An Investigation of a Feedback Control System for Stabilization of Microwave Radiometers*

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Summary—A method of stabilizing receivers for radio telescopes is discussed and shown to be capable of substantially reducing sensitivity to gain fluctuations. The system employs a variable noise source as a controlled feedback element.

Such a system does not require long warm up times since the output is dependent only upon the stability of the variable noise source and reaches stabilization very rapidly.

Investigations were made of a number of variable noise sources for use in the system, including: gas discharge tubes with variable attenuators, crystal diodes, and gas discharge tubes with variable duty cycles. Several crystal diodes were measured and the noise output was found to be linear with current for temperatures up to approximately 5000°K. A variable noise source using a gas discharge tube with variable duty cycles to adjust the average temperature of the comparison termination of the radiometer is also discussed.

Results are given for an experimental X-band system using a crystal diode as a variable noise source. For this system, a reduction of gain by 5 db had no measureable effect on the accuracy of measurement.

MICROWAVE radiometers are generally operated as straightforward receiver-detector combinations. As a result, gain fluctuations in a radiometer will affect the output signal and in high sensitivity applications such as radioastronomy, gain fluctuations can seriously limit the usefulness of the system.

One method recently used[1,2] to minimize the effects of gain fluctuations is to inject excess noise into the antenna transmission line of a radio astronomy receiver. Sufficient noise is added when no signal is present so that the temperature of the antenna transmission line is equal to that of the reference termination used. Gain variations then do not affect the system output unless a signal is present. This adds greatly to the zero stability of the instrument, but gain fluctuations still affect the signal.

Feedback control techniques can be used to further minimize the effects of gain fluctuations. A microwave radiometer system using a feedback technique was used by Ryle and Vonberg in making solar measurements.[3] In this system, a temperature-limited diode was used as the variable noise source, and the amplified error signal from the receiver detector controlled the filament current of the diode so that the diode temperature equaled that of the antenna.

The application of this technique at frequencies above 1000 Mc has been hampered by the lack of a suitable variable noise source in these frequency regions. In this paper, a microwave radiometer control system is discussed using, as the feedback signal, a variable noise source. The differential temperature between the input signal and the variable noise source is used as the error signal to control the variable noise source.

I. System Analysis

In microwave comparison radiometers, there are two sources of noise which give rise to errors in measurements, thermal fluctuations and gain fluctuations. Thermal fluctuations are determined by the excess system noise and the received signal itself. Gain fluctuations cause variations when signals are present. Expressed in terms of an equivalent input temperature, the mean square fluctuation of the system output is

$$\sigma_T{}^2 = \left[\frac{C(T_N + T_A)}{\sqrt{B\tau}}\right]^2 + \left[2C\Delta T\frac{\Delta K}{K}\right]^2, \qquad (1)$$

where

$\sigma_T{}^2$ = mean square fluctuation $(°K)^2$
C = radiometer system constant determined by the system configuration
T_N = system excess noise temperature °K
T_A = antenna temperature °K
B = radiometer receiver bandwidth (cps)
τ = radiometer integration time (seconds)
$\Delta T = T_A - T_R$ (°K)
T_R = reference termination temperature (°K)
$\Delta K/K$ = fractional gain fluctuations.

The first term is due to thermal variations, the second to gain variations.

Using a feedback control system, the system reference temperature is continuously varied so that $T_R \approx T_A$, and thus errors due to gain fluctuation are reduced to a value below the thermal noise in the system.

In considering the microwave radiometer as a feedback system, the analysis is identical to other feedback systems, complicated somewhat by the presence of random fluctuations. The block diagram of the basic feedback radiometer system is shown in Fig. 1.

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[1] J. C. Greene, "Stability requirements and calibration of radiometers when measuring small noise powers," PROC. IRE, vol. 45, pp. 359–360; March, 1957.

[2] F. D. Drake and H. I. Ewen, "A broadband microwave source comparison radiometer for advanced research in radio astronomy," PROC. IRE, vol. 46, pp. 53–60; January, 1958.

[3] M. Ryle and D. D. Vonberg, "An investigation of radio frequency radiation from the sun," *Proc. Roy. Soc. (London)*, vol. 193, pp. 112–117; April, 1948.

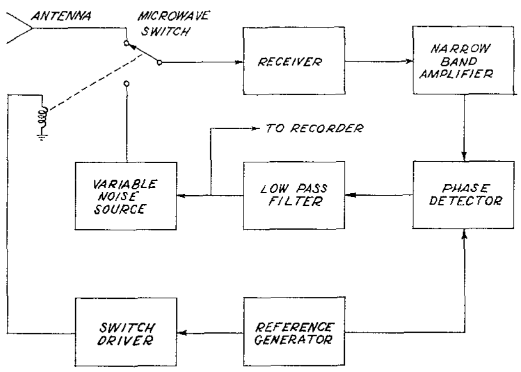

Fig. 1—Basic system block diagram.

