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Measurements of the impedance uniformity of radio frequency cables by complex and scalar methods

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Summary. The inhomogeneity of the characteristic impedance (structural return loss) of RF cables can be expressed by the input reflection factor of the cable as function of frequency. Random's distributed inhomogeneities of the cable geometry result in irregularly distributed reflection factors of statistical nature without any significant peaks. Regularly spaced arrays of small identical inhomogeneities produce resonant like sharp peak reflections at discrete frequencies. Conventional bridge or coupler measurement circuits do not allow to distinguish between set-up (bridge and connector) reflection errors and cable reflections. A modification of a scalar or complex set-up by introducing an additional phase variable offset reflection enables to separate the inherent reflection errors of the bridge, connections and cable end load from the cable reflections, even for the measurement of low loss or short length cables.

1 Introduction

One major item for quality specification of a RF cable is the inhomogeneity of the characteristic impedance, causing what is often designated as 'structural return loss'. This inhomogeneity can be evaluated by measuring the input reflection factor of the cable as function of frequency, the relatively long cable being terminated by a matched load. The indispensible interface to the connector equipped test set-up is always a cable connector, which produces its own reflection error. In a well-designed measuring set-up-connector-cable system, the reflections from the set-up (residual directivity of a bridge or coupler) and test connection set-up/cable will often be of the same order of magnitude as that of the cable alone.

2 Cable reflection types

In general, two significant types of reflections of a RF cable are distinguished:

Type I. Structural reflections caused by random's distributed inhomogeneities of the cable geometry or of the dielectric constant, yielding a curve of irregularly distributed reflection factors of statistical nature as function of frequency without any significant peak reflections.

Type II. Peak or resonant reflections caused by a regularly spaced array of small identical inhomogeneities along the cable. The waves reflected at frequencies for which $1 = n\lambda/2$ (1 = distance of irregularities, λ = wavelength in cable, n = integer) add to resonance like sharp peaks, corresponding to a resonance with high Q at the input of the cable. Their magnitude often exceeds by far the reflection of type I.

In real cables, the combination of both types I and II also exists, creating multiple peak reflections.

3 Measurement possibilities

In conventional scalar bridge or directional coupler measurement circuits *(fig. 1)*, the above mentioned test port plus cable input connector reflection errors sum up to $\bar{r}_b$ and cannot be distinguished from the cable reflections $\bar{r}_c$. This becomes especially evident at higher frequencies.

It is, therefore, necessary to apply other methods with error recognition possibilities. The complex plane-network-analyzer (CNA) is a convenient, precise but expensive solution with one major drawback:

It is easy to subtract the residual input error reflection phasor $\bar{r}_b$ visually (or by calculation) from the measured sum reflection factor curve $\bar{r}_b + \bar{r}_c$ in the polar display of the CNA. But it is cumbersome to analyze the frequency behaviour of the cable reflection $\bar{r}_c$ over wide frequency ranges because a frequency axis cannot be displayed in the complex reflection plane (fig. 3).

