A New Algorithm for the Accurate Alignment of Microwave Networks

Paulo M. Marshall and Plinio Tissi, *Senior Member, IEEE*

***Abstract*—This paper presents a new algorithm suitable for the accurate alignment of microwave networks. The algorithm is developed from the sensitivity analysis of the network response with respect to the adjustable elements and does not require a knowledge of the network model. The algorithm computes the required adjustment as the solution of a Gauss–Newton system of equations and is implemented by quantifying the adjustment of each individual element setting. This procedure does not demand a previous characterization or calibration of the adjustable elements and has been proved to be efficient for the accurate alignment of different types of microwave filters.**

I. Introduction

The traditional approach to the alignment of a microwave device is the empirical adjustment of a set of variable elements in order to bring the network response within some predefined specification. Specific tuning strategies have been developed to aid in the alignment of microwave filters [1]–[4]. These procedures, however, are prone to be very time consuming, and usually require experienced and skilled operators. Computer-aided tuning, therefore, plays an important role in the cost-effective production of microwave networks when an accurate alignment is desired. Previous work on the computer-aided alignment of microwave networks has been limited to applications where models are used [5]–[7] and previous characterization and precise calibration of the adjustable elements are required [5]–[8]. This calibration is lengthy and sometimes has to be repeated after each set of adjustments, making the procedure inefficient. One of the drawbacks of the model-based methods is that they cannot be generalized to other types of networks. In addition, it is frequently difficult, and sometimes impossible, to derive a network model in which all adjustable elements are accurately represented. This occurs because a typical microwave tuning element, such as a metallic or dielectric screw or post, usually affects several parameters of the model simultaneously. As an example, microwave filter intercavity coupling screws may also affect the resonant frequencies of the adjacent cavities, and tuning screws in multiple-mode cavity filters may act upon the resonant frequencies of two or more modes. As a result, the presently available computer-aided tuning methods often fail to yield accurate and close-to-theoretical responses [5]–[7].

This paper presents a new algorithm for the accurate alignment of microwave networks. A set of adjustments is computed by the Gauss–Newton solution of a system of equations resulting from a sensitivity analysis of the measured network response. An error vector is given by the difference between the measured response and the objective, and a quadratic error function is defined. The adjustment of each element is given by the corresponding component of the solution vector and is quantified in terms of the error to be attained. This procedure does not call for any type of modeling, either of the whole network or of the adjustable elements.

The reported results demonstrate the efficiency of the method and its applicability to the challenging problem of the cost-effective and accurate alignment of networks with a large number of adjustable elements. The generality of the algorithm is further demonstrated by the successful alignment of an LC-tuned band-pass filter.

Manuscript received November 5, 1990; revised March 18, 1991.
P. M. Marshall was with the Institute of Space Research—INPE, São Jośe dos Campos, Brazil. He is now with PROMON Electronica, Campinas SP, Brazil.
P. Tissi is with the Institute of Space Research—INPE, CP 515, São José dos Campos, SP, Brazil.
IEEE Log Number 9102335.

II. Mathematical Formulation

Let m denote the number of adjustable elements available to the operator, and let the setting of element i be represented by x_i. Depending on the nature of each element, x_i may represent angular displacement (for tuning screws), depth of penetration (for plungers), width or length of a coupling slot, or, finally, any other mechanical or electrical measurable quantity. Let $\boldsymbol{x}=(x_1, x_2, \cdots, x_m)$ and let $\boldsymbol{F}(\boldsymbol{x})=(F_1, F_2, \cdots, F_p)$ represent the actual response of the network, $\boldsymbol{F}_o$ being the desired response, or objective. As an example, $\boldsymbol{F}_o$ may contain the transmission and reflection responses, evaluated at an appropriately chosen set of frequencies. Assuming that a setting $\boldsymbol{x}_o$ exists such that $\boldsymbol{F}(\boldsymbol{x}_o)=\boldsymbol{F}_o$ and that the initial setting $\boldsymbol{x}$ is sufficiently close to $\boldsymbol{x}_o$, i.e., that fine-tuning of the network is required, it is possible to describe a change in the response, $\Delta\boldsymbol{F}$, caused by a small change in the adjustable elements, $\Delta\boldsymbol{x}$, by a linear relationship, so that $\Delta\boldsymbol{F}=\boldsymbol{F}(\boldsymbol{x}+\Delta\boldsymbol{x})-\boldsymbol{F}(\boldsymbol{x})=S\Delta\boldsymbol{x}$, where S is the Jacobian matrix defined by $S_{ij}=\partial F_i/\partial x_j$, $i=1,\cdots,p$ and $j=1,\cdots,m$. The error vector being given by $\boldsymbol{e}=\boldsymbol{F}-\boldsymbol{F}_0$, its squared norm $q=\boldsymbol{e}^T\boldsymbol{e}$, after adjusting $\boldsymbol{x}$ to $\boldsymbol{x}+\Delta\boldsymbol{x}$, is computed as

