Computer-Aided Testing of Mixers Between 90 and 350 GHz

MAREK T. FABER AND JOHN W. ARCHER, SENIOR MEMBER, IEEE

Abstract **—Two computer-controlled measurement systems have been constructed to allow testing of millimeter-wave Schottky-barrier diode mixers in the frequency range from 90 to 350 GHz. A theoretical background to mixer measurement is presented and the design of the instruments and associated computer software is described. In a companion paper [1], a typical application of the measurement system to the testing and evaluation of a practical *W*-band, cryogenic, fixed-tuned Schottky diode mixer is used to demonstrate the performance and versatility of the instruments.**

I. Introduction

Accurate testing of microwave mixers has been an important problem in mixer development for more than 40 years. Advances in microwave receiver technology have resulted in high-sensitivity receivers becoming practical at increasingly higher frequencies. The need for low-noise mixers, especially in the field of millimeter-wave radio astronomy, has stimulated a considerable amount of research into the theory, design, and development of mixers and mixer diodes. To achieve improved mixer designs required more accurate measurement methods and more complete testing and characterization of mixers. The lack of coherent signal generators with a known output power at millimeter-wave frequencies resulted in the adoption of measurement methods [2] requiring the use of noise sources only. These methods came into use in the late sixties and were used for simultaneous measurements of gain and noise of amplifiers at lower microwave frequencies. Utilization of hot (at room temperature) and cold (at liquid nitrogen temperature) matched RF loads as noise sources allowed these methods to be utilized in millimeter-wave mixer measurements [3] and resulted in a noise temperature meter which was used in fundamental work on cryogenic cooling of mixers [4]. Measurement setups that evolved from this early design were then used successfully in further development of millimeter-wave, low-noise Schottky-diode mixers (e.g., [5]–[12]). Although coherent signal generators were still sometimes used either for conversion loss measurements [13] or as a "narrow-band noise source" [14], millimeter-wave mixer testing has usually been carried out using the hot and cold load measurement technique (in various forms, e.g., [15], [16]) because of its inherent simplicity, accuracy, and speed.

In the late seventies, researchers began to use desktop computers to process data and account for many systematic effects that were very time-consuming to correct without the aid of a computer, and were often accepted as measurement errors.

The measurement systems reported in this paper employ a computer not only for processing data but also for controlling the operation of the test apparatus. This approach allows the user to carry out a much more extensive set of mixer performance tests, as well as to obtain data that could not be measured without the aid of high-speed, real-time system control and data processing. The computer-controlled instrument provides a more accurate, reliable, versatile, and efficient means of testing and developing millimeter-wave mixers than previously available.

The theoretical basis for the hot and cold load measurement is briefly reviewed in Section II, where formulas utilized in the data-processing software are given. The hardware and software used in the measurement systems is described in Sections III and IV, respectively. In a companion paper [1], computer printouts that resulted from the testing of a sample mixer are used to illustrate the operation of the measurement system and to show the versatility of the test instrument and the variety of data that can be obtained describing mixer performance.

II. Measurement Formulas

The gain and noise of a linear, two-port device can be determined, for specified input and output frequencies and terminating immittances, by measuring the values of output noise that result from sequentially applying two different known values of input noise [2]. At millimeter-wave frequencies, well-matched RF loads made of absorber are used as input noise sources. Usually one load has a physical temperature of about 295 K (room or "hot" load) while the other ("cold" load) is cooled by immersion in liquid nitrogen (77 K).

A system for simultaneous measurements of conversion loss and mixer noise temperature (i.e., effective input noise temperature) of a millimeter-wave, cryogenic mixer is shown schematically in Fig. 1. The IF radiometer/reflectometer is used to measure noise and reflections at the mixer output. Well-matched standard hot and cold loads are used to

Manuscript received January 20, 1985; revised June 17, 1985.

M. T. Faber was with the National Radio Astronomy Observatory, Charlottesville, VA 22903. He is currently with the Institute of Electronics Fundamentals, Warsaw Technical University, Nowowiejska 15/19, 00-665 Warsaw, Poland.

J. W. Archer was with the National Radio Astronomy Observatory. He is currently with CSIRO, Division of Radiophysics, P.O. Box 76, Epping, New South Wales, Australia 2121.

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

0018-9480/85/1100-1138$01.00 ©1985 IEEE

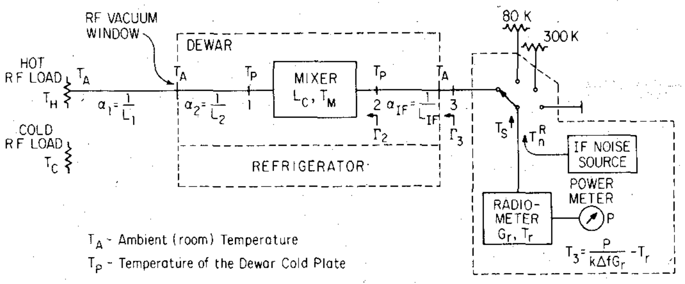


Fig. 1. General measurement setup for simultaneous measurements of the mixer noise temperature and conversion loss of a cryogenic mixer.

determine the available power gain G_r and the effective input noise temperature T_r of the radiometer at each measurement frequency. The third calibration standard is a short circuit, which is used to calibrate the reflectometer, i.e., to determine noise temperatures T_S and $T_S^R = T_S + T_n^R$ of noise waves which are sent outward from the reflectometer when its noise source is turned off and on, respectively. Such a noise measuring system, once calibrated (i.e., G_r, T_r, T_S, and T_S^R are determined), can measure the absolute noise temperature and the magnitude of reflection coefficient of a device connected to its input (port number 3 in Fig. 1).

