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Performance of a Dual Six-Port Automatic Network Analyzer

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***Abstract*—Initial results of the performance of an experimental dual six-port automatic network analyzer operating in the 2–18-GHz range with thermistor-type power detectors are given. The imprecision in measuring reflection coefficients of one-port devices, or the scattering parameters of two-port devices is 4×10^{-5}, excluding connector repeatability. At 3 GHz, the imprecision in measuring attenuation varies from 0.0003 dB at low values of attenuation to 0.15 dB at 60 dB. The systematic error in measuring attenuation appears to be less than the imprecision. The systematic error in measuring reflection coefficient appears to be less than 0.0004. Additional systematic errors caused by changes in the calibration constants over a 20-week period were observed to be less than 0.003 dB in attenuation and less than 0.002 in reflection coefficient.**

I. Introduction

An EXPERIMENTAL automatic network analyzer (ANA) incorporating two six-port reflectometers has been constructed at NBS for measuring the network parameters of one-port and two-port devices from 2–18 GHz. The precision, accuracy, and stability of the ANA are now being investigated. Results obtained so far are summarized in this paper.

II. System Description

A block diagram of the dual six-port ANA is shown in Fig. 1. Measurements of the reflection coefficient Γ of one-port devices are made by connecting the termination to either six-port reference plane. The network parameters of a two-port device are measured by inserting the two-port between the two six-port reflectometers. The theory of operation and a description of the basic system have already been published [1].

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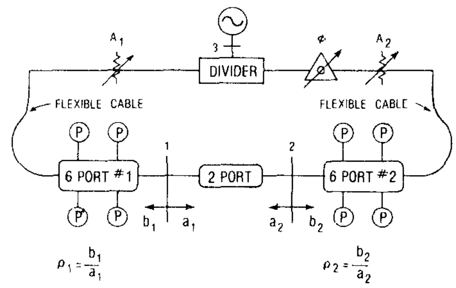

Fig. 1. Block diagram of a dual six-port automatic network analyzer, where *P* indicates power detector. When a termination is connected to either measurement plane, ρ_1 or ρ_2 becomes the usual reflection coefficient Γ_1 or Γ_2 of the termination.

The accuracy of a six-port measurement is primarily a function of the quality of the connectors, quality of the standard transmission line used in the calibration, and of the resolution, stability, and linearity of the four sidearm power detectors. Greatest accuracy has been obtained with NBS Type IV power meters [2] using thermistor type power detectors. The thermistor detectors are housed in an aluminum block whose temperature is held constant to 0.01°C. The present system has a phase-locked source whose output power is externally leveled. Connectors at the measurement planes are GPC-7. The system is controlled by a programmable calculator.

III. Calibration Techniques

The technique used to calibrate the dual six-port ANA is the "thru-reflect-line" (TRL) technique [4] augmented by including a nominal 10-dB pad in the set of measurements. The steps in the calibration are shown in Fig. 2 and outlined below.

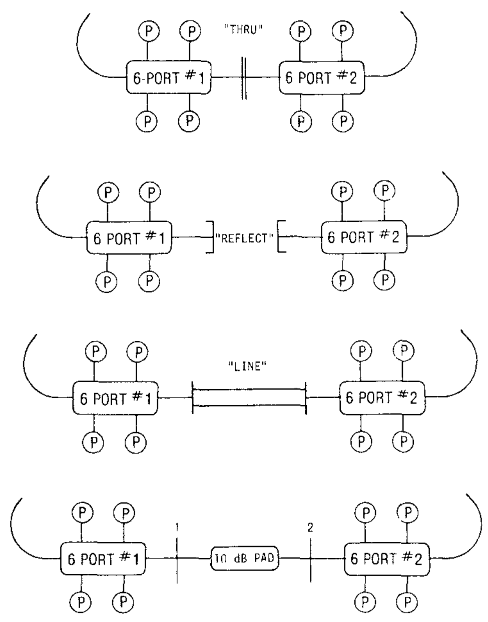

Fig. 2. The four different connections made in calibrating the NBS dual six-port ANA.

