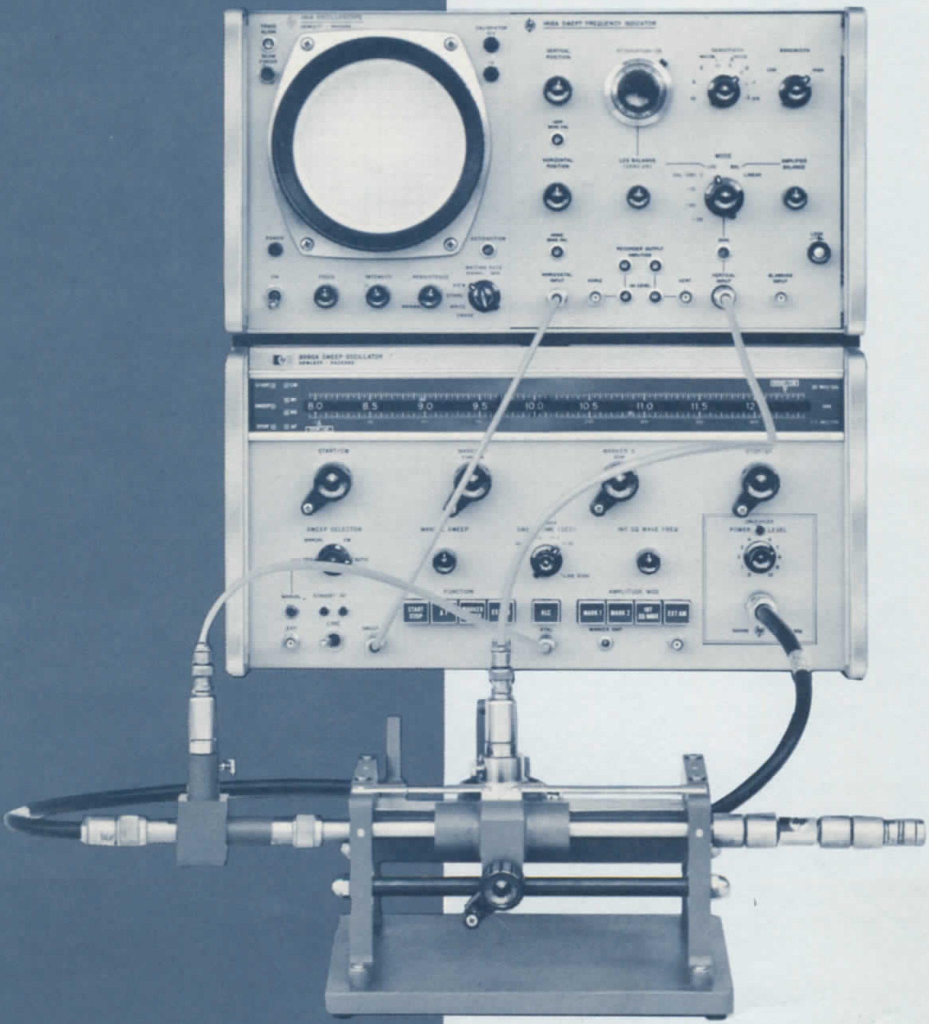
HEWLETT hp PACKARD

Swept SWR Measurement in Coax

application note 84

1 FEB 67

- Slotted Line Accuracy
- 2 to 18 GHz



An important new swept-frequency technique permits quick and accurate measurements of SWR in coaxial systems up to 18 GHz.

COAXIAL COMPONENTS are lighter and smaller and generally have much wider bandwidths than equivalent waveguide units. However, despite these advantages of coax, its use has until recently been limited to frequencies below a few GHz, mainly because the best 7-mm connectors available — the type N connectors developed during World War II — have had excessive standing wave ratios at high frequencies. Now, as a result of the urging of the IEEE Subcommittee on Precision Connectors and the ASA C83.2 Committee, the microwave industry has developed precision 7-mm coaxial connectors which will operate at frequencies up to 18 GHz with respectably low SWR.[1] Consequently, coax can be expected to replace waveguide in this frequency range, at least for those applications where the lower insertion loss and higher power-handling capabilities of waveguide are not needed.