In practical measurements of cryogenically cooled microwave devices, neither the input port nor the output port of a mixer is directly accessible and measurements have to be made through lossy IF cables and RF components.

A. Effect of Loss in RF Components

RF and local oscillator signals are usually fed to the mixer input through a quasi-optical or waveguide diplexing system, a dewar vacuum window and, possibly, lossy waveguide components. In the most general case, the RF path can be divided into two parts as shown in Fig. 1: one at room temperature T_A outside the dewar (losses L_1; $\alpha_1 = 1/L_1$) and the other (losses L_2; $\alpha_2 = 1/L_2$) inside the dewar. The latter guiding structure might have one end at physical temperature T_A and the other end at the dewar cold plate temperature T_P.

Because of the loss in the RF path, the mixer sees noise temperatures at its input which are different from the hot and cold load temperatures T_H and T_C. This is because a lossy RF component adds thermal noise power $P_T = kT_{\text{eq}}(1-1/L)\Delta f$, where T_{eq} is the equivalent temperature which depends on the temperature distribution along the lossy guide [17]. The simplest model assumes a linear distribution and T_{eq} is then the average of temperatures at device input and output.

Assuming that the matched hot RF load is at room temperature, $T_H = T_A$, the noise temperatures seen by the mixer at port 1 are

$$T_{1H} = T_H - \frac{1}{2}(1-\alpha_2)(T_H - T_P) \leqslant T_H \tag{1}$$

$$T_{1C} = T_C + (T_H - T_C)(1-\alpha_1\alpha_2) - \frac{1}{2}(1-\alpha_2) \times (T_H - T_P) \geqslant T_C \tag{2}$$

and their difference is determined by $T_H - T_C$ and the total RF losses

$$\Delta T_1 = T_{1H} - T_{1C} = \alpha_1\alpha_2(T_H - T_C). \tag{3}$$

Thus, the RF losses result in the room-temperature load appearing to be colder and the cold load hotter than the true temperatures when measured at the input of a cryogenically cooled mixer. This results in a reduction in the input noise temperature difference by a factor of $\alpha_1\alpha_2$. It is clear, therefore, that in order to preserve the accuracy of mixer parameter measurements, it is essential to keep RF input losses to a minimum, consistent with other constraints such as the thermal design of the cryostat.

B. Effect of Loss in IF Cable

The noise measured by the IF radiometer is composed of the noise delivered from the mixer output into the IF cable, the noise transmitted outward from the radiometer and reflected back from the mixer IF terminals, and the thermal noise generated in the lossy IF cable. It has been shown [18] that the noise radiated from the two ends of the lossy cable is uncorrelated, i.e., in Fig. 1, the thermal noise power incident on port 3 is not dependent on the phase of the reflection coefficient Γ_2.

At each measurement frequency, three noise temperatures need to be measured.

1) Hot load (T_{1H}) at mixer input; reflectometer noise source off

$$T_{3H} = \alpha_{\text{IF}}(1-|\Gamma_2|^2)T_{2H} + \alpha_{\text{IF}}^2|\Gamma_2|^2 T_S + \delta T_3. \tag{4}$$

2) Hot load (T_{1H}) at mixer input; reflectometer noise source on

$$T_{3H}^R = \alpha_{\text{IF}}(1-|\Gamma_2|^2)T_{2H} + \alpha_{\text{IF}}^2|\Gamma_2|^2 T_S^R + \delta T_3. \tag{5}$$

3) Cold load (T_{1C}) at mixer input; reflectometer noise source off

$$T_{3C} = \alpha_{\text{IF}}(1-|\Gamma_2|^2)T_{2C} + \alpha_{\text{IF}}^2|\Gamma_2|^2 T_S + \delta T_3 \tag{6}$$

where $\delta T_3 = (1-\alpha_{\text{IF}})(1+\alpha_{\text{IF}}|\Gamma_2|^2)T_{\text{ceq}}$; and T_{ceq} is the equivalent temperature of IF cable [17]. From these measurements

$$\alpha_{\text{IF}}^2|\Gamma_2|^2 = \frac{T_{3H}^R - T_{3H}}{T_S^R - T_S} = |\Gamma_3|^2. \tag{7}$$

Because noise temperatures are defined in terms of available noise power [19], [20], it is necessary to derive an "available conversion loss" L_a, which corresponds to the available power gain relating noise temperatures at the output and input of a linear two-port [21], [22]. L_a, defined as the ratio of available power of the RF source to available power at the mixer IF output, can be expressed as

$$L_a^{\text{DSB}} = \frac{\Delta T_1}{\Delta T_2} = \frac{T_{1H} - T_{1C}}{T_{2H} - T_{2C}} = \frac{\alpha_{\text{IF}}^2 - |\Gamma_3|^2}{\alpha_{\text{IF}}} \cdot \frac{T_{1H} - T_{1C}}{T_{3H} - T_{3C}} = \frac{\alpha_{\text{IF}}^2 - |\Gamma_3|^2}{\alpha_{\text{IF}}} \frac{\Delta T_1}{\Delta T_3}. \tag{8}$$

The mixer conversion loss L_c, (i.e., ratio of available power of the RF source to power delivered to IF load) can be derived from measured quantities as

$$L_c^{\mathrm{DSB}} = \frac{L_a^{\mathrm{DSB}}}{1-|\Gamma_2|^2} = \alpha_{\mathrm{IF}} \frac{\Delta T_1}{\Delta T_3}. \tag{9}$$