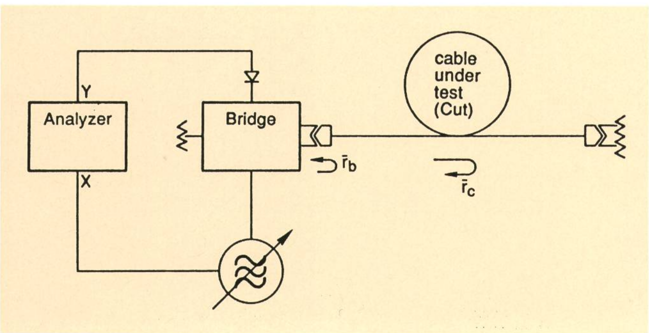


Fig. 1
Conventional bridge set-up

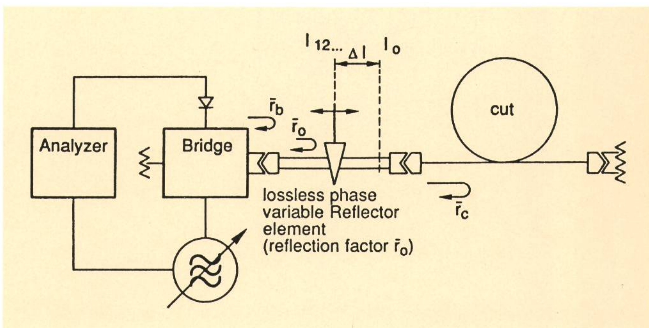


Fig. 2
Bridge, offset reflector set-up

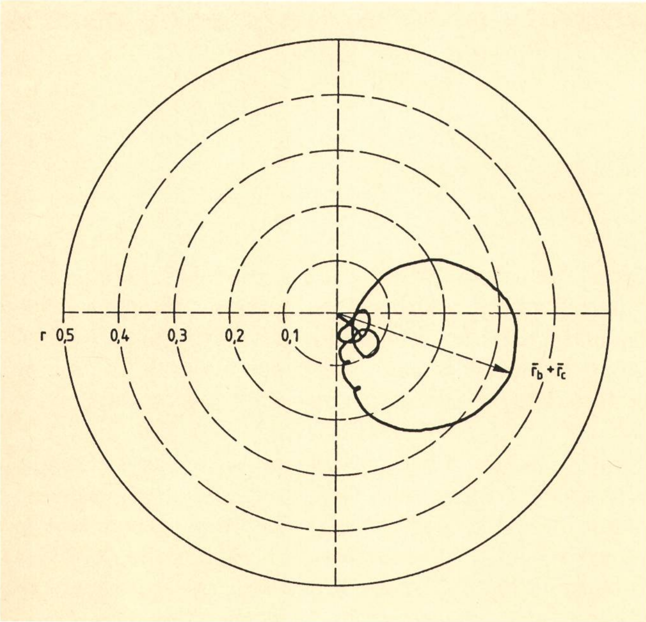


Fig. 3
Complex reflection factor of 50 m RG2/4/U cable with one resonance peak reflection between 2.3 GHz and 2.5 GHz

4 Addition of a variable phase offset reflection to the complex measurement circuit

Due to the insertion of a variable phase offset reflection $\bar{r}_o$ between the bridge test port and the cable input connector *(fig. 2)*, the total reflection sum $\bar{r}_b + \bar{r}_c$ of *figure 3* will be moved away from the centre (r = 0) of the polar display according to the new phasor sum $\bar{r}_o + \bar{r}_b + \bar{r}_c$ and can be turned around the centre as a function of the phasing position of the offset reflector (the phase relationship between $\bar{r}_b$ and $\bar{r}_c$ in respect to the cable input port remaining unchanged *(fig. 4)*). The *magnitudes* of the reflection sum $\bar{r}_o + \bar{r}_b + \bar{r}_c$ can be plotted in a diagram with *reflection magnitude* as ordinate versus *frequency (fig. 5)*. The minimum and maximum values a′, b′, c′, d′, e′, f′, g′, h′, in figure 5 remain well within the CNA accuracy of the dotted line magnitudes a, b, c, d, e, f, g, h in figure 4. This shows that the *worst case reflection factor magnitude* of every peak reflection can be found and extracted from a *complex* or *scalar* measuring set-up by introducing a variable phased offset reflection in the circuit.

A sufficient number of curve plots with offset phase as parameter must be taken (~ 6 plots) to make sure that the *worst case phase condition* for the peak reflections appears at least on one plot (curve x′....x′ in fig. 5). The reflection factor of the pure cable, worst condition, is then the largest difference $r_{cmax} = r_{max} - r_{min}$ within the measured frequency range.

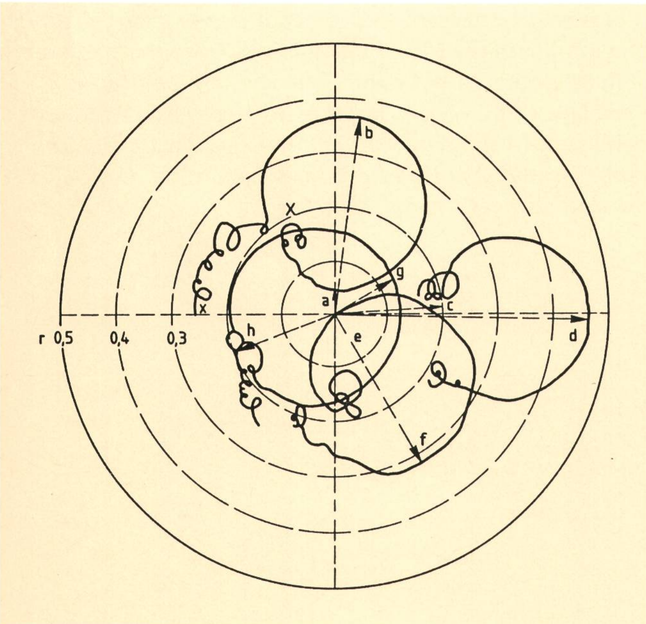


Fig. 4
Same cable as above, peak resonance reflection plus different phased offsets

