·100
1·099
1·098
1·097
1·096
1·095
1·094
RSRE ON TR IN 1978
RSRE ON SL IN 1978
NBS ON TR IN 1978
NML ON TR IN 1978
NML ON SL IN 1978
ETL ON TR IN 1979
IEN ON TR IN 1980
RSRE ON TR IN 1980
NRC ON TR IN 1981
TRAVELLING STANDARD : RSRE 1·1

FIG. 2

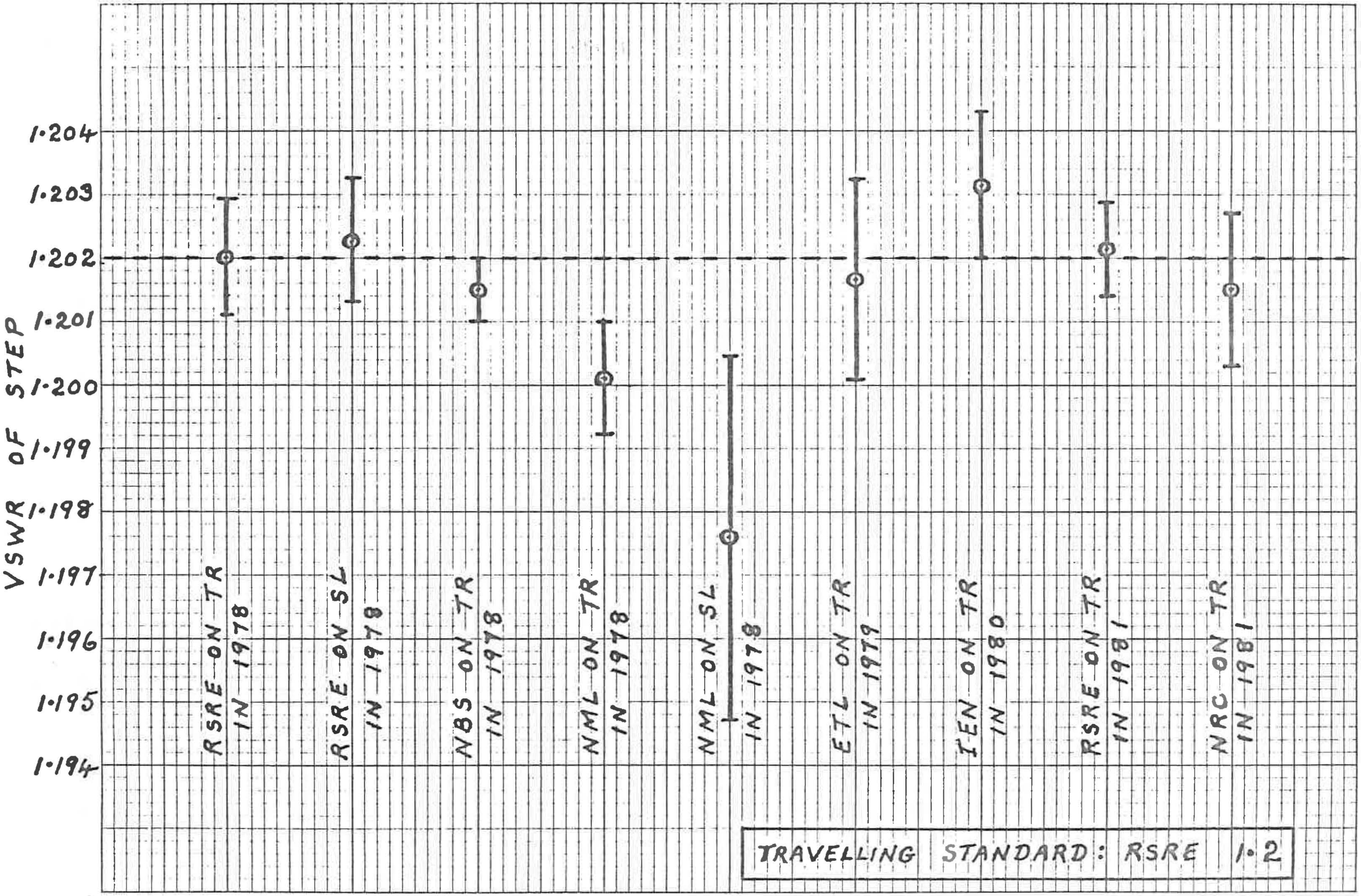