The mixer noise temperature (i.e., effective input noise temperature [1]) is given by

$$T_M^{\mathrm{DSB}} = T_{2H} \cdot L_a^{\mathrm{DSB}} - T_{1H} \tag{10}$$

which can be expressed in terms of measured quantities as

$$T_M^{\mathrm{DSB}} = \left(T_{3H} - |\Gamma_3|^2 T_S\right) \frac{\Delta T_1}{\Delta T_3} - T_{1H} - \delta T_M \tag{11}$$

where

$$\delta T_M = (1-\alpha_{\mathrm{IF}}) \left(1 + \frac{1}{\alpha_{\mathrm{IF}}} |\Gamma_3|^2\right) T_{\mathrm{ceq}} \cdot \frac{\Delta T_1}{\Delta T_3}. \tag{12}$$

For a double sideband mixer [4], [23]

$$T_M^{\mathrm{SSB}} = T_M^{\mathrm{DSB}} \left(1 + \frac{L_s}{L_i}\right) \text{ and } L_c^{\mathrm{SSB}} = L_c^{\mathrm{DSB}} \left(1 + \frac{L_s}{L_i}\right) \tag{13}$$

which, for a broad-band mixer having equal conversion losses from both sidebands, $L_s = L_i$, gives:

$$T_M^{\mathrm{SSB}} = 2 T_M^{\mathrm{DSB}} \text{ and } L_c^{\mathrm{SSB}} = 2 L_c^{\mathrm{DSB}}. \tag{14}$$

The above formulas show the corrections that need to be applied at each measurement frequency in order to determine mixer conversion loss and mixer noise temperature from the measured quantities T_{3H}, T_{3H}^R, and T_{3C}. They also indicate sources of potential measurement inaccuracies inherent in the hot/cold load measurement technique employing a calibrated IF radiometer/reflectometer to make noise measurements. The formulas derived also indicate which parts of the test system need to be carefully designed and how to optimize system software to minimize measurement errors in various tests.

III. Measurement Systems

Two measurement systems have been constructed to allow simultaneous testing of millimeter-wave mixers in two different frequency ranges. One setup covers 90–190 GHz in two subranges, while the other is used at frequencies from 200 to 290 GHz and also allows measurements up to 350 GHz. Both setups employ the same cryogenic systems, similar IF radiometers/reflectometers, and both are controlled by Apple II+ desktop computers running the same software. The major differences between the systems lie in the design of the quasi-optical diplexers and the local oscillator sources.

A simplified block diagram of the measurement setup is shown in Fig. 2. The cryogenic system is a double dewar arrangement devised for a multiple mixer radio astronomy receiver [24]. The mixer under test and IF amplifier are mounted in a cryogenic sub-dewar, comprising a separate vacuum chamber and a cold stage which can be readily thermally connected to or disconnected from the main dewar cold plate by a mechanical heat switch. Such an arrangement allows the sub-dewar to be warmed up without turning off the refrigerator. Thus, the mixer can be changed and then rapidly cooled again by closing the heat switch to the cold main dewar plate.

A Teflon lens matches the diverging radiation pattern of the mixer feed horn to the quasi-collimated beam within the LO diplexer and serves as a RF vacuum window. Polarizing-type diplexers [25] are used in both systems for LO/RF combining and filtering. The higher RF frequency diplexer is similar to one described previously [9]. The other diplexer is an implementation of that design scaled down in frequency. The polarizing grids used in the diplexers are free-standing 0.05-mm-diam BeCu grids with 75 wires per centimeter mounted on removable forms.

Four different sets of feed horns and lenses give a far-field −11-dB full beam-width of 4.2° independent of frequency in each of the four frequency subranges, namely in 90–120 GHz, 130–190 GHz, 200–290 GHz, and 280–360 GHz. The feed horns have a flare angle of 4.57° and are corrugated with the first 10 slots tapered in depth in order to improve the horn SWR and reduce coupling to the EH_{12} mode in the throat region [26], [27]. The circular waveguide at the throat of the horn is coupled to a standard rectangular guide via a five-section, quarter-wave transformer.

The circularly symmetric lenses are made from Teflon. The lens is designed on the basis of geometrical optics and is constructed so that the surface towards the feed is plane. The lens thickness, at a given radial distance from the center, was derived from the parametric formulas given in [28]. The lens surfaces are concentrically grooved in order to reduce reflection losses at the air/dielectric interface. The grooves have an easily machined triangular cross section and are designed [29] to result in a power reflection coefficient for the lens of less than 0.01 over the entire frequency subrange. The total loss of the lens, including the effects of dissipation in the dielectric and reflections at the air/dielectric interface is less than 0.15 dB.

Both diplexers have been measured to evaluate their performance and to obtain necessary calibration data. The lower RF frequency diplexer has a total loss, including lens reflection and feed coupling losses, of less than 0.4 dB when operating with a 1.5-GHz IF. The total loss of the higher frequency diplexer operating with the same IF is between 0.4 and 0.6 dB at frequencies from 200 to 290 GHz and increases to ~ 0.8 dB at 350 GHz. The diplexers provide more than 20-dB rejection of the local oscillator noise sidebands.

The local oscillator sources used in measurement setups are frequency-multiplied klystrons. Four frequency multipliers have been developed to cover the entire frequency

[1]The effective input noise temperature is the temperature to which the source conductance of an identical, but noiseless, two-port must be heated in order to provide an available noise power spectral density at the output equal to that generated by the noisy two-port with source conductance at absolute zero temperature.