$$q=\boldsymbol{e}^T\boldsymbol{e}+\boldsymbol{e}^TS\Delta\boldsymbol{x}+\Delta\boldsymbol{x}^TS^T\boldsymbol{e}+\Delta\boldsymbol{x}^TS^TS\Delta\boldsymbol{x}. \quad (1)$$

0018-9480/91/1000-1754$01.00 ©1991 IEEE

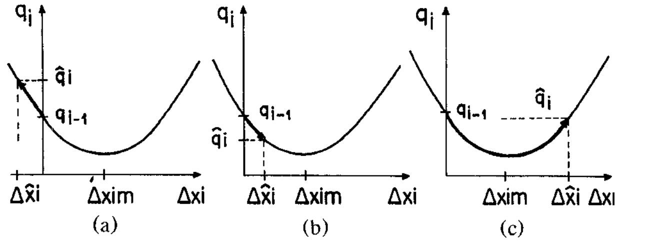


Fig. 1. Quadratic error as a function of the adjustment of element i. (a) $\Delta\hat{x}_i$ opposed to Δx_{im}: $\hat{q}_i > q_{i-1}$. (b) $\Delta\hat{x}_i$ toward Δx_{im}: $|\Delta\hat{x}_i| < |\Delta x_{im}|$. (c) $\Delta\hat{x}_i$ toward Δx_{im}: $|\Delta\hat{x}_i| > |\Delta x_{im}|$.

The generalized least-squares, or Gauss–Newton, solution for the adjustment that leads to the minimum value of the error q is given by [9]

$$\Delta\hat{x} = -(S^TS^{-1})S^Te = -S^{\dagger}e \qquad (2)$$

and the resulting error by $\hat{q} = e^T(I - A - A^T + A^TA)\,e$, with $A = SS^{\dagger}$. In the actual implementation of well-known optimization strategies, such as Newton and gradient methods, the minimum error is sought in the direction of the solution vector. For the tuning problem, however, this is not physically possible because the operator can only perform the adjustment of one element at a time. It is therefore necessary to separate and adequately quantify the adjustment of each tuning element, which is represented by the corresponding component of $\Delta\hat{x}$. To this end, we shall consider partial adjustments of the type $\Delta\hat{x}_i = (0, 0, \cdots, \Delta\hat{x}_i, 0, \cdots, 0)$, where $\Delta\hat{x}_i$ is the ith component of $\Delta\hat{x}$, as given by (2). This adjustment is quantified by the value of the error, $\hat{q}_i$, to be attained after x is altered to $x + \Delta\hat{x}_i$. As a function of an arbitrary Δx_i, q_i is given by

$$q_i = |s_i|^2\Delta x_i + 2s_i^Te\Delta x_i + e^Te \qquad (3)$$

s_i being the ith column of S. Fig. 1 shows that the sense of the adjustment may not be toward the one-dimensional minimum of the error, located at $\Delta x_{im} = -s_i^Te/|s_i|^2$. This occurs because the projections of the solution vector $\Delta\hat{x}$ on the base vectors of the m-dimensional space where x belongs are not necessarily coincident in length with the vectors defined by the one-dimensional minima, i.e., $\Delta\hat{x}_i \neq \Delta x_{im}$. In the extreme case when these two vectors are opposed to each other, as indicated in Fig. 1(a), the error $\hat{q}_i$, after the adjustment $\Delta\hat{x}_i$ is performed, will be larger than the error before the adjustment, q_{i-1}. If $\Delta\hat{x}_i$ points toward Δx_{im}, element i should be adjusted until the first occurrence of q_i is attained if $|\Delta\hat{x}_i| < |\Delta x_{im}|$ (Fig. 1(b)). The second occurrence of q_i is chosen when $|\Delta\hat{x}_i| > |\Delta x_{im}|$ (Fig. 1(c)).