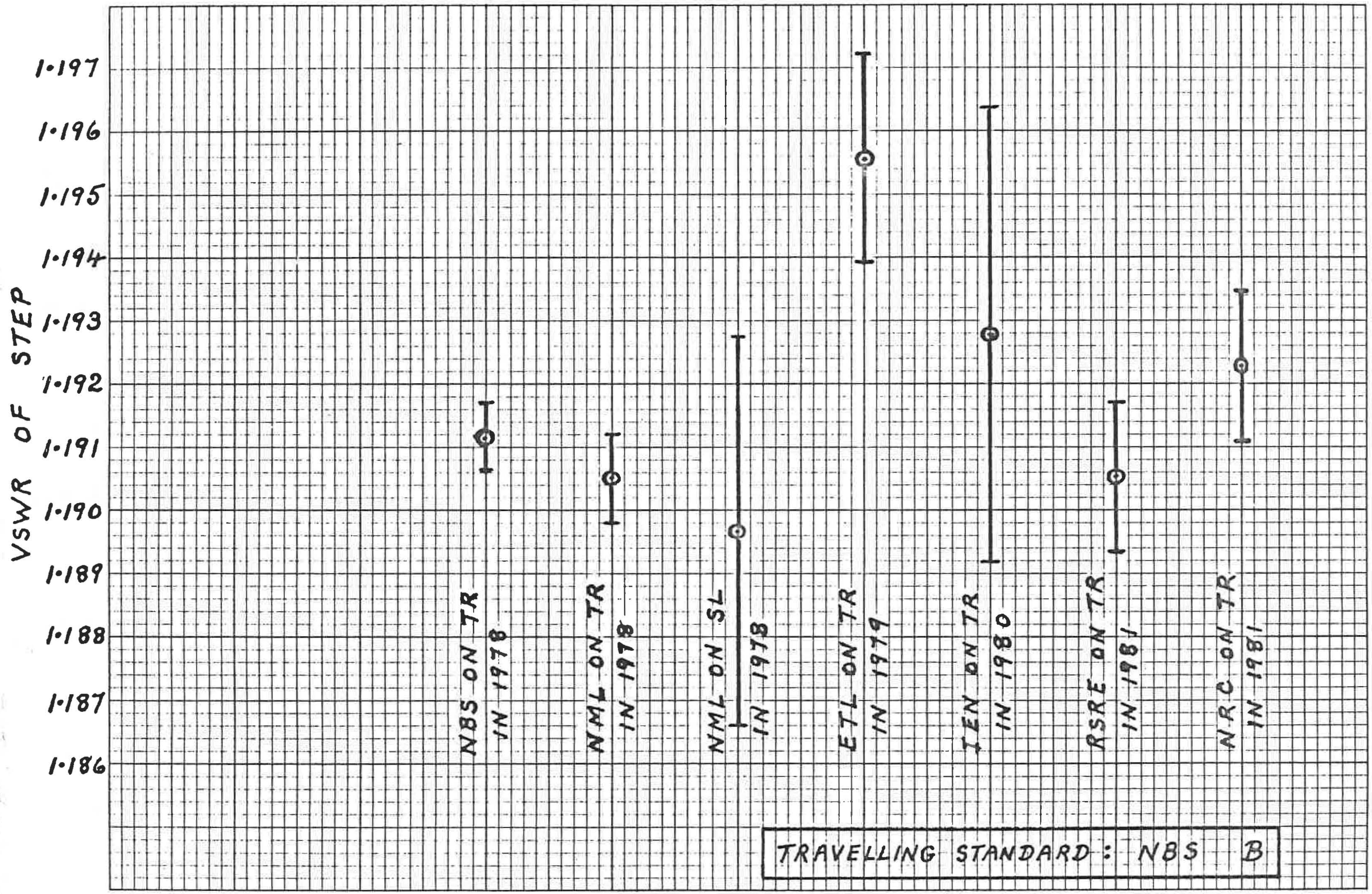

VSWR OF STEP
1·204
1·203
1·202
1·201
1·200
1·199
1·198
1·197
1·196
1·195
1·194
RSRE ON TR IN 1978
RSRE ON SL IN 1978
NBS ON TR IN 1978
NML ON TR IN 1978
NML ON SL IN 1978
ETL ON TR IN 1979
IEN ON TR IN 1980
RSRE ON TR IN 1981
NRC ON TR IN 1981
TRAVELLING STANDARD: RSRE 1·2