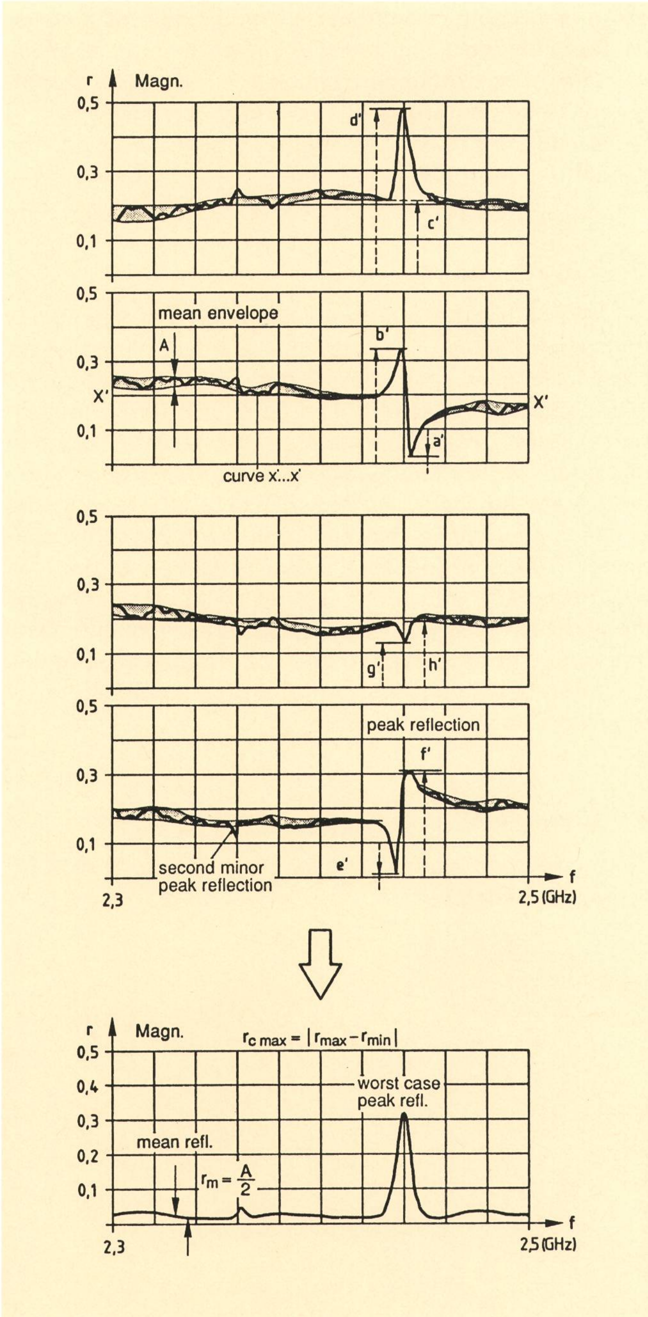


Fig. 5
Worst case reflection factor magnitude of the same cable: 4 upper diagrams with offset, lower diagram reflection factor extracted

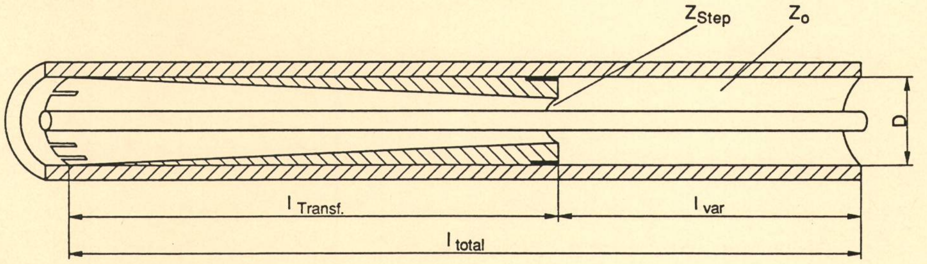


Fig. 6
Variable phase offset reflector element, overall length l_{total} ~ 500 mm, adjustable length l_{var} = 100 mm
Z-transformation length l_{Transf} ~ 300 mm
Zo = 50 Ω (N-connectors) Z_{step} = 33.3 Ω, resulting reflection factor r = 0,2 from 200 MHz to 18 GHz
D = 7,0 mm Ø

5 Test set-up in details

A practical set-up using a bridge or directional coupler is shown in figure 2. The offset reflector element consists of a longitudinal adjustable impedance step, mounted in an almost lossless coaxial air line, according to *figure 6*. The maximum adjustment length should be at least one quarter of a wavelength at the lowest measurement frequency (this maximum length can be increased by inserting additional air lines or rigid cables length between the cable under test [CUT] and the offset reflector element).