Swept-frequency SWR-measuring techniques for coaxial systems, chiefly reflectometer methods, have also been unsatisfactory at frequencies above 2 or 3 GHz, not only because of the high SWR of the connectors, but also because of the low directivity of directional couplers at these frequencies.[2] Fortunately, there is a new swept-frequency technique for measuring SWR in coax.[3] This method employs a slotted line fitted with the new connectors, and its accuracy is excellent from 2 GHz to 18 GHz. Hence the method is suitable for testing all of the new coax components.

As might be expected with a new technique, the convenience and accuracy of the slotted-line method are greatest when equipment is used which has been specially designed for the application. In this instance only one special item is needed, a slotted-line sweep adapter designed and built by the *-hp-* Microwave Division. The other instruments needed are general-purpose *-hp-* instruments, although one of them, an 18-GHz, low-SWR slotted line fitted with the new connectors, is also a new development. Besides the slotted line sweep adapter and the slotted line and its carriage, the slotted-line method requires a sweep oscillator and an oscilloscope. The *-hp-* variable-persistence oscilloscope with the swept-frequency indicator plug-in turns out to be ideally suited for this application.

SWEPT-FREQUENCY SWR MEASUREMENT WITH A SLOTTED LINE

The equipment setup for the new SWR-measuring technique is illustrated in Fig. 1. The sweep oscillator output is connected to the input of the slotted-line sweep adapter, which is essentially a short piece of slotted line with a stationary detector probe. The output of the adapter's probe is connected to the ALC input of the sweep oscillator, forming a power-leveling feedback loop. The slotted line is placed between the slotted-line sweep adapter and the device whose SWR is being measured, and the output of the detector probe of the slotted line goes to the vertical input of the oscilloscope. The horizontal input of the oscilloscope is taken from the sweep output of the sweep oscillator.

To permit the slotted-line probe output to be displayed on the oscilloscope with sensitivities as high as 0.5 dB/cm, the sweep-oscillator output must be held reasonably constant as the frequency varies. The function of the slotted-line sweep adapter is to level the oscillator power output in such a way that the voltage output of the slotted-line probe remains constant with frequency, except for the variations caused by the SWR being measured. The adapter consists of a short length of slotted line, a well-matched 6-dB attenuator, and two *matched* detector probes, one for the adapter and one for the slotted line. Matching the two probes makes the frequency response of the adapter probe, which samples the oscillator power, exactly equal to the frequency response of the slotted-line probe. Thus the oscillator power is adjusted to keep the output of the slotted-line probe constant with frequency. The 6-dB attenuator improves the frequency response, probe isolation, and impedance match of the adapter.

The slotted line shown in Fig. 1 is a new precision 'slab-type' line with very well matched transitions at each end. Connectors can be either the precision 7-mm type or improved type N connectors which also operate up to 18 GHz but have slightly higher SWR. With the 7-mm connectors, the residual SWR of the slotted line varies from 1.02 at 2 GHz to 1.04 at 18 GHz. With

[1] SWR $<1.003 + 0.002 \times$ frequency (GHz). See IEEE Transactions on Instrumentation and Measurement, Vol. IM-13, No. 4, December, 1964, p. 285.

[2] Hewlett-Packard Application Note 65, 'Swept Frequency Techniques.'

[3] G. V. Sorger and B. O. Weinschel, 'Swept Frequency High Resolution VSWR Measuring System.' Weinschel Engineering Company Internal Report 90-117, 723-3/66, March, 1966.