FIG. 3



VSWR OF STEP
1·197
1·196
1·195
1·194
1·193
1·192
1·191
1·190
1·189
1·188
1·187
1·186
NBS ON TR IN 1978
NML ON TR IN 1978
NML ON SL IN 1978
ETL ON TR IN 1979
IEN ON TR IN 1980
RSRE ON TR IN 1981
NRC ON TR IN 1981
TRAVELLING STANDARD : NBS B

FIG. 4

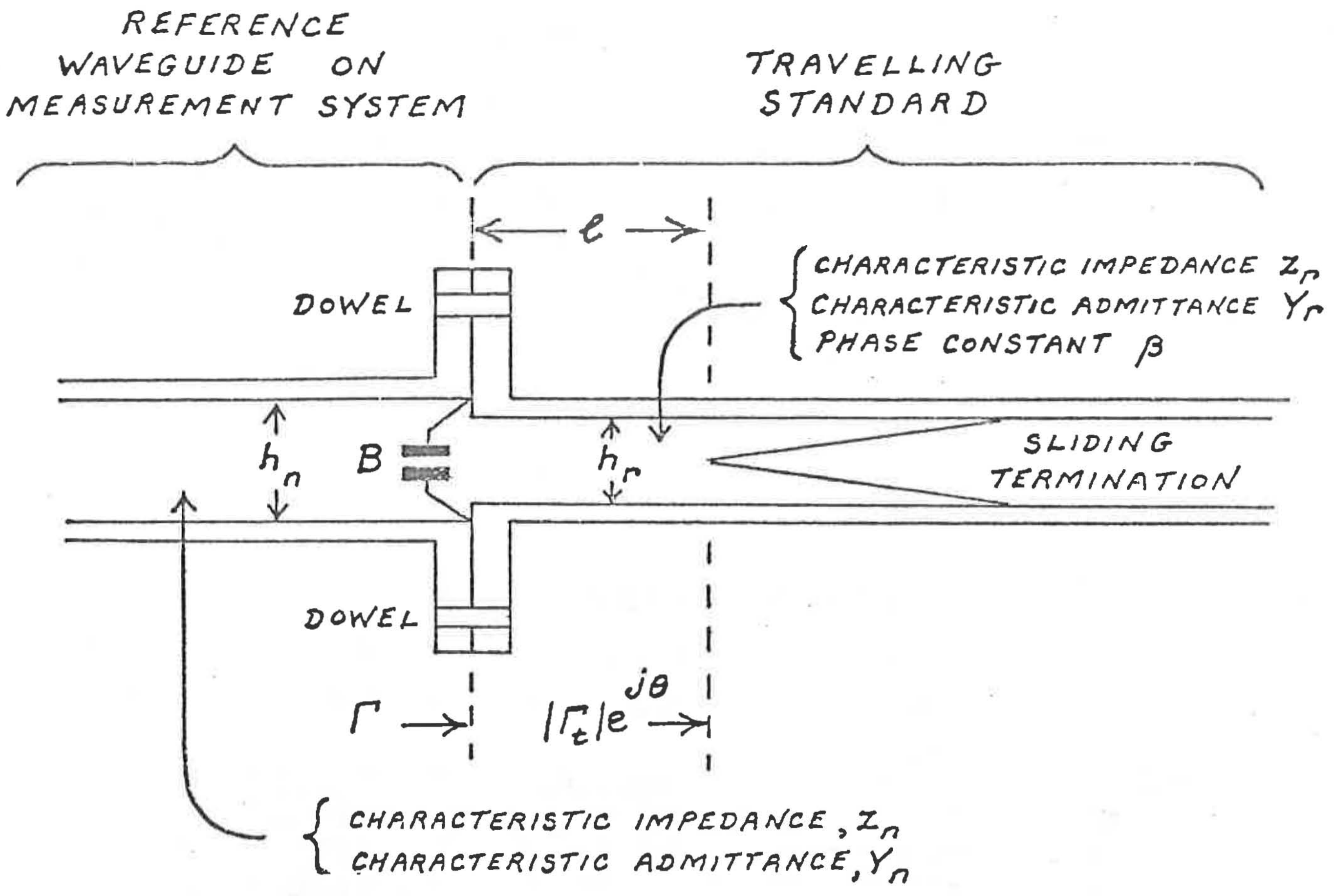