1) With the reference planes together, all sidearm power readings are recorded for the four different settings of phase shifter ϕ. The settings are such that a_2/a_1 at the common measurement plane has a magnitude approximately equal to 1 and phase angles of approximately 0°, 90°, 180°, and −90°.

2) If the connectors are sexless, a highly reflecting termination (such as a nominal short) of *unknown* Γ is connected first to one six-port measurement plane, and then the other. In each connection, the corresponding sidearm power readings are recorded.

3) Next, an unknown length of precision transmission line is inserted, and all sidearm power readings are recorded for the four different settings of the phase shifter as in step 1.

4) Finally, a nominal 10-dB pad of unknown attenuation is inserted, and all sidearm power readings are again recorded at the four different settings of the phase shifter.

The phase shift and loss through the phase shifter ϕ do not need to be known or be repeatable.[1] Neither do the phase shift and loss of the length of precision transmission line need to be known. However, the length of the line must not be too near a multiple of a half-wavelength at the various frequencies of operation.

The six-port calibration constants are calculated using all 104 power readings. Using these constants and the appropriate power readings, the Γ of the highly reflecting termination, the complex propagation constant of the line, and the S-parameters of the 10-dB pad are also obtained.

If the connectors are not sexless, the "thru-short-delay" [3] calibration technique would be used, again augmented by including a nominal 10-dB pad in the set of measurements.

[1]These settings do need to be repeatable if the ANA is being calibrated to measure the phase angles ψ_{12} and ψ_{21} of nonreciprocal two-ports [1].

A. Measuring a Short

The TRL calibration technique could possibly be the most accurate experimental method for determining the reflection coefficient of a nominal short having sexless connectors. The highly reflecting termination which is connected to both measurement planes in step 2) can, of course, be a nominal short. In this case the calibration yields a value of Γ for the short. Twenty nine repeated calibrations over a 20-week period of the dual six-port ANA at 3 GHz using a GPC-7 flat short, yield a reflection coefficient for the short of 0.99965 ($s=0.00035$) and 179.92° ($s=0.06$). Each s is the computed standard deviation based on these 29 measurements. In addition to the imprecision (s's), there is a systematic error which has not yet been completely determined. Preliminary results indicate that the systematic error is less than 0.0004 and 0.04°.

B. Why the 10-dB Pad?

The set of measurements with the 10-dB pad inserted is only required if the dual six-port ANA is to be used for measuring the different phase shifts through nonreciprocal two-ports. However, it is useful at all times to include the 10-dB pad in the calibration sequence as a check standard, and also to increase the amount of redundant data available in calibrating each six-port.

Still another reason for including the 10-dB pad is to increase the accuracy of the initial estimate of certain constants in the TRL solution [4]. The values of $|\rho_1|$ and $|\rho_2|$ as defined in Fig. 1 can all be approximately equal to one for the TRL measurements. When this happens, the solution for the initial estimate of certain calibration constants becomes ill-conditioned unless data such as for a lossy two-port having $|\rho_1|$ and/or $|\rho_2|$ considerably different from one are included in the calibration.

IV. Performance in Measuring Attenuation

The performance of the dual six-port ANA is expressed here in terms of imprecision and systematic error [5]. The imprecision is a measure of repeatability, and will be defined as the standard deviation. The systematic error is an estimate of unknown bias or offset. As will be shown below, the systematic error appears to be less than the imprecision.

A. Imprecision

The performance of the dual six-port ANA in measuring attenuation of reciprocal two-ports at 3 GHz is summarized in Fig. 3. The solid line is the imprecision expressed as the standard deviation for individual measurements. It varies from 0.0003 dB at low values of attenuation to 0.15 dB at 60 dB. The observed imprecision follows closely that predicted by theory [1]. The imprecision from 2 to 12 GHz is essentially the same as that at 3 GHz. From 12 to 18 GHz the imprecision increases to about twice that shown at 3 GHz.