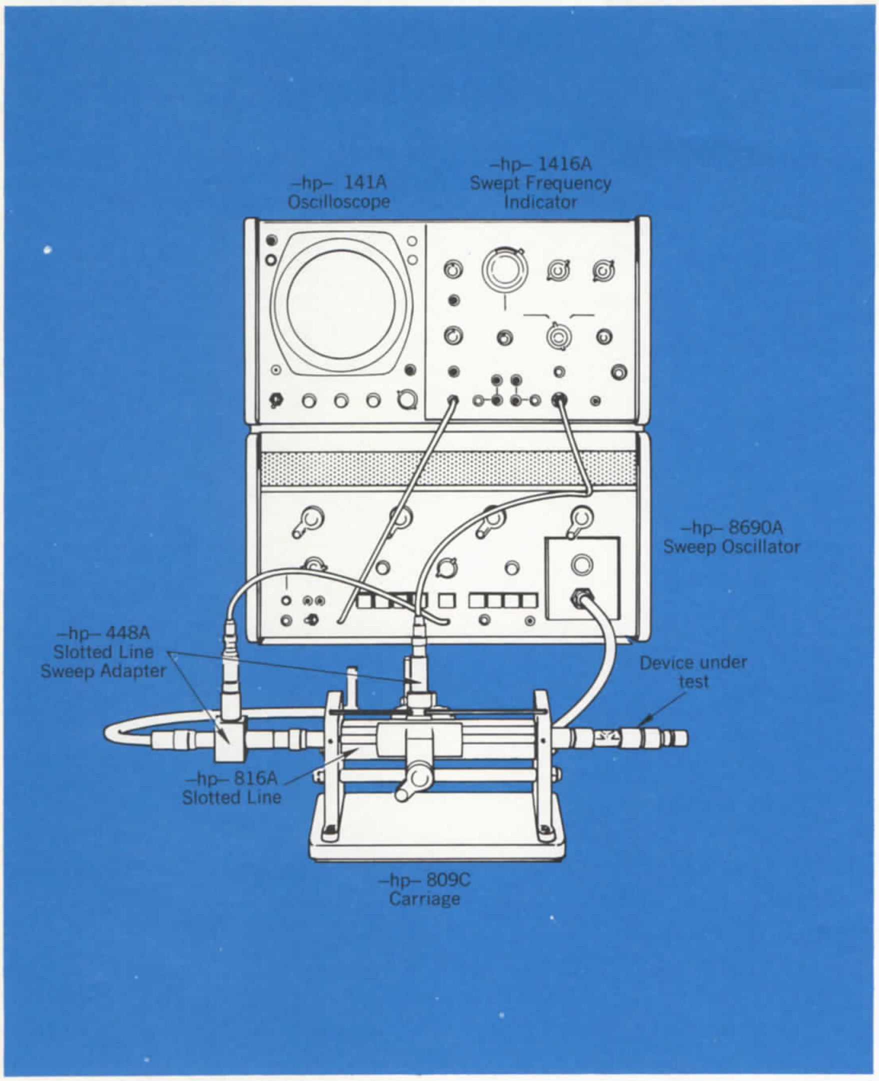


Fig. 1. *Equipment setup for swept-frequency SWR measurements described in text. Method is highly accurate from 2 GHz to 18 GHz.*

the type N connectors, SWR is 1.03 at 2 GHz and 1.06 at 18 GHz.

Although any oscilloscope can be used for displaying the slotted-line output, the variable persistence and storage feature of the one shown in Fig. 1 is particularly useful because it permits the unknown SWR to be read directly from the display. If a non-storage oscilloscope is used, the SWR data has to be photographed, using a time exposure. The swept-frequency-indicator plug-in is also a great convenience because it has a logarithmic vertical amplifier which makes it possible to read SWR directly in dB.

OPERATION AND THEORY

Although in operation the sweep oscillator will be swept internally, the new SWR-measuring technique can be explained best by pointing out what happens at a fixed frequency. Fig. 2 is a series of oscillograms taken with the equipment of Fig. 1. In Fig. 2, points on the horizontal axis correspond to frequencies between 8.2 and 12.4 GHz. The vertical scale factors are all 0.5 dB/cm.

Fig. 2(a) shows what happens at a single frequency when the slotted-line carriage is moved over at least one-half wavelength: the oscilloscope traces out a vertical line whose length is equal to the SWR (in dB) of the device being tested. That this is true can be shown as follows.

Transmission-line theory tells us that a uniform, lossless line terminated in an impedance which is not equal to its characteristic impedance will have two waves traveling on it in opposite directions. Besides the incident wave E_i traveling towards the load, there will be a reflected wave E_r going in the opposite direction. The incident and reflected waves will interfere and form a standing-wave pattern on the line. If the voltage on the line is measured, it will be found that there are points of maximum voltage

$$E_{max} = |E_i| + |E_r|$$

and points of minimum voltage

$$E_{min} = |E_i| - |E_r|$$

The maxima and minima will be one-half wavelength apart.