FIGURE 5. TRAVELLING STANDARD CONNECTED TO REFERENCE WAVEGUIDE ON MEASUREMENT SYSTEM

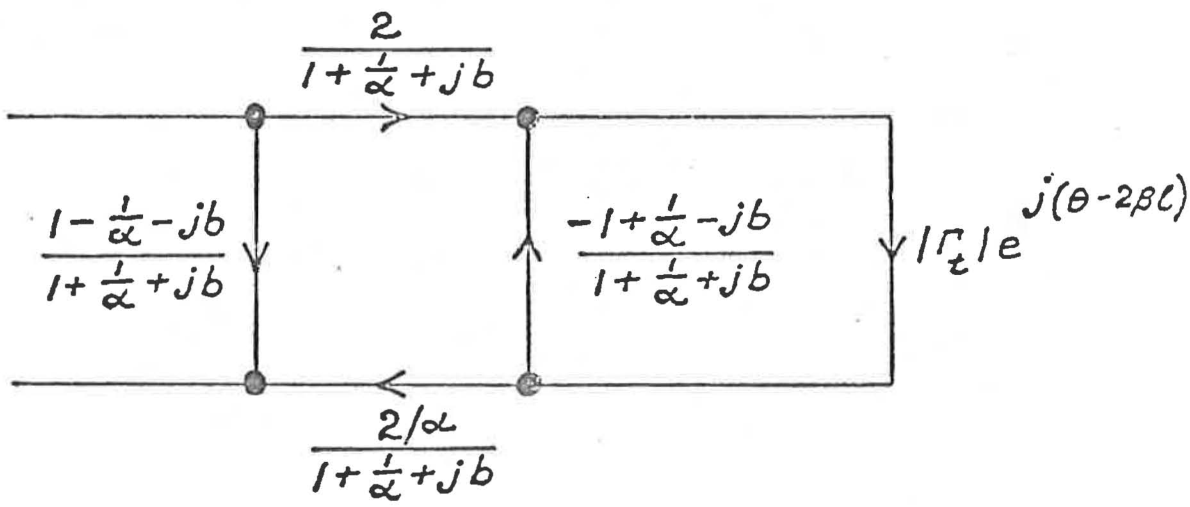


FIGURE 6. SIGNAL FLOW GRAPH FOR STEP AND SLIDING TERMINATION

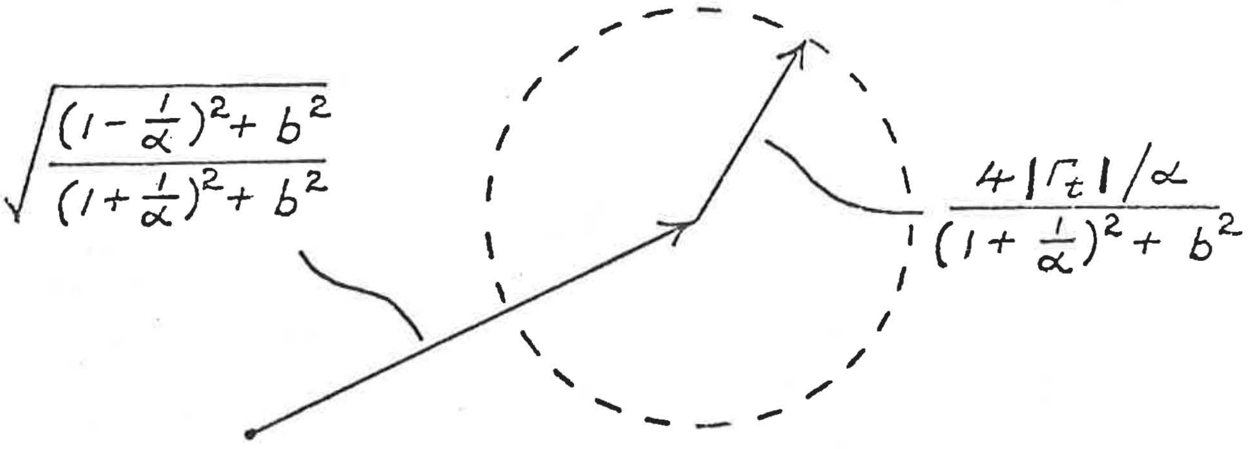


FIGURE 7. VECTOR DIAGRAM SHOWING THE TWO SIGNIFICANT COMPONENTS OF THE REFLECTION COEFFICIENT.