The above concepts allow the formulation of the following tuning algorithm: 1) define the desired response and the set of elements to be adjusted; 2) measure the actual response of the network and compute e; 3) perform the determination of S by sequentially altering the adjustable elements; 4) compute $\Delta\hat{x}$; 5) adjust element i until the desired value of the error, $\hat{q}_i$, is achieved, observing the behavior of q_i as a function of Δx_i; 6) repeat steps 4 and 5 until $i = m$; 7) restart from step 3 if the error is not acceptable.

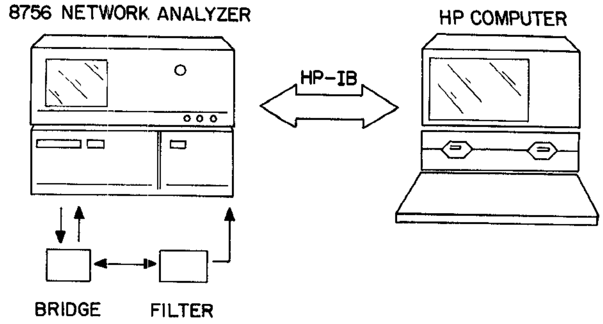


Fig. 2. Schematic diagram of the setup used in the filter tuning applications.

In step 3, any individual change should be no larger than the minimum required to produce measurable variations in the response. Each column of S is given by $s_i = (\Delta F_1, \Delta F_2, \cdots, \Delta F_p)$, where ΔF_j, $j = 1, 2, \cdots, p$, are the measured response variations caused by a change in element i. Although the matrix S so obtained clearly depends on the amplitude of the changes operating on the adjustable elements, the Appendix shows that the numerical value of the error to be attained in step 5, $\hat{q}_i$, is unique. As a result, the alignment can be performed without the need to calibrate the adjustable elements.

The algorithm was implemented on the setup shown in Fig. 2, which is suitable for the production-line alignment of a large class of microwave devices. The network analyzer (HP8756) is controlled by an HP200 series microcomputer through an IEEE-488 interface bus (HPIB). The algorithm was incorporated as a subroutine of a BASIC control program which performs setup calibration, display characteristics definition, and data transfer control between computer and network analyzer. Since it takes less than 3 s to complete one data transfer and error function computation, the error-oriented adjustment of an element can almost be performed in real time. The precise return of each adjustable element to its original value after the determination of the corresponding column of S is achieved by previous storage of trace data into the memory channels of the HP8756. More details on the use and availability of the control program are given in [11].

III. Examples

The algorithm was applied to the fine alignment of round-rod interdigital band-pass filters, one of which is depicted in Fig. 3 [10]. Adjustments in this type of filter are made by varying the penetration of metallic screws, some of which are aligned with the resonators for the tuning of their resonant frequencies while others are positioned between resonators, for interresonator decoupling. The initial responses in these examples may be achieved after a preliminary "coarse" tuning of the filters by application, for example, of Dishal's method [1]. Fig.

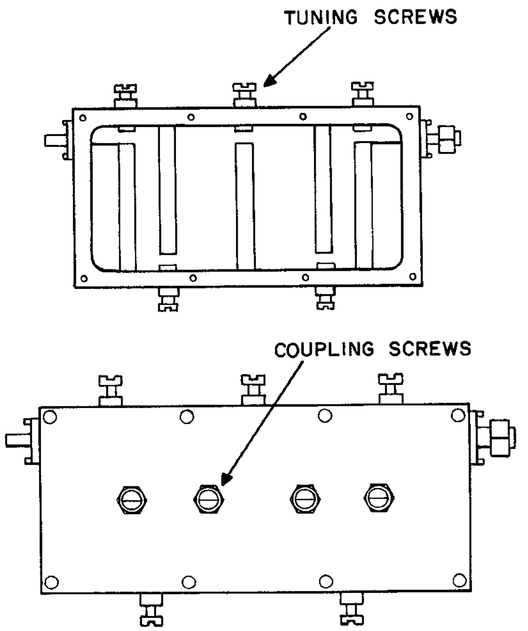


Fig. 3. Three-section interdigital band-pass filter.