The imprecision in measuring attenuation was determined by repeated calibrations of the system and

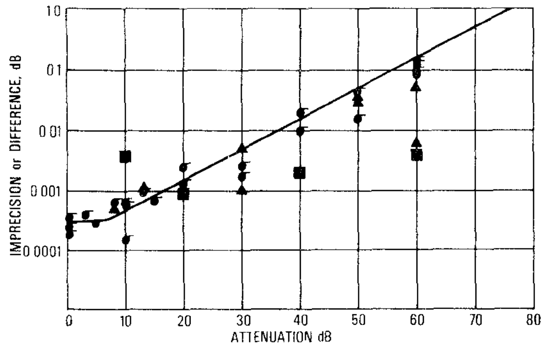

Fig. 3. Performance in measuring attenuation. The solid line represents the imprecision (one standard deviation) in measuring attenuation with the dual six-port ANA using thermistor type detectors. Each σ represents the standard deviation of five measurements of attenuation. Each triangle represents the difference in the measured attenuation of two cascaded pads from the attenuation calculated from their individually measured S-parameters. Each square indicates the difference in the attenuation of a pad measured on the dual six-port ANA and on the NBS 100-kHz–IF ANA.

measurements of seven pads having nominal values of 0, 3, 5, 10, 20, 40, and 60 dB. The imprecision is indicated by the σ's in Fig. 3. Each σ is the computed standard deviation based on five calibration and measurement cycles.

B. Systematic Error

Three different sets of measurements were made to determine limits of the systematic error in measuring attenuation: consistency checks, comparison with NBS 100-kHz–IF ANA, and comparison with rotary vane attenuator. All three indicate that the systematic error is less than the imprecision.

1) Consistency Checks: An indication of the systematic error in measuring attenuation was obtained by measuring the S-parameters of the seven pads mentioned above, and then measuring the S-parameters of different combinations of two of these pads in cascade. The measured value of attenuation of the cascaded pair was then compared to that calculated from the individually measured S-parameters for each pad.

The measurements and calculations are outlined in Fig. 4 for an example using the 10- and 20-dB pads. The measured scattering matrices S_{10} and S_{20} of the individual pads were converted to cascading matrices C_{10} and C_{20} which were then multiplied in the same order in which the two pads were cascaded for the measurement of S_{30}. The matrix product C_{10} C_{20} was then converted to a scattering matrix S_{30} (cal). Any difference between the two matrices S_{30} and S_{30} (cal) which is greater than that expected from the imprecision of the measurements is an indication of the presence of systematic errors in the measurement process. The difference between the two values of attenuation at 30 dB is plotted as a triangle ($\triangle$) in Fig. 3. The different combinations that were measured are 3+5, 3+10, 10+20, 10+40, and 20+40 dB.

In all cases, the difference between the measured cascade value of attenuation and that calculated from the individual measurements fell along a curve determined by the precision of the measurements. This is an indication that the systematic error in the measurements is less than

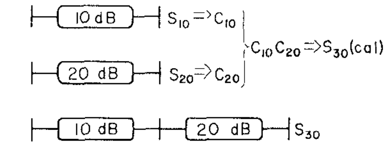

Fig. 4. Outline of the measurements and calculations made to determine systematic error in measuring attenuation.

the imprecision in the measurements. The solid curve in Fig. 3 was obtained by drawing a line through the upper values of the σ's and Δ's.

2) Comparison with NBS 100-kHz–IF ANA: The 10- , 20- , 40- , and 60-dB pads were also measured on an NBS-ANA which uses a precision 100-kHz–IF detection system [6]. The difference between the average of six measurements on this NBS-ANA and the average of 10 measurements on the dual six-port ANA is shown as a square in Fig. 3 for each pad. The differences at 3 GHz are

-0.0035 dB at 10 dB
$+0.001$ dB at 20 dB
$+0.002$ dB at 40 dB
$+0.005$ dB at 60 dB.