Standing-wave ratio is defined as

$$SWR = \frac{E_{max}}{E_{min}}$$

If the slotted-line carriage of Fig. 1 is moved over at least one-half wavelength, the oscilloscope spot will move up and down between E_{max} and E_{min}, and will trace out a line like that shown in Fig. 2(a). If the oscilloscope has a linear vertical amplifier, E_{max} and E_{min} can be read from the display and the SWR can be calculated. However, it is much better if the oscilloscope has a logarithmic vertical amplifier, because the oscilloscope will then display a vertical line with length

$$\log_{10}E_{max} - \log_{10}E_{min} = \log_{10}\frac{E_{max}}{E_{min}}$$
$$= \log_{10} SWR.$$

If the vertical amplifier is calibrated in dB/cm the SWR in dB is simply the length of the vertical line traced out on the display as the slotted-line carriage is moved over one-half wavelength or more. The SWR can easily be read from the trace and then converted to a voltage ratio by the formula

$$SWR = \log^{-1}\left(\frac{dB}{20}\right)$$

For the single frequency of Fig. 2(a), the SWR is about 0.5 dB or 1.06. Notice that when the display is logarithmic, only the vertical length of the trace is significant, and the baseline does not have to be displayed. Fig. 2(b) shows a series of traces corresponding to SWR measurements at several fixed frequencies.

Now if the sweep oscillator is swept internally several times per

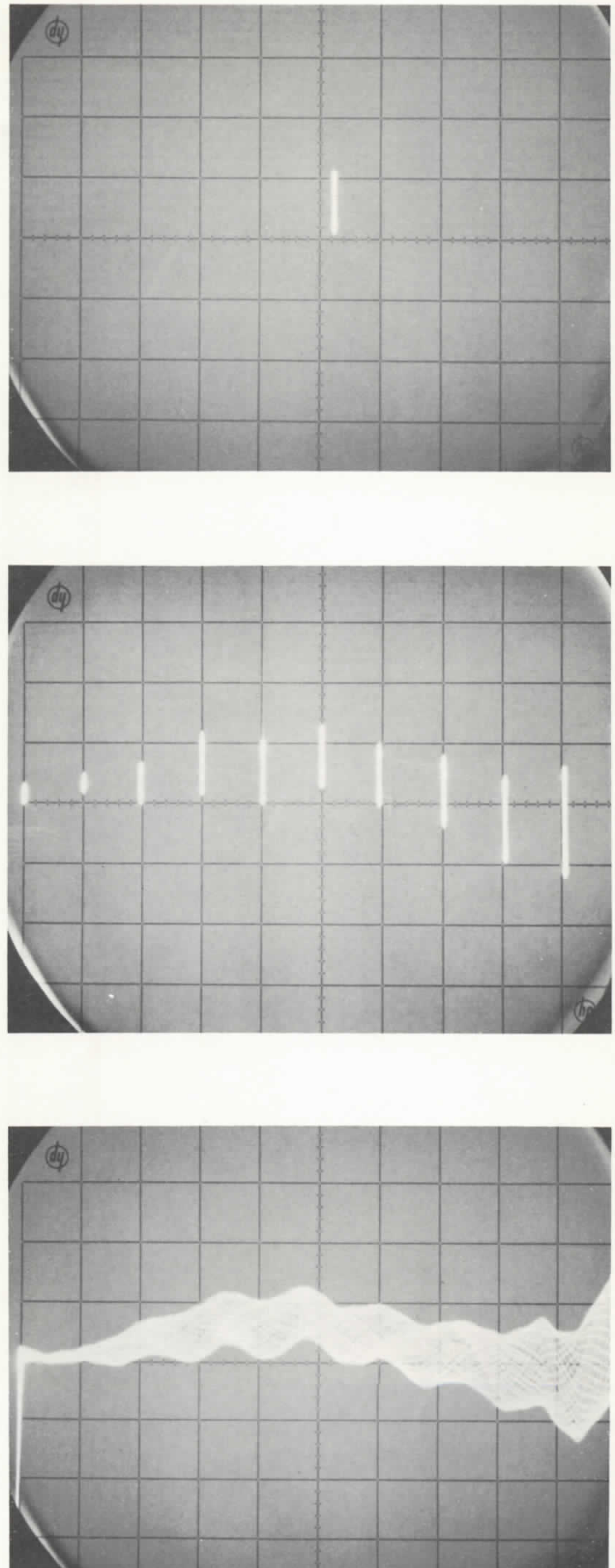


Fig. 2. *Oscillograms made with setup of Fig. 1, showing measurement of SWR of a load.*