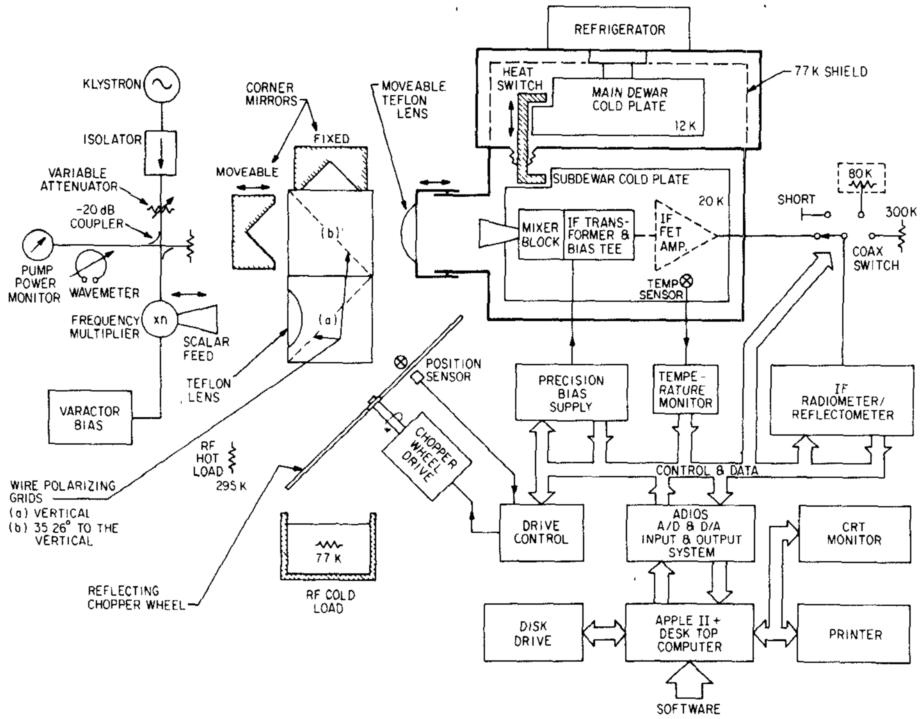


Fig. 2. Simplified block diagram of the measurement system.

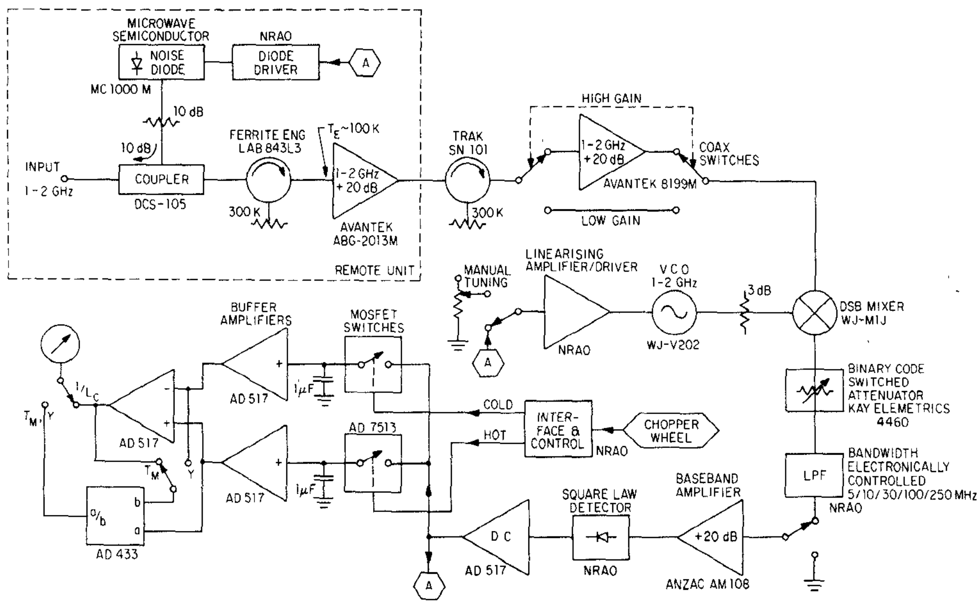


Fig. 3. Simplified diagram of the computer-controlled 1–2-GHz radiometer/reflectometer. ⬡ indicates signals coming to or from other components of the measurement system ("A" represents the computer interface input and output system ADIOS).

range from 90 to 350 GHz. Crossed-waveguide frequency doublers provide an LO signal in the two lower frequency subranges [30], [31]. In the frequency range from 200 to 290 GHz, an efficient frequency tripler [32] is used. The LO source used in measurements at 310 to 350 GHz is a $6\times$ multiplier chain composed of a quasi-optical tripler [33] driven by high-output power frequency doublers [34].

RF loads made from Eccosorb AN72 formed into a pyramidal shape for minimal error due to reflections from the terminations are used as input noise sources. One load is at room temperature, while the other is immersed in liquid nitrogen enclosed in a styrofoam bucket. The diplexer RF input beam is switched between the two loads by a rotating reflecting chopper wheel made from aluminum.

DC bias from a computer controllable precision bias supply is fed to the mixer under test through an IF transformer and bias tee [9] which is integrated with the mixer block. The IF output form the transformer is usually connected to the radiometer/reflectometer through a gold-plated, stainless steel, coaxial air line having 0.15 dB of loss. A low-noise IF amplifier [35] can be inserted between the transformer output and IF line if the performance of the mixer in a receiver configuration is to be tested. The amplifier is mounted on the sub-dewar cold plate close to the mixer and when cooled to 20°K has input noise temperature less than 10°K between 1.2 and 1.8 GHz with a gain of 30 dB and an input VSWR of less than 1.4:1 over the same range.