The scalar analyzer should display the reflection factor in a linear mode, because the extraction of the pure cable reflection is done by subtracting $r_{max} - r_{min}$ values from the several $\bar{r}_b + \bar{r}_o + \bar{r}_c$ versus frequency plots with the offset reflection phase positions as parameter. The linear reflection magnitude display can also serve to maximise every resonance peak reflection on the screen to its worst case condition whilst moving the phase of the offset reflector. This reduces the number of needed X-Y plots. If only return loss [dB] display is available, a reflection factor scale grid has to be drawn to allow easy extraction of the final cable reflection values.

6 Test procedure

a) Set swept frequency range (max. relative range 1:3.16). Short the bridge test port and terminate the bridge reference port with a precise load of nominal impedance value (the reference load is already included, when a directional coupler is used). Plot a reflection factor calibration grid (ordinate), using the internal range of the employed scalar analyzer or a variable attenuator between bridge and detector part.

b) Insert the offset reflector element and connect the (CUT). Terminate the cable with a precise load ($r_{load} \leq 0.05$). The cable insertion loss should be at least 10 dB at the lowest test frequency, because about 10 dB are necessary to allow to build up the maximum magnitude of a resonance peak reflection (if cable loss is less than 10 dB, see section 7).

Record reflection factor versus frequency curves with different phase positions of the offset reflector element (according to fig. 8 and note 3).

c) Draw the envelope contours according to figure 5 and extract r_c from the differences $r_{max} - r_{min}$.

The ordinate span of the envelope represents two times the *average cable reflection factor* as function of frequency (type I reflections) r_m = A/2 (of fig. 5).

The peak reflection difference, taken from the curve which shows the largest deviation of the reflection magnitude (in positive, negative, or positive to negative direction from the mean value), corresponds to the *worst case type II peak reflection factor* at that particular frequency (similar to the max. in fig. 5, curve x'....x').

Notes

1. Cable resonance peak reflections may be extremely narrow: It must be verified that the indicating or recording devices properly follow these fast variations. If fixed frequency step systems are used, the maximum step spacings must be $\Delta f \leq 1$ MHz.

2. Although it is recommended to use an offset reflection with a reflection factor of $r_o \sim 0.20$ *(fig. 7)* to exclude measuring ambiguities, even $r_{cpeak} > 0.20$ can be measured correctly, if the two phasors $\bar{r}_o$ and $\bar{r}_c$ are ap-

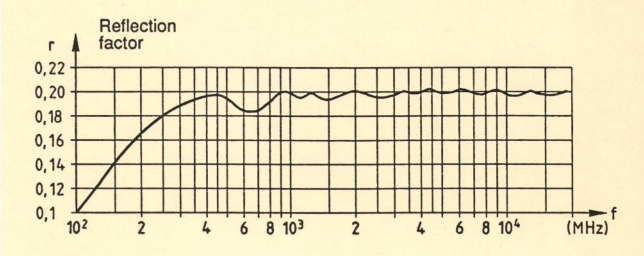
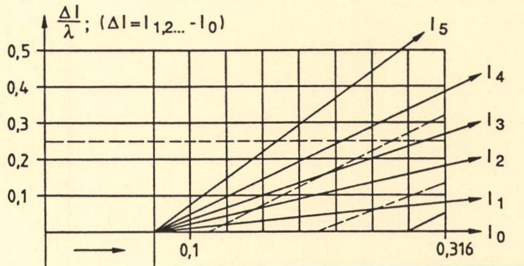
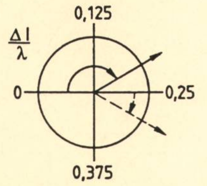


Fig. 7
Variable phase offset reflector, reflection factor magnitude from 100 MHz to 18 GHz





f (GHz)		l_0	l_1	l_2	l_3	l_4	l_5
		(mm)					
0,1	0,316	0	79	180	255	365	503
0,316	1	0	25	54	80	114	166
1	3,16	0	7,9	18	25,5	36,5	50,3
3,16	10	0	2,5	5,4	8	11,4	16,6

Fig. 8
Offset impedance step displacement positions for worst case reflection evaluation (6 measurement cycles $l_0 ... l_5$)

proximately equally phased (which is to be achieved by adjusting the phase of the offset reflection at a position such that the highest maximum value of the measured reflection appears).