(a) *At single frequency, trace moves up and down as slotted-line carriage moves over at least one-half wavelength. With logarithmic display unit, length of vertical line is SWR in dB.*

(b) *Multiple exposure showing SWR measurements at several fixed frequencies across band.*

(c) *Typical pattern produced by swept-frequency measurement. Vertical: 0.5 dB/cm; Horizontal: 8.2 to 12.4 GHz.*

second across the frequency band, and if at the same time the carriage of the slotted line is moved manually over at least one-half wavelength of the lowest frequency in the band, either a time exposure of the oscilloscope display or a stored pattern will look like Fig. 2(c). This technique, i.e., manually moving the slotted-line carriage while the oscillator sweeps automatically, is the normal one for making swept-frequency SWR measurements. It yields results like Fig. 2(c), in which the width of the pattern as a function of frequency corresponds to the SWR (in dB) of the device being tested.

ERRORS

Sources of error in the swept-frequency slotted-line SWR-measuring technique are as follows.

1. RESIDUAL SWR OF THE SLOTTED LINE. *This is the principal source of uncertainty and the limiting factor on the accuracy of the measurements. For the slotted line shown in Fig. 1, residual SWR (including the 'slope' of the slotted line, or the change in SWR with carriage position due to attenuation) is less than 1.03 to 12.4 GHz and less than 1.04 to 18 GHz, with the precision sexless 7-mm connectors. SWR with the improved type N male and female connectors is slightly higher. A residual SWR of 1.04 causes an uncertainty of ±2% in the measured reflection coefficient ρ, which is related to the measured SWR by the relation*

$$SWR = \frac{1 + |\rho|}{1 - |\rho|}.$$

2. SQUARE LAW ERROR OF THE CRYSTAL DETECTOR IN THE PROBE OF THE SLOTTED LINE. *The detector probes of Fig. 1 have square law errors which are specified to be less than 0.05 dB so long as the output voltage from the crystal is less than 5 mV. The oscilloscope can be used to check the probe output of the slotted line to make certain that it is within this limit over the entire frequency range. Square law error can then usually be neglected in comparison to the residual SWR of the slotted line. If desired, the probe can be calibrated by precision instruments and its error eliminated entirely.*

3. CALIBRATION ERROR OF THE OSCILLOSCOPE. *Specified error of the swept-frequency-indicator plug-in shown in Fig. 1 is less than 0.02 dB/dB. This error is also small enough to be neglected in comparison to the slotted-line SWR, but it may be eliminated if desired by calibrating the display unit.*

4. FINITE WIDTH OF THE OSCILLOSCOPE TRACE. *This should be measured and subtracted from the width of the finished SWR pattern of Fig. 2(c). Fig. 3 is an example of a single trace, showing its thickness.*

5. IMPROPER BANDWIDTH/SWEEP RATE COMBINATION. *The sweep rate of the sweep oscillator and the bandwidth of the swept-frequency-indicator plug-in (Fig. 1) are adjustable. If the bandwidth is too low or the sweep rate too high, some of the fine structure of the SWR pattern will be lost. Usually the widest bandwidth and a fairly high sweep rate give the best pattern, but the optimum combination can easily be determined experimentally, by keeping the slotted-*