Noise at the sub-dewar IF output is measured by a stable, precisely calibrated, computer-controlled 1–2-GHz radiometer/reflectometer mentioned in the preceding section and shown schematically in Fig. 3. The remote unit is placed close to the sub-dewar IF output in order to minimize the length of the input cable. The radiometer/reflectometer has an effective input noise temperature of about 300°K when the 60-MHz measurement bandwidth is selected and is sufficiently stable for recalibration to be required every three or four hours.

An output signal from an accurate square law detector (detector error less than 0.5 percent at < -16-dBm IF input level) incorporated in the radiometer is processed not only by the computer but also by a noise monitoring circuitry which provides readings proportional either to the mixer noise temperature or the Y factor, or to the reciprocal of the mixer conversion loss. Such an arrangement greatly simplifies the optimization of mixer tuning and bias where only relative changes in mixer performance need to be monitored.

An electrically controlled coaxial switch at the radiometer input (Fig. 2) is used to select either the mixer (or receiver) output or any of three calibration standards. The short circuit and the well-matched loads which are accurate, absolute standards of noise devised by Weinreb [36] are connected to the switch through coaxial cables of exactly the same length as the fourth (mixer) cable. The radiometer/reflectometer may then be calibrated at the plane of the sub-dewar output connector including the IF cable in the radiometer/reflectometer calibration.

The operation of each measurement setup is controlled by an Apple II+ desktop computer which is interfaced to the setup through an input and output system (ADIOS) [37] comprising digital interfaces and analog-to-digital and digital-to-analog converters. User oriented "friendly" interactive software completes the test system.

IV. Operation of the Measurement System

The performance of the computer-aided system can be optimized not only by instruments employed in measurements but also by careful design of the software which controls system operation in various tests and which can compensate hardware deficiencies.

A. Measurements During Cooling or Warming of a Mixer

Fast and accurate measurements and real-time data processing are indispensable to successfully test the mixer during cooling because measurements at a given temperature have to be made within a period of time that is short enough for little temperature change to occur. This can be achieved only with the aid of a computer. It is also necessary to limit the measurements to the most important tests.

A simplified block diagram of the software controlling the measurements during cooling or warming is shown in Fig. 4. Before starting the measurements, the computer assists the user in setting a test program for the cooldown or warmup. If noise temperature is to be measured, the computer checks the radiometer/reflectometer calibration and returns to the main menu if recalibration is needed. A measurement loop employed has been carefully optimized to obtain high accuracy and to minimize the effect of temperature change between the first and the last measurement points. The measured data are stored on the disk for further processing by the computer at a later time to produce plots of the measured diode parameters at specified temperatures or as a function of temperature.

At each temperature, the system measures the I–V characteristic of the mixer diode and the equivalent IF noise temperature with dc bias only, T_{dc}[2], employing the formulas given in Section II. The measurements are made at bias currents in the range from 10 nA to 10 mA and at an IF frequency preset by the test program to any value from 1 to 2 GHz. The results of measurements and real-time calculations are plotted versus bias current on a CRT monitor. When the measurements at a given temperature are completed, the computer attempts to fit the data to a model response of an ideal exponential diode with a series resistor [38], [39] (i.e., $V_D = V_j + I_D R_s = V_j + R_s I_{sat} [\exp(qV_j/\eta kT) - 1]$) using the least-squares method. It also computes residuals of the fit and derivatives

[2] The measured quantity T_{dc} includes noise contributions from sources other than just the diode, i.e., from mount losses, and is quite distinct from the noise temperature of the dc biased diode [4], [23].