The NBS-ANA and the dual six-port ANA differ completely in their measurement concept, hardware, calibration, and standards. This excellent agreement is, therefore, an indication that the systematic error in either system at 3 GHz is quite small. These differences are within the estimated limits of systematic error in the NBS 100-kHz–IF ANA.

3) Comparison with Rotary Vane Attenuator: As a further check on the systematic error in measuring attenuation, the dual six-port ANA was used to measure the attenuation of a precision X-band waveguide rotary vane attenuator having an optical readout [7]. The differences at 10 GHz between the calculated values of attenuation for the rotary vane attenuator and the average of three calibration and measurement runs made by the dual six-port ANA are

$+0.0000$ dB at 1 dB
$+0.0004$ dB at 3 dB
$+0.0009$ dB at 6 dB
$+0.0005$ dB at 10 dB
$+0.0010$ dB at 20 dB
-0.0016 dB at 30 dB
$+0.008$ dB at 40 dB
$+0.16$ dB at 58 dB.

The systematic error of the rotary vane attenuator is believed to be less than 0.001 dB up to 20 dB, and less than 0.01 dB up to 60 dB. These results again indicate that the systematic error of the dual six-port ANA in measuring attenuation is less than its imprecision.

V. Performance in Measuring Γ

An indication of the systematic error in measuring reflection coefficients was obtained by first measuring Γ of four terminations having nominal values of $|\Gamma|$ equal to

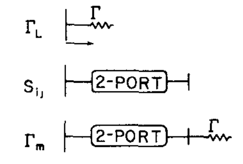

Fig. 5. Outline of the measurements made to determine systematic error in measuring reflection coefficient.

0.01, 0.05, 0.1 and 1.0. The S-parameters S_{ij} $(i,j=1,2)$ of four attenuators having nominal values of attenuation equal to 0, 3, 6, and 10 dB were also measured. Then the reflection coefficient Γ_m at port one of each attenuator was measured when port two was terminated by each of the terminations as shown in Fig. 5. The measured value Γ_m of each of these 16 attenuator-termination combinations was then compared to Γ_c which is calculated from the individually measured S-parameters of each attenuator and the measured Γ_L of each individual termination

$$\Gamma_c = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}.$$

The differences between the measured $|\Gamma_m|$ of the combinations and $|\Gamma_c|$ calculated from individual measurements are shown in Fig. 6 for three calibration and measurement runs. The differences between the corresponding phase angles ψ_m and ψ_c are shown in Fig. 7 multiplied (normalized) by $|\Gamma_m|$. Any difference which is greater than that expected from the imprecision of the individual measurements is an indication of the presence of systematic errors in the measurement process. Since the number of measurements in Figs. 6 and 7 covers the complex Γ-plane rather completely, we tentatively conclude that the limits of systematic error are revealed by the differences in these figures.

The imprecision in measuring $|\Gamma|$ or the magnitude of any individual S-parameter is about 0.00004, excluding connector repeatability. Including connector repeatability, the imprecision in $|\Gamma|$ is about 0.00015. The calculated value of Γ of an attenuator–termination combination would be expected to have an imprecision of about twice this value or 0.0003. Since some of the differences shown in Fig. 6 are significantly larger than 0.0003, they indicate a systematic error of up to 0.0004 in measuring $|\Gamma|$. The total uncertainty in measuring $|\Gamma|$ is determined by this systematic error and the imprecision including connector repeatability.

One possible source of this systematic error is in the precision transmission line used in calibrating the two six-port reflectometers. This line is assumed to be nonreflecting. Any reflections in the line such as those caused by connector discontinuities will cause a systematic error in measuring Γ.