3. Diagram *figure 8* shows graphically how many different phase positions must be chosen within a given relative frequency range of 1 to 3.16 to ensure the worst case peak reflection of a cable. In the case of using a

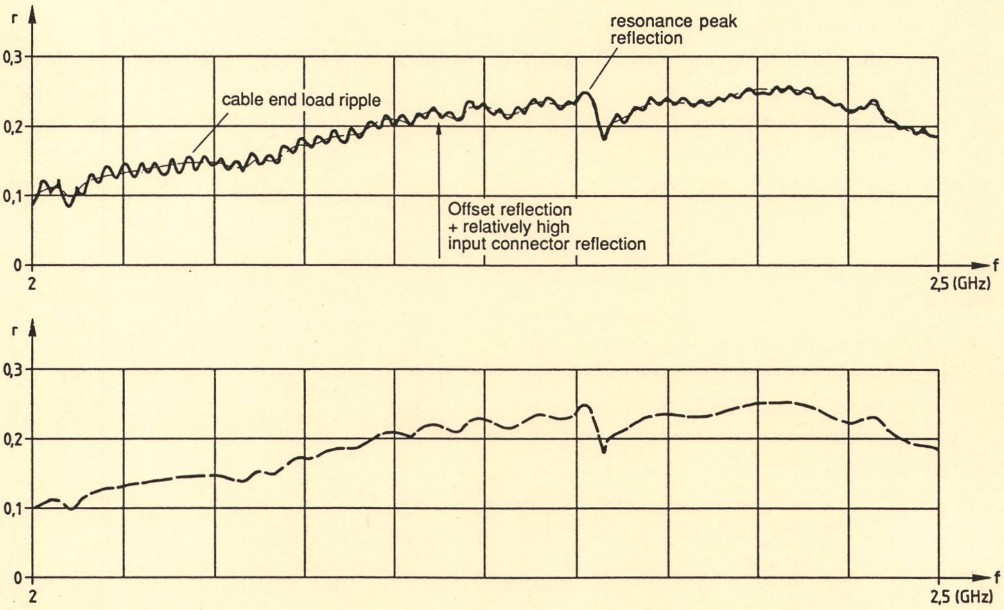


Fig. 9
10 m RG58/U, attenuation < 10 dB, lower diagramm 'cleaned' from terminating load reflection influence

linear mode display of the reflection factor, one X-Y plot per peak resonance reflection is enough, because maximising of the worst case is done by observing the magnitude during the change of the offset reflector phase.

4. The insertion of the 50 cm long offset reflector element between bridge test port and cable input connector creates a phase delay between the bridge error reflection and the offset reflection, producing a slowly varying reflection ripple. The envelope contour to be drawn according to figure 5 has at least to follow this ripple variation to guarantee a correct elimination of the influence of errors, created by the cable input connector.
5. The absolute magnitude of the offset-, bridge error- and cable input connector reflection combination does not affect the overall accuracy because a *subtraction* technique for signal extraction is used.
6. The influence of mismatch loss and line attenuation of the variable phase reflection on the calibration accuracy is practically negligible. But if highest precision is needed, an additional air line with a calibrated and known mismatch as a load, connected to the offset reflector instead of the (CUT), may be used to verify the calibration error for final correction.

7 Measurement of low loss or short length cables (cable attenuation < 10 dB)

The influence of reflections of the far end connector and termination is no more negligible for the cable reflection measurement of large size, low loss cables or relatively short cable lengths. Utilization of the offset method and of averaging out the fastest turning reflection ripple allow to eliminate the cable end error reflection. The dotted average curve *(fig. 9)* represents the 'cleaned' cable reflection response without any contribution of the cable end connector/termination reflection. It may even be convenient to increase the far end reflection value to a discernible amount (e.g. by loosing the end connection) which facilitates the averaging procedure. After averaging, proceed according to section 6c).