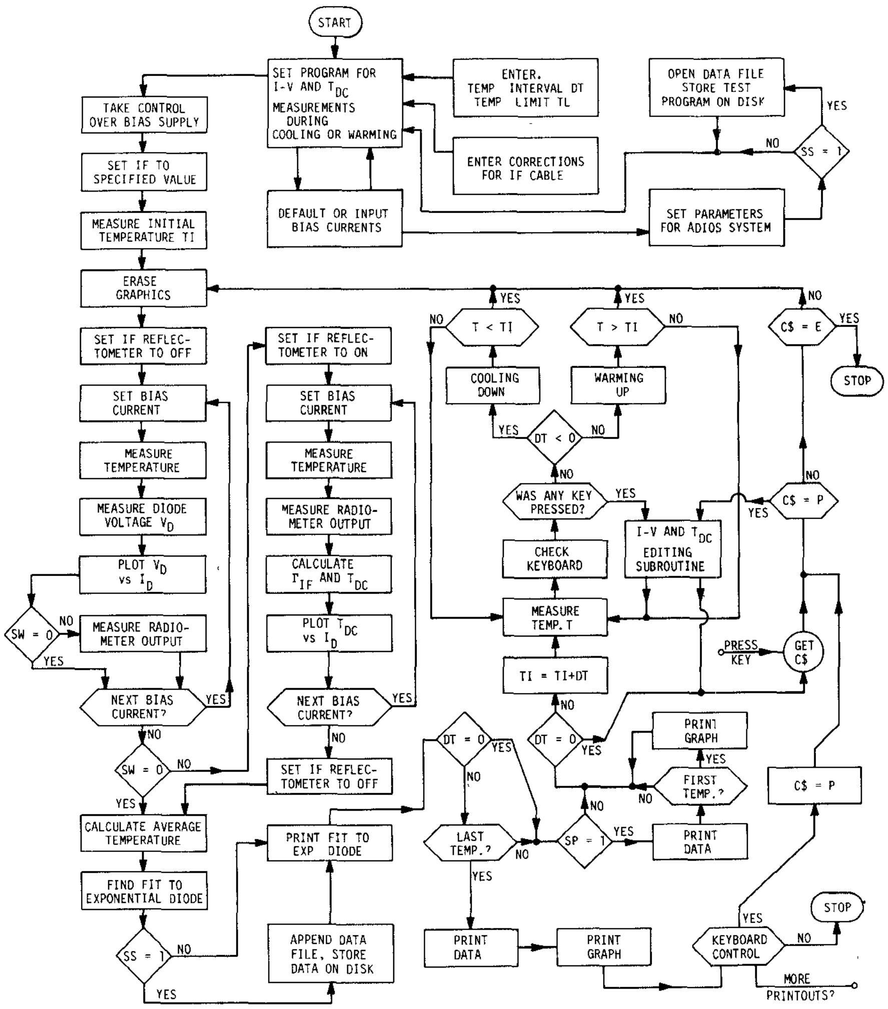


Fig. 4. Simplified block diagram of the software controlling the measurements and data processing during cooling or warming of a mixer. Operation of the system depends on control variables the values of which are set in establishing the test program: $SW=0$—no noise temperature measurements are to be made; $SS=1$—data is to be stored on disk; $SP=1$—full printouts at each temperature.

$dV_D(I_D)/d\log(I_D)$ and $dV_j(I_D)/d\log(I_D)$. These are very useful in characterizing the quality of a Schottky-barrier mixer diode and provide more insight into the diode performance than the commonly used parameter $\Delta V = V_D(100\ \mu A) - V_D(10\ \mu A)$. Any deviation in the diode $I-V$ characteristic from the exponential response can easily be traced because the latter derivative is independent of $\log(I_D)$ for the ideal diode. A correlation between the $I-V$ characteristic and an excess noise sometimes present in cooled Schottky diodes can also be studied. Effects of a whisker losing contact with the diode's anode or punching through the diode epilayer can be monitored as the temperature is varied, thus providing indications for diode contacting and mixer assembling.

B. Measurements at Constant Temperature

Different criteria may be applied in optimizing the operation of the measurement system if the temperature of the mixer is constant or varies very slowly. The accuracy of measurements is of primary importance while the speed is no longer a limiting factor. Thus, more complexity and versatility both in testing and data processing is permissible and more information may be printed out between measurements. Therefore, the software used in mixer testing at a constant temperature includes also $I-V$ characteristics and T_{dc} measurements, but different measurement loops are now employed. The equivalent IF noise temperature of the mixer with dc bias only T_{dc} may be measured not only at a fixed IF frequency, but also with the IF swept from 1 to 2 GHz in steps preset by the software. However, only that section of the software that supervises tests performed on the mixer with the LO signal applied is shown in Fig. 5.

Mixer noise temperature and conversion loss may be measured at a fixed IF frequency and also with IF center frequency swept from 1 to 2 GHz in preprogrammed steps. At a given frequency and level of the millimeter-wave local-oscillator signal and for given dc mixer diode bias,

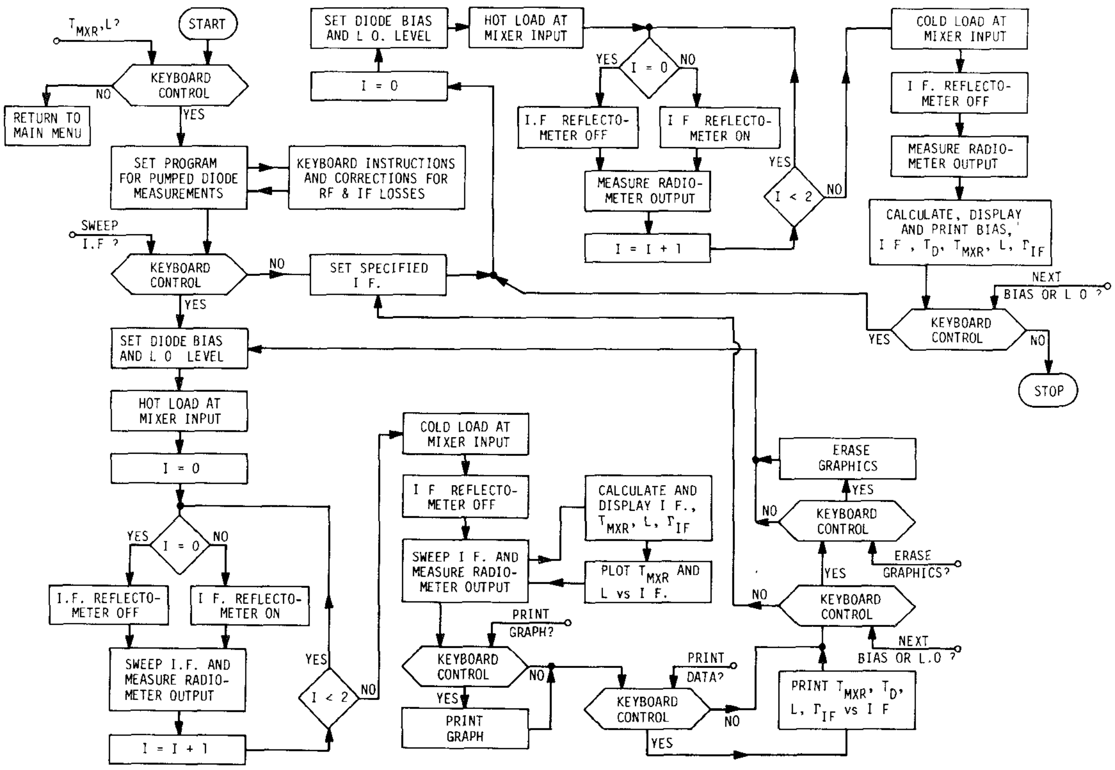


Fig. 5. Simplified block diagram of the software controlling the measurements and data processing at constant temperature.

the IF frequency is swept three times as indicated in Fig. 5. In the first and second sweeps, the RF hot load is in front of the mixer input, while in the third sweep, the RF cold load is seen by the mixer. The IF reflectometer noise source is turned on during the second sweep only. The mixer noise temperature and conversion loss are calculated and plotted versus IF during the last sweep.