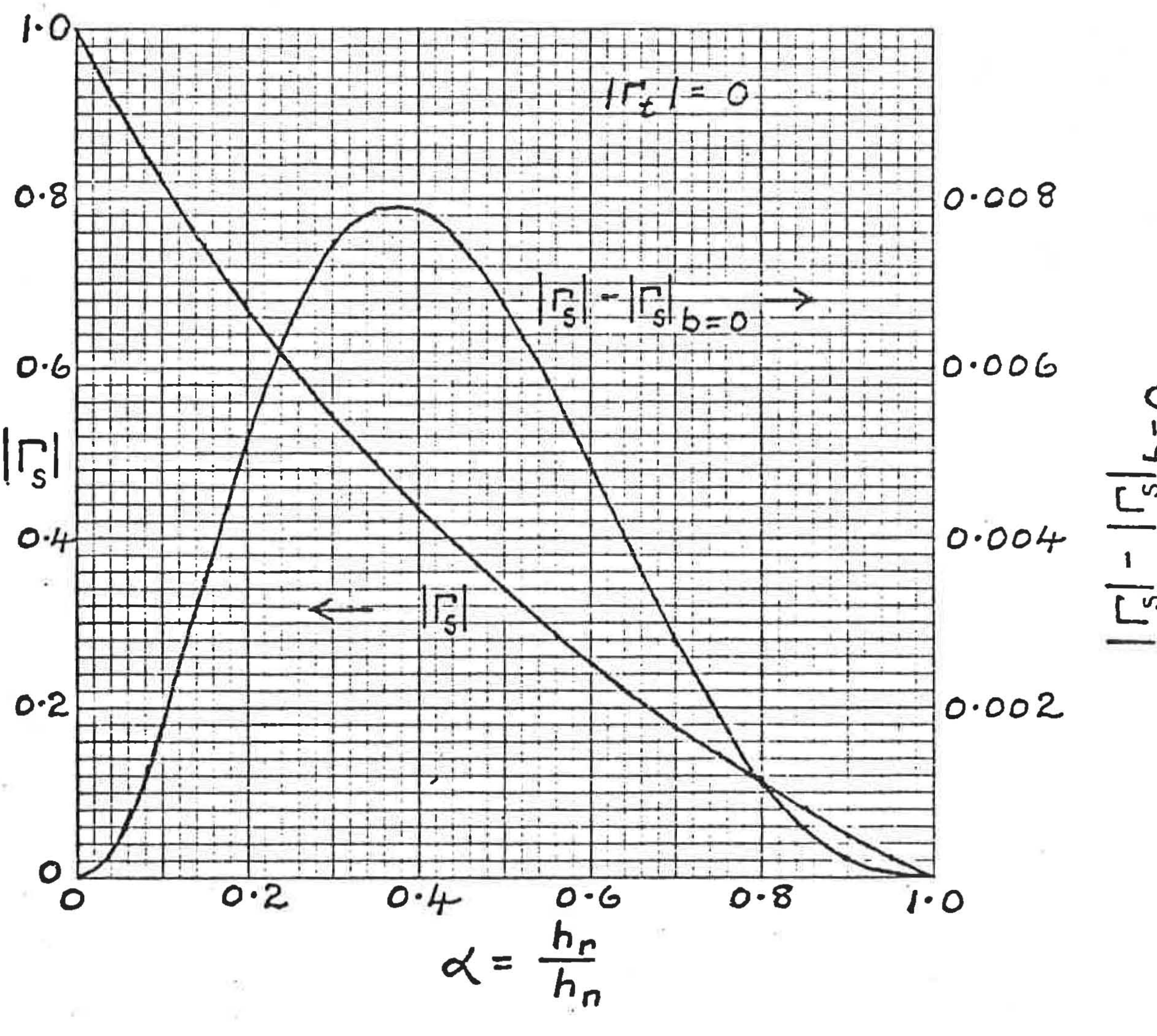


FIGURE 8. VARIATION OF $|\Gamma_s|$ AND $|\Gamma_s| - |\Gamma_s|_{b=0}$ WITH α