The imprecision in measuring ψ, the phase angle of Γ is about $0.002/|\Gamma|$ degrees, excluding connector repeatability. Including connector repeatability, the imprecision in ψ is about $0.006/|\Gamma|$ degrees. Following the same reasoning as for the systematic error in $|\Gamma|$ leads to a number for the systematic error in ψ of up to $0.02/|\Gamma|$ for all of the

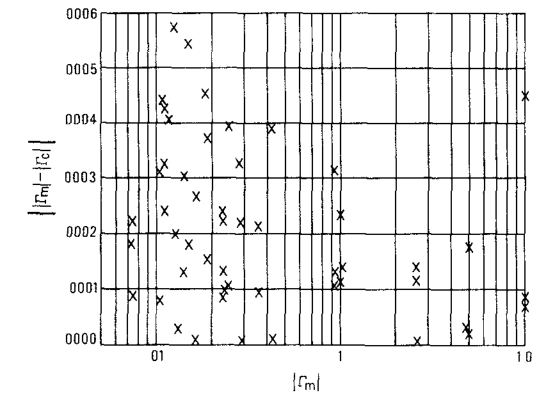

Fig. 6. Difference between the magnitude of the measured reflection coefficient Γ_m of an attenuator-termination combination and the magnitude of a corresponding Γ_c calculated from the measured S-parameters of the attenuator and the measured Γ of the termination.

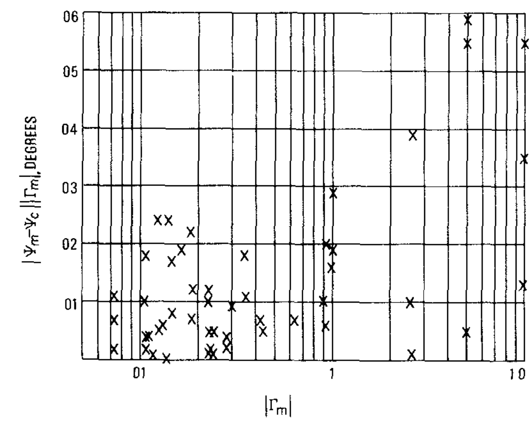

Fig. 7. Difference between the phase angle ψ_m of the measured reflection coefficient Γ_m of an attenuator-termination combination and the phase angle ψ_c of a corresponding Γ_c calculated from the measured S-parameters of the attenuator and the measured Γ of the termination.

combinations except those with the short which have values up to 0.04°. This suggests an overall expression for the systematic error in ψ of $0.02(1+|\Gamma|)/|\Gamma|$ degrees.

VI. Stability of Calibration Constants With Time

Repeated calibrations of the dual six-port ANA over a 20-week period indicate that the calibration constants are quite stable with time. Beginning November 9, 1978, the dual six-port ANA was calibrated each week at 3 GHz to determine how the calibration constants change with time. After each calibration, five pads having nominal values of attenuation of 3, 10, 20, 40, and 60 dB were measured. Their S-parameters were calculated using calibration constants from the fresh calibration and then calculated again with constants from the original calibration of November 9. The difference in the calculated values of $|S_{11}|$ and $|S_{22}|$ as well as of attenuation and phase shift are shown in Fig. 8. These curves show the *effect* of changes in the calibration constants, which is more meaningful than plotting the actual calibration constants themselves. The curves indicate that if the constants from the original calibration had been used throughout the 20-week period, the calculated