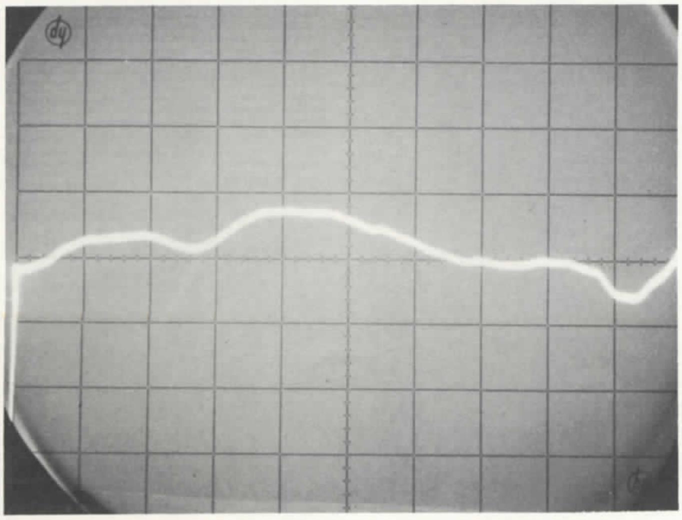


Fig. 3. *Oscillogram made with slotted-line carriage stationary, showing finite width of trace which must be subtracted from SWR measurements.*

line carriage stationary and adjusting the sweep rate and bandwidth for the most crooked trace.

6. EXCESSIVE PROBE PENETRATION. *To minimize reflections from the probe of the slotted line, probe penetration should be the minimum amount consistent with the sensitivity of the display unit. This source of error is not significant in the setup of Fig. 1 because of the high (50 μV) sensitivity of the display unit and the high power (>40 mW at 18 GHz) available from the sweep oscillator.*

SLIDING LOAD FOR TWO-PORT DEVICES

When the SWR being measured is at one of the ports of a two-port device (e.g., a section of line, a connector, or an attenuator), the 'unmeasured' port of the device must be terminated in its characteristic impedance. If the device under test has low loss (e.g., a line or a connector), the quality of the termination is very important, because any reflection from it will add vectorially to the voltage reflected by the device being tested.

In single-frequency SWR measurements and in swept-frequency reflectometer measurements where imperfectly-matched loads have been troublesome, it has become standard practice to use a 'sliding load' for a termination.[5] A sliding load is simply a length of line with a movable termination; it permits the phase angle of the voltage reflected by the load to be varied without changing the magnitude of the reflection. By manipulating the phase of the load reflection, it is possible to separate the voltage reflected by the load from the voltage reflected by the device under test.

By terminating a two-port device in a sliding load, load-reflection errors can be eliminated from the results of the swept SWR-measuring technique described in this article. The sliding load is *mechanically linked* to the slotted-line carriage, so the distance between the slotted-line probe and the sliding termination is constant.[6] This keeps a constant phase angle between the incident voltage E_i and the part of the re-

[5] J. K. Hunton and W. B. Wholey, "'The 'Perfect Load' and the Null Shift — Aids in VSWR Measurements,'' **Hewlett-Packard Journal**, Vol. 3, No. 5-6, Jan.-Feb., 1952.

[6] B. O. Weinschel, G. U. Sorger, S. J. Raff, and J. E. Ebert, 'Precision Coaxial VSWR Measurements by Coupled Sliding-Load Technique,' IEEE Transactions on Instrumentation and Measurement, Vol. IM-13, No. 4, December, 1964.

STEPHEN F. ADAM

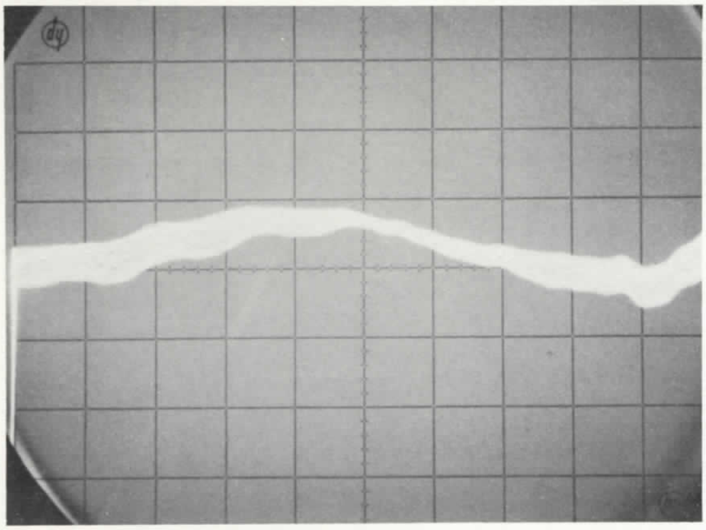
Steve Adam studied mechanical and electrical engineering at the Technical Institute of Budapest, Hungary. He holds a degree equivalent to an M.S. in electrical engineering.