4(a) shows the untuned response of a three-section 2 GHz filter whose tuning screws had been turned away from their nominal positions. Only five iterations of the algorithm, corresponding to a total of 13 individual adjustments, were necessary to reduce the error from its initial value of 1936 to 6.4, resulting in the tuned filter response shown in Fig. 4(b). The filter was also adjusted by an intuitive procedure in which each element was adjusted until the minimum error was obtained. The initial positions of the screws were carefully reproduced, resulting in the same untuned response of Fig. 4(a). The step-by-step value of the error is presented in Fig. 4(c). This figure shows that, as opposed to what occurs for the intuitive procedure, the algorithm does not necessarily lead to a decrease of the error at each step but, nevertheless, yields faster convergence to the objective.

The alignment of networks with a larger number of adjustable elements provides a challenging problem for testing the efficiency of the algorithm. To this end, we have applied the algorithm to the alignment of an eight-section, 1.2 GHz, 0.1 dB ripple Chebyshev filter in which a total of 15 adjustable elements were present (eight tuning and seven coupling screws). Fig. 5(a) presents the untuned response of the filter which resulted from the misalignment of all 15 adjustment screws. Tuning and coupling screws were alternatively used during seven iterations. The final alignment of the filter, presented in Fig. 5(b), shows that an accurate and very close-to-theoretical response was achieved.

This algorithm has been successfully applied to the alignment of these two filters under different initial conditions, as well as to a 7 GHz waveguide filter with a Butterworth response [11]. The application of the algorithm, however, is not limited to microwave networks. As a matter of fact, the generality of its formulation allows its