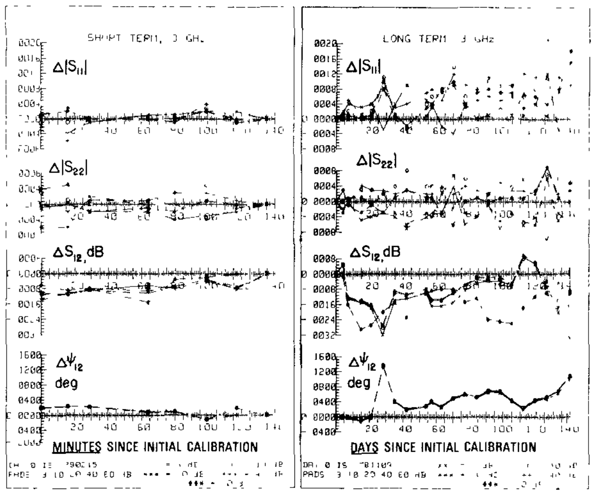

Fig. 8. Effect of short term and long term changes in the calibration constants. The points plotted show the difference in calculated values of $|S_{11}|$, $|S_{22}|$, and S_{12} (decibels and degrees) using calibration constants obtained at the time indicated, and constants obtained either at time 135 min for the short-term run, or at day zero for the long-term run.

values of attenuation would have been off no more than 0.003 dB and 0.15° from that obtained from a fresh calibration every day. The calculated values of $|S_{11}|$ and $|S_{22}|$ would have been off no more than 0.002 from that obtained from a fresh calibration every day.

To compare the long-term repeatability of the calibration constants to the short-term repeatability, the dual six-port ANA was calibrated eight times in one morning, beginning 3 min after turning the system on.[2] After the eighth calibration, the same five pads as mentioned above were measured. Their S-parameters were calculated using the calibration constants obtained from each of the eight runs. The differences between these S-parameters and those obtained for the eighth run are shown in Fig. 8 on the left of the corresponding long-term results for ease in comparing the two runs.

From a comparison of the short- and long-term runs, it appears that the results of week-to-week variation in the calibration constants are not much worse than the hour-to-hour variation. This probably indicates that most of the variation from calibration-to-calibration is due to the imprecision of each single calibration, rather than a drift in the actual components of the six-port.

Most of the imprecision in each calibration seems to be due to the connectors. One can draw this conclusion from the curves of the change in S_{12} in Fig. 8. Note that the differences in S_{12} calculated from the fresh or old calibration constants are essentially independent of the value of S_{12} for pads up to 40 dB. This type of constant offset can be caused by a slight change in the loss and phase shift through the connectors at the six-port reference planes. This change in the connectors can be measured by connecting the two reference planes together and measuring the S-parameters using the old calibration constants. Ideally the attenuation of this "thru" measurement would be zero with zero phase shift. In actual measurements, these values of attenuation and phase are not zero, and can take on positive or negative values. Beginning on day 15 of the long-term run, data for the "thru" measurement was saved along with that for the pads so corrections could be made for wear on the connectors. The correction was made by subtracting the value of S_{12} (in decibels and degrees) for the "thru" measurement from S_{12} for each pad, both calculated using the original day zero calibration constants. The differences between the corrected S_{12} for each pad and that obtained from fresh calibration constants are less than 0.002 dB and 0.03° as shown in Fig. 9. The improvement is quite significant, especially for ψ_{12}.

[2]The power meters and the temperature controllers are left on all the time.

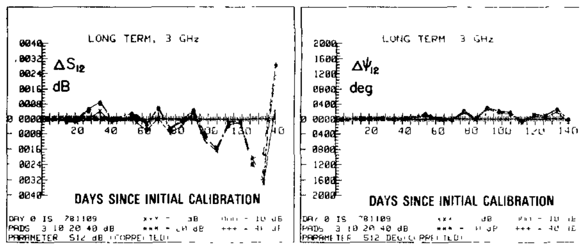

Fig. 9. Difference between the corrected value of S_{12} (S_{12} of the pad $- S_{12}$ of the thru) calculated using old calibration constants obtained on day zero, and S_{12} of the pad calculated using fresh calibration constants obtained on the day indicated.

VII. Conclusion

The results shown in Fig. 9 imply that a simple correction can be made for day-to-day changes in the connectors by measuring S_{12} of a "thru" connection and subtracting this S_{12} from the S_{12} of other two-ports being measured. This correction is essentially as good as a complete recalibration in the measurement of attenuation.