Steve joined the –hp– Microwave Division in 1957, after several years as a research and development engineer in Budapest. At –hp– he contributed to the design of the 532-series Waveguide Wavemeters and the 382-series Rotary-vane Attenuators, and was project supervisor for the 536A and 537A Coaxial Wavemeters and the 8491A, 8492A, and 354A Coaxial Attenuators. He has several patents pending. He is now an engineering group leader in the –hp– Microwave Laboratory and has responsibility for the development of a number of passive components.

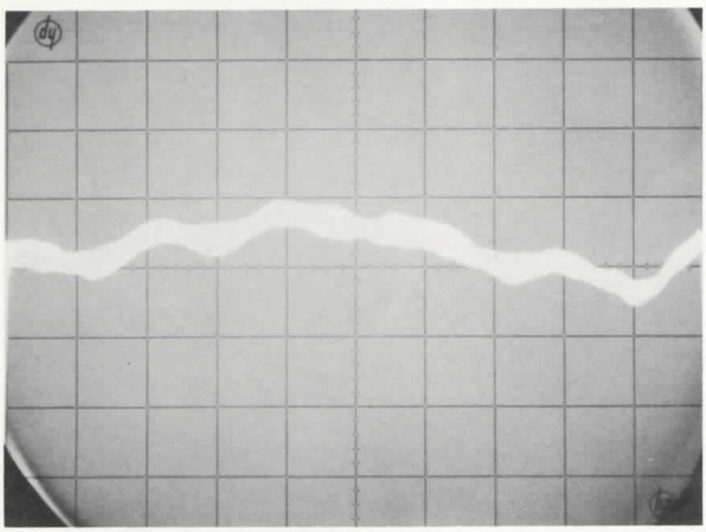
Steve is a member of IEEE and an instructor of microwave electronics at Foothill College. He has recently been elected to the Board of Directors of the Bay Area Council for Electronics Education, an advisory group made up of representatives of northern California colleges and industries. "Among our present efforts is a program for improving the mathematics background of high school graduates in order to provide our engineering schools with more capable freshmen," he says.

Reprinted Compliments of Hewlett-Packard Journal

VOL. 18, NO. 4 hp *DEC. 1966*



(a)



(b)

Fig. 4(a). *Typical pattern for swept SWR measurements on slotted line with fixed load.* (b) *SWR pattern for same slotted line with sliding load mechanically linked to slotted-line carriage. Linking load and carriage eliminates load mismatch errors. Vertical: 0.5 dB/cm; Horizontal: 8.2 to 12.4 GHz.*

flected voltage due to the sliding load (E_L). The width of the oscilloscope pattern is then

$$\log_{10} \frac{|E_i + E_L| + |E_r|}{|E_i + E_L| - |E_r|}$$

where E_r is the voltage reflected by the device under test. If, as is usually the case,

$$|E_L| << |E_i|,$$

then the width of the oscilloscope pattern is due principally to E_r and is an excellent approximation to the SWR being measured. The principal effect of the load reflection is to move the entire pattern up and down; the effect of E_L on the width of the pattern is negligible.

The oscillograms of Fig. 4 show how much the width of the oscilloscope pattern changes when a sliding load is linked to the slotted-line carriage instead of remaining stationary. This change represents an improvement in the accuracy of the measurement. In Fig. 4 the measured SWR was the residual SWR of the slotted line and its connectors. When the load and carriage were linked, the apparent SWR at 12.4 GHz changed from roughly 0.35 dB, or 1.04, to roughly 0.15 dB, or 1.02.

ACKNOWLEDGMENTS

The slotted-line sweep adapter, the slotted line, and the slotted-line carriage shown in Fig. 1 were designed by Lawrence B. Renihan. I am also grateful to Richard W. Anderson for many helpful suggestions.

—Stephen F. Adam

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5952-0916

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