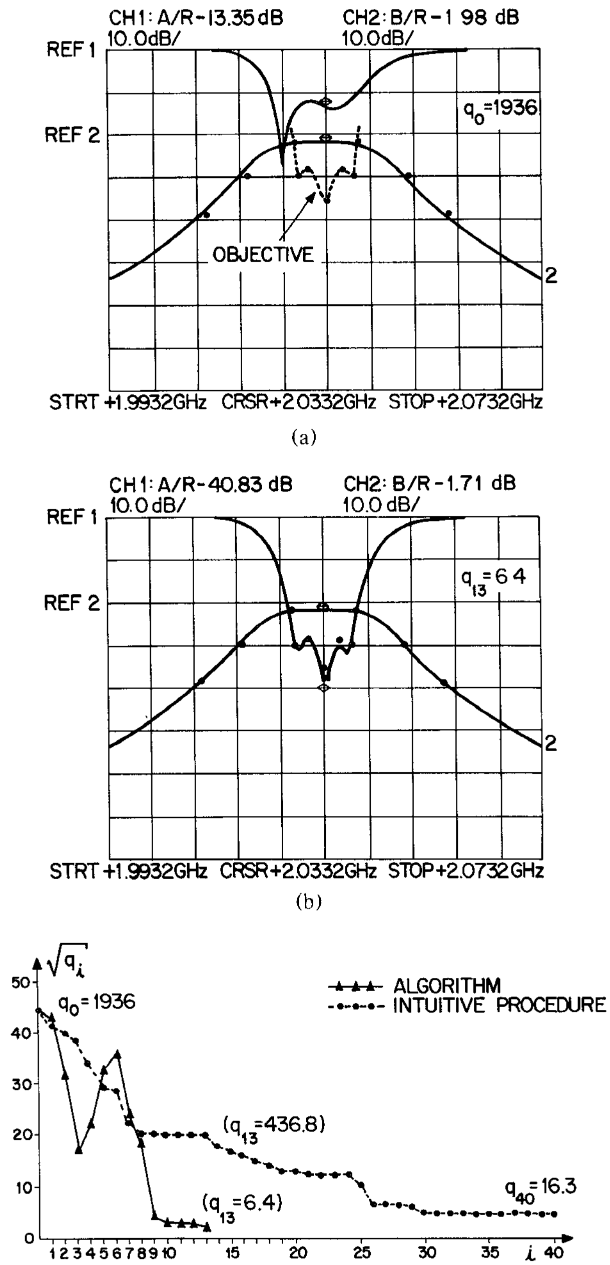
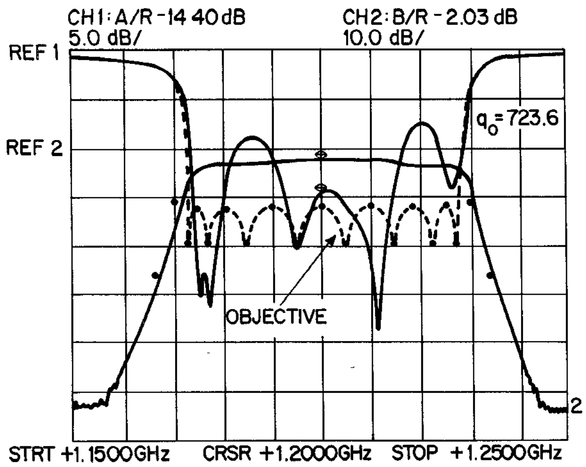
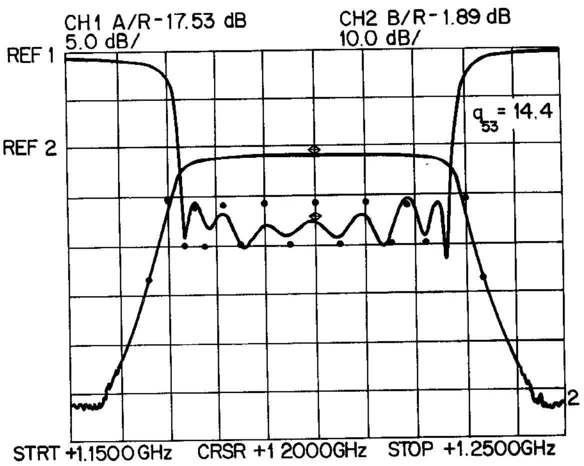


Fig. 4. Three-section, 2 GHz interdigital band-pass filter. (a) Untuned response. (b) Filter response after 13 steps of the algorithm. (c) Square root of the error q_i as a function of the number of adjustments.

application to the alignment of several different types of networks. Consider, for example, the alignment of RF (>100 MHz) LC-tuned band-pass filters with air-core inductors. Fine adjustment of these filters is frequently performed by manually varying the spacings between the wire turns of each coil. Such an adjustment, however, can hardly be quantified in geometrical terms. Even the tedious modeling and characterization of each adjustment, as required for the implementation of certain specific tuning methods [12], cannot be applied for this type of inductor. As a result, the presently available computer-aided tuning algorithms either cannot be applied or else fail to yield accurate and close-to-theoretical responses.

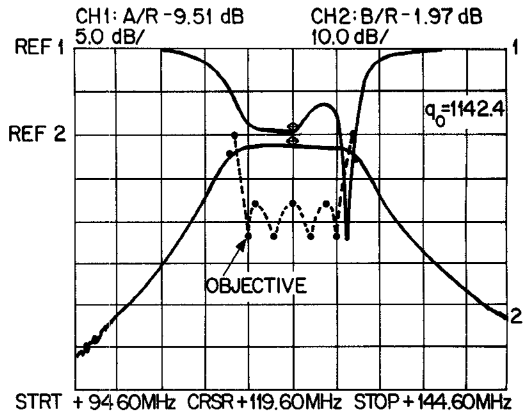


(a)