The data taken so far suggests that a dual six-port ANA can be designed so that it need not be calibrated more often than once every several months, but that the "thru" measurement should be made daily or more often depending on connector wear or abuse. The systematic error caused by drift in the calibration constants in the NBS experimental dual six-port ANA at 3 GHz was less than 0.002 in $|S_{11}|$ and $|S_{22}|$, and less than 0.003 dB and 0.15° in S_{12} over a 20-week period.

The systematic error in measuring attenuation appears to be less than the imprecision. The imprecision at 3 GHz is less than 0.001 dB up to 15 dB, increasing to 0.15 dB at 60 dB.

The systematic error in measuring Γ appears to be less than 0.0004 and $0.04/|\Gamma|$ degrees. The imprecision is determined primarily by connectors. For GPC-7 connectors, the observed imprecision in Γ was 0.00015 and $0.006/|\Gamma|$ degrees. Excluding connector repeatability, the imprecision is 0.00004 and $0.002/|\Gamma|$ degrees.

A thorough experimental determination of errors at other frequencies has not yet been completed. Preliminary results indicate that the errors approximately double as the frequency increases to 18 GHz.

Acknowledgment

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Technology Considerations for the Use of Multiple Beam Antenna Systems in Communication Satellites

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Abstract—**The general usage of multibeam antennas in satellite communication systems is reviewed, and design constraints for a six-beam reconfigurable satellite antenna system are considered. These show that losses in the variable beam-forming network (BFN) limit performance achievable with a conventional common-power-amplifier/receiver system. An alternative design for an active BFN is presented, and relative performance predicted at 4/6, 11/14, and 20/30 GHz.**

I. Multibeam Antenna Techniques

MODERN communication satellites place ever increasing demands on their antenna systems, to accomplish such functions as: 1) improving EIRP over prescribed areas through pattern shaping; 2) allowing frequency reuse by both spatial and polarization diversity; and 3) reducing interference outside desired coverage areas, to meet new WARC requirements on both copolar and cross-polarized energy. Solutions to these problems generally result in larger, more complex antenna structures and systems, which soon become an overriding factor in the design of the entire satellite.

One technique which has evolved to meet these needs is the use of multiple beam antenna (MBA) systems [1]–[5], which are capable of creating multiple simultaneous beams, each of which may be shaped from a number of smaller constituent beams by the principle of superposition. This principle is illustrated in Fig. 1, showing a set of three adjacent constituent beams added together in space to produce a single broader beam with a relatively flat top and steep "skirts". This allows more uniform coverage of the desired area, and more rapid decay of energy outside this area, to reduce interference while also improving efficiency. The antenna designer would prefer to use the narrowest possible constituent beams spaced as closely as possible together; this leads to very large antenna structures and numbers of constituent beams, each of which must be individually formed and fed. A natural limitation occurs in the allowable spacing of feed horns, based on their minimum size; this generally occurs at a spacing of about 0.6 beamwidths. Table I denotes the approximate number of beams which would be required for earth coverage from synchronous altitude (18°) for various

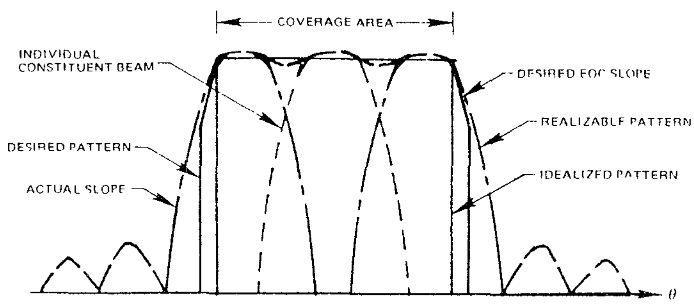

Fig. 1. Superimposed coverage patterns.

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