The results of the measurements may be further processed with the aid of the computer, which provides an easy and convenient means for optimizing, characterizing, and documenting the RF performance of the mixer.

V. Summary

The theory for accurate measurements of millimeter-wave mixers has been presented. The corrections that need to be applied in order to determine mixer parameters from measured quantities have been derived and sources of potential measurement inaccuracies inherent in the hot/cold load measurement technique have been indicated.

Two computerized measurement systems operating on the basis of this theory have been constructed to allow testing of millimeter-wave mixers in the frequency range from 90 to 350 GHz. The design criteria and descriptions of both the hardware and the software have been given. The measurement systems have been extensively used in testing of millimeter-wave mixers, e.g., [26], [40], and have been an essential and invaluable asset in mixer development.

A *W*-band, fixed-tuned, cryogenic mixer has been selected to illustrate in the companion paper [1] the operation of the measurement system and to show the versatility and thoroughness of the available tests, which in many cases would not be feasible without the aid of a computer.

Acknowledgment

The authors are grateful to W. Luckado, G. Taylor, and D. Dillon for their excellent work in fabricating the many components of the measurement systems. Prof. R. Mattauch of the University of Virginia is thanked for supplying the Schottky-barrier varactor diodes. Thanks also go to N. Horner, Jr., for his assembly of the frequency multipliers.

References

[1] M. T. Faber and J. W. Archer, "Millimeter-wave, shot-noise limited, fixed-tuned mixer," *IEEE Trans. Microwave Theory Tech.*, this issue, pp. 1172–1178.

[2] J. M. Kenney, "The simultaneous measurement of gain and noise using only noise generators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 603–607, Sept. 1968.

[3] M. Akaike and S. Okamura, "Semiconductor diode mixer for millimeter-wave region," *Electron. Commun.* (Japan), vol. 52-B, pp. 84–93, 1969.

[4] S. Weinreb and A. R. Kerr, "Cryogenic cooling of mixers for millimeter and centimeter wavelengths," *IEEE J. Solid-State Circuits*, vol. SC-8, no. 1, pp. 58–63, Feb. 1973.

[5] A. R. Kerr, "Low-noise, room temperature and cryogenic mixers for 80–120 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 781–787, Oct. 1975.

[6] A. R. Kerr, R. J. Mattauch, and J. A. Grange, "A new mixer design for 140–220 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 399–401, May 1977.

[7] H. Cong, A. R. Kerr, and R. J. Mattauch, "The low-noise 115-GHz receiver on the Columbia-GISS 4-ft. radio telescope," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 245–248, Mar. 1979.

[8] J. W. Archer and R. J. Mattauch, "Low noise, single-ended mixer for 230 GHz," *Electron. Lett.*, vol. 17, no. 5, pp. 180–181, 5 Mar. 1981.

[9] J. W. Archer, "All solid-state, low-noise receivers for 210–240 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1247–1252, Aug. 1982.

[10] N. R. Erickson, "A cryogenic receiver for 1 mm wavelength," in *6th Int. Conf. Infrared Millimeter Waves Dig.*, 1981, p. W-3-7.

[11] B. Vowinkel, K. Grüner, H. Süss, and W. Reinert, "Cryogenic all solid-state millimeter wave receivers for airborne radiometry," in *1983 IEEE MTT-S Int. Microwave Symp. Dig.*, 1983, pp. 566–568.

[12] C. R. Predmore, A. V. Räisänen, N. R. Erickson, P. F. Goldsmith, and J. L. R. Marrero, "A broad-band, ultra-low-noise, Schottky diode mixer receiver from 80 to 115 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 498–506, May 1984.

[13] E. R. Carlson, M. V. Schneider, and T. F. McMaster, "Subharmonically pumped millimeter-wave mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 706–715, Oct. 1978.

[14] E. L. Kollberg and H. H. G. Zirath, "A cryogenic millimeter-wave Schottky diode mixer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 230–235, Feb. 1983.

[15] N. Keen and S. Lidholm, "*K* factor simplifies chopped noise readings," *Microwaves*, p. 59, Apr. 1981.

[16] R. Trambarulo and H. S. Berger, "Conversion loss and noise temperature of mixers from noise measurements," in *1983 IEEE MTT-S Int. Microwave Symp. Dig.*, 1983, pp. 364–365.

[17] C. T. Stelzried, "Microwave thermal noise standards," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 646–654, Sept. 1968.

[18] A. R. Kerr, "The thermal noise of lossy cables used in noise measurements" NASA/Goddard Institute For Space Studies Int. Rep., New York, Dec. 1980.

[19] "Description of the noise performance of amplifiers and receiving systems," *Proc. IEEE*, vol. 51, pp. 436–442, Mar. 1963.

[20] A. V. Räisänen, "Formulas for the noise temperature and noise figure of a mixer and a heterodyne receiver derived from the basic noise figure definition," Five College Radio Astronomy Observatory Rep. No. 132, Univ. of Massachusetts, Amherst, 1979.