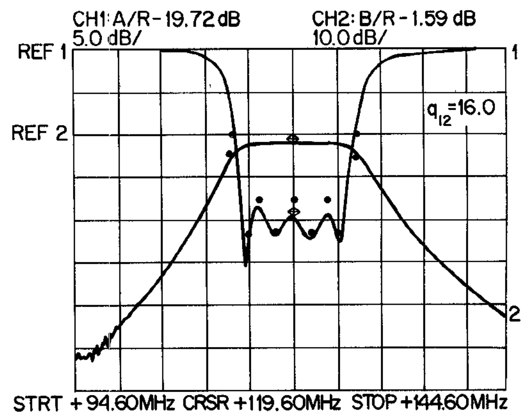


(b)

Fig. 5. Eight-section, 1.2 GHz, 0.1 dB ripple chebyshev filter. (a) Untuned response. Objective return loss response is indicted by dashed line. (b) Tuned filter response after seven iterations (53 steps).



(a)



(b)

Fig. 6. 119 MHz *LC*-tuned band-pass filter. (a) Untuned and objective responses. (b) Aligned filter response.

The present algorithm provides a method for the accurate alignment of such networks. Fig. 6(a) presents the initial response of a five-section 119 MHz Chebyshev *LC* band-pass filter where all five inductors were randomly misaligned. Three iterations were required to achieve the close-to-theoretical final response, shown in Fig. 6(b).

IV. Conclusions

A fast and accurate algorithm suitable for the cost-effective alignment of microwave networks has been described. The algorithm overcomes some of the limitations of the presently available computer-aided tuning methods, which usually require detailed modeling of the network and/or previous calibration of its adjustable elements. Because of the generality of the mathematical formulation of the algorithm, it is applicable to the alignment of a large class of networks. Examples have been given of the accurate alignment of two interdigital microwave filters and of one RF *LC*-tuned filter. The reported results suggest its application to microwave networks whose traditional alignment is known to be very time consuming, usually requiring experienced and skilled operators, as is the case with waveguide multiplexers.

Appendix
Numerical Quantification of the Adjustment

Consider two different determinations of the Jacobian, S and S', obtained by two different sets of alterations of the adjustable elements, $\Delta \boldsymbol{x}$ and $\Delta \boldsymbol{x}'$, respectively. The quantities $\Delta \boldsymbol{x}$ and $\Delta \boldsymbol{x}'$ are related by

$$\Delta \boldsymbol{x}' = K \Delta \boldsymbol{x} \tag{A1}$$

with $K = \mathrm{diag}(k_1, k_2, \cdots, k_m)$; therefore, $S' = SK$. The response $\boldsymbol{F}$ after the adjustment $\Delta \hat{x}'_i$ is given by

$$\boldsymbol{F}(\boldsymbol{x} + \Delta \hat{\boldsymbol{x}}'_i) = \boldsymbol{F}(\boldsymbol{x}) + S' \Delta \hat{\boldsymbol{x}}'_i. \tag{A2}$$

Now, $\Delta \hat{\boldsymbol{x}}'_i$ can be expressed as a function of the solution vector $\Delta \hat{\boldsymbol{x}}'$ as $\Delta \hat{\boldsymbol{x}}'_i = P_i \Delta \hat{\boldsymbol{x}}'$, with $P_i = \mathrm{diag}(0, 0, \cdots, 1, \cdots, 0)$, where the unit is in position i. Therefore,

$$\begin{aligned}\boldsymbol{F}(\boldsymbol{x} + \Delta \hat{\boldsymbol{x}}'_i) &= \boldsymbol{F}(\boldsymbol{x}) - S' P_i (S')^{\dagger} \boldsymbol{e} = \boldsymbol{F}(\boldsymbol{x}) - SKP_i K^{-1} S^{\dagger} \boldsymbol{e} \\ &= \boldsymbol{F}(\boldsymbol{x}) - SP_i S^{\dagger} \boldsymbol{e} = \boldsymbol{F}(\boldsymbol{x} + \Delta \hat{\boldsymbol{x}}_i).\end{aligned} \tag{A3}$$

Therefore, the value of the error to be attained after the adjustment of element $i, \hat{q}_i$, when the set of changes $\Delta \boldsymbol{x}' = (k_1 \Delta x_1, k_2 \Delta x_2, \cdots, k_m \Delta x_m)$ is applied to the determination of the Jacobian is the same as the one that would have been computed if the set $\Delta \boldsymbol{x} = (\Delta x_1, \Delta x_2, \cdots, \Delta x_m)$ had been used.