[21] T. Y. Otoshi, "The effect of mismatched components on microwave noise temperature calibrations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 675–686, Sept. 1968.

[22] H. Fukui, "Available power gain, noise figure and noise measure of two-ports and their graphical representations," *IEEE Trans. Circuit Theory*, vol. CT-13, no. 2, pp. 137–142, June 1966.

[23] A. R. Kerr, "Shot-noise in resistive diode mixers and the attenuator noise model," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 135–140, Feb. 1979.

[24] J. W. Archer, "A Multiple mixer, cryogenic receiver for 200–350 GHz," *Rev. Sci. Instr.*, vol. 54, no. 10, pp. 1371–1376, Oct. 1983.

[25] D. H. Martin and E. Puplett, "Polarized interferometric spectroscopy for the millimeter and submillimeter spectrum," *Infrared Phys.*, vol. 10, pp. 105–109, 1969.

[26] J. W. Archer and M. T. Faber, "A very low-noise receiver for 80–120 GHz," *Int. J. Infrared Millimeter Waves*, vol. 5, no. 8, pp. 1069–1081, Aug. 1984.

[27] J. W. Archer and M. T. Faber, "Low-noise, fixed-tuned, broadband mixer for 200–270 GHz," *Microwave J.*, no. 7, pp. 135–142, July 1984.

[28] J. Silver, *Microwave Antenna Theory and Design*, (M.I.T. Rad. Lab Series, vol. 12). New York: McGraw-Hill, 1949, ch. 11.

[29] J. W. Archer and M. T. Faber, "A simple model for computer-aided analysis and design of grooved dielectric panels and lenses," in preparation, Apr. 1984.

[30] J. W. Archer, "A high performance frequency doubler for 80 to 120 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 824–825, May 1982.

[31] J. W. Archer, "Millimeter wavelength frequency multipliers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 552–557, June 1981.

[32] J. W. Archer, "An efficient 200–290-GHz frequency tripler incorporating a novel stripline structure," *IEEE. Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 416–420, Apr. 1984.

[33] J. W. Archer, "A novel quasi-optical frequency multiplier design for millimeter and submillimeter wavelengths," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 421–427, Apr. 1984.

[34] J. W. Archer and M. T. Faber, "High-output, single- and dual-diode, millimeter-wave frequency doublers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 533–538, June 1985.

[35] S. Weinreb, D. L. Fenstermacher, and R. Harris, "Ultra low-noise, 1.2–1.7 GHz, cooled GaAs FET amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-30, pp. 849–853, June 1982.

[36] S. Weinreb, private communication, 1982.

[37] G. Weinreb and S. Weinreb, "ADIOS—Analog-digital input output system for Apple computer," National Radio Astronomy Observatory, Electronics Division Int. Rep. No. 212, Apr. 1981.

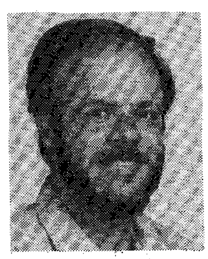
[38] D. N. Held and A. R. Kerr, "Conversion loss and noise of microwave and millimeter-wave mixers: Part 1—Theory," and "Part 2—Experiment," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 49–61, Feb. 1978.

[39] M. T. Faber and W. K. Gwarek, "Nonlinear-linear analysis of microwave mixer with any number of diodes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT–28, pp. 1174–1181, Nov. 1980.

[40] J. W. Archer and M. T. Faber, "Low-noise, fixed-tuned, broadband mixer for 200–270 GHz," in *1984 IEEE MTT-S Int. Microwave Symp. Dig.*, 1984, pp. 557–559.

Marek T. Faber was born in Skierniewice, Poland, in 1947. He received the M.Sc. (honors) degree in electronic engineering from the Warsaw Technical University, Warsaw, Poland, in 1970, the M.Sc. degree from the University of Manitoba, Winnipeg, Man., Canada, in 1975, and the D.Sc. (with highest distinction) degree from the Warsaw Technical University in 1980.

Since 1970, he has been with the Institute of Electronics Fundamentals, Warsaw Technical University, where he is an Assistant Professor. Since 1982, he has been on a three-year leave of absence at the National Radio Astronomy Observatory, Charlottesville, Virginia. His research activities have been in the field of microwave circuit theory and techniques, especially in microwave receivers and general theory of microwave multidiode mixers. Currently, he is working on low-noise, millimeter-wave mixers and frequency multipliers.



John W. Archer (M'82–SM'83) was born in Sydney, Australia, in 1950. He received the B.Sc., B.E. (with first class honors), and Ph.D. degrees from Sydney University in 1970, 1972, and 1977, respectively.

From 1974 to 1977, he was responsible for the successful development of a unique (at that time) variable baseline, phase stable, two-element interferometer for solar astronomical investigations at 100 GHz. During this period, he was associated with both Sydney University and CSIRO, Division of Radiophysics, in Australia. From 1977 to 1979, he was with the NRAO's VLA project. During this period, he was responsible for the evaluation and improvement of the performance of the over-dimensioned waveguide system, as well as for the design of components for the IF section of the array. From 1979 to 1984, he was at NRAO's Central Development Laboratory, where his main responsibility was to coordinate the development of state-of-the-art millimeter wavelength receiver technology for use at the NRAO Kitt Peak antenna. This work entailed the development of low-noise mixers, harmonic generators, and novel mechanical and quasi-optical structures for millimeter-wave receivers. Since 1984, he has been with CSIRO Division of Radiophysics, where he leads a group developing microwave GaAs devices for commercial applications and for applications to radio astronomy.

Dr. Archer is a member of the Astronomical Society of Australia.