References

[1] M. Dishal, "Alignment and adjustment procedure of synchronously tuned multiple resonant circuit filters," *Proc. IRE.*, vol. 39, pp. 1448–1455, Nov. 1951.

[2] H. A. Wheeler, "Tuning of waveguide filters by pretuning of individual sections," in *Symp. Modern Advances in Microwave Tech.*, 1954, pp. 343–353.

[3] A. E. Atia and A. E. Williams, "Nonminimum phase optimum amplitude band pass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 425–431, Apr. 1974.

[4] A. E. Atia and A. E. Williams, "Measurements of intercavity couplings," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 519–522, June 1975.

[5] L. Accatino, "Computer-aided tuning of microwave filters," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1986, pp. 249–252.

[6] H. L. Thal, "Computer aided filter alignment and diagnosis," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 958–963, Dec. 1978.

[7] T. Ishizaki, H. Ikeda, T. Uwano, M. Hatanaka, and H. Miyake "A computer aided accurate adjustment of cellular radio RF filters," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990, pp. 139–142.

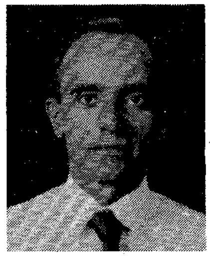
[8] A. R. Mirzai, C. F. N. Cowan, and T. M. Crawford, "Intelligent alignment of waveguide filters using a machine learning approach," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 166–173, Jan. 1989.

[9] R. Fletcher, "Generalized inverse methods for the best least squares solution of systems of non-linear equations," *Computer J.*, vol. 10, pp. 392–399, Feb. 1968.

[10] P. M. Marshall, "Design and sensitivity analysis of round-rod interdigital bandpass filters," in *Proc. SBMO Int. Microwave Symp.* (São Paulo, Brazil), 1989, pp. 679–685.

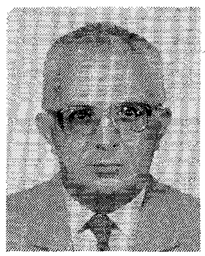
[11] P. M. Marshall, "Algorithm for the optimized adjustment of microwave networks," D. Sc. dissertation, Technology Institute of Aeronautics, São José dos Campos, SP, Brazil, June 1990 (in Portuguese).

[12] B. W. Jervis and M. Crofts, "Sensitivity-based filter tuning," *Electronics and Wireless World*, vol. 94, pp. 429–432, May 1988.



Paulo M. Marshall was born in Rio de Janeiro, Brazil, in 1956. He graduated in electrical engineering from PUC—Catholic University of Rio de Janeiro in 1978. He received the M.Sc. degree in electronics and telecommunications from INPE— National Institute of Space Research in 1981 and the D.Sc. degree in electronics and computer sciences from ITA—Technology Institute of Aeronautics in 1990.

He worked ten years as an assistant researcher and development engineer at INPE, performing research, design, and development of RF and microwave circuits for both ground and space applications. He was a visiting engineer at SPAR Aerospace in 1983. From 1985 to 1990 he was project leader for the design and development of space-qualified TT&C equipment (antennas, TT&C transponder, telecommand decoder) for the Brazilian environmental data collection satellites. His is areas of interest are RF and microwave filters and oscillators and satellite communications. He joined PROMON Electronica, Campinas, Brazil, in April 1991.



Plinio Tissi (A'59–SM'90) was born in Italy on June 14, 1931. He graduated as a Mechanical and Electrical Engineer from São Paulo University, Brazil. He received the M.S. and Ph.D. degrees in electrophysics in 1964 and 1966, respectively, from the Polytechnic Institute of Brooklyn, New York.

Until 1971 he was a member of the staff of the Electronics Division of the Technological Institute of Aeronautics, São José dos Campos, Brazil. Since 1971 he has been with the Brazilizn Space Research Institute (INPE), where he has occupied several positions. His areas of interest are network theory, microwaves, and satellite communications.