Fig. 2 is a block diagram showing the system as a simple feedback control system.

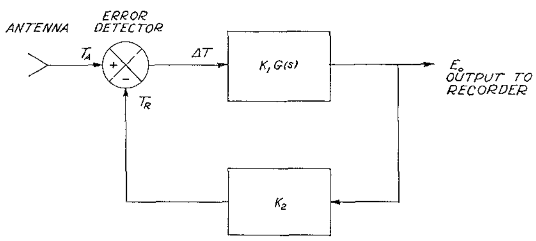

Fig. 2—Simplified block diagram.

In this system, the error detector is the microwave switch, and the block labeled $K_1G(s)$ represents the lumped components of receiver, post detector amplifiers, detectors and filters, with gain K_1 and frequency function $G(s)$. The block labeled K_2 represents the variable noise source, with transfer function K_2. It is assumed that the frequency response of the variable noise source does not affect overall system operation (*i.e.*, its response is fast compared to the rest of the system). For this analysis, K_1 has the dimension of v/°K while K_2 has the dimension of °K/v. The input temperature is T_A and the comparison temperature is T_R.

$$\frac{E_0}{T_A} = \frac{K_1 G(s)}{1 + K_1 K_2 G(s)} \cdot \tag{2}$$

For $K_1 K_2 G(s) \gg 1$

$$E_0 \approx \frac{T_A}{K_2} \cdot \tag{3}$$

Thus the stability and linearity of the output is dependent upon the stability and linearity of the variable noise source.

The steady-state error of the system, ϵ, is the difference between the output voltages of (3) and (2) and is,

$$\epsilon = \frac{E_0}{K_1 K_2} \cdot \tag{4}$$

The time constant of the closed loop system is determined by the open loop transfer function. For a single section RC filter on the output, that has a time constant long compared with the other elements in the system the open loop frequency function is

$$G(s) = \frac{1}{1 + \tau s} \tag{5}$$

where

s = Laplace operator (jw)
τ = filter time constant RC (seconds)

Substituting this value for $G(s)$ in (2),

$$\frac{E_0}{T_A} = \frac{K_1}{1 + K_1 K_2} \cdot \frac{1}{1 + \dfrac{\tau s}{1 + K_1 K_2}} \cdot \tag{6}$$

Therefore the time constant of the closed loop system is smaller by a factor $(1 + K_1 K_2)$ than the open loop time constant.

The effect of gain fluctuations can be obtained by differentiating (2). For the region where $G \approx 1$,

$$\frac{dE_0}{E_0} = \frac{dK_1}{K_1} \cdot \frac{1}{1 + K_1 K_2} \cdot \tag{7}$$

That is, the effect of gain variations is reduced by a factor of $(1 + K_1 K_2)$.

Substituting (4) into (7) and for $K_1 K_2 \gg 1$,

$$dE_0 = \frac{dK_1}{K_1} \epsilon.$$

Therefore, the errors arising from gain fluctuations are always less than the static errors of the system since $dK_1/K_1 < 1$.

Effects of System Noise

Random thermal noise in the system can also contribute errors when the system is operated near the end of its linear range. Consider a voltage variable noise source with the characteristics shown in Fig. 3.

The noise source is linear for voltages from zero to E max. Beyond that range the noise source has an output independent of the applied voltage. The minimum temperature is determined by the physical temperature of the noise source, and the maximum temperature is determined by the physical and electrical properties of the noise source itself.

If the input voltage to the noise source is a random noise voltage with zero mean and a variance of $\sigma_{E_0}{}^2$ the mean temperature of the noise source is not its minimum value, but due to the rectifying action around zero voltage, the mean output temperature $\overline{T}_R$ will be

$$\overline{T}_R = K_2 \frac{\sigma_{E_0}}{\sqrt{2\pi}}, \tag{8}$$

where K_2 is the slope of the temperature-voltage curve of the noise source.

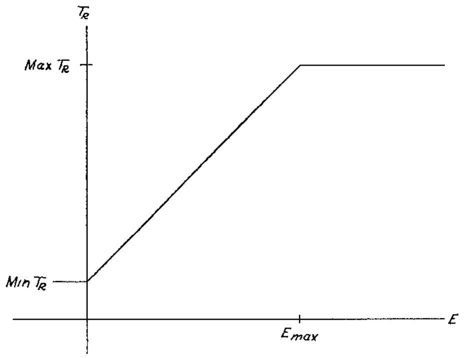

Fig. 3—Noise source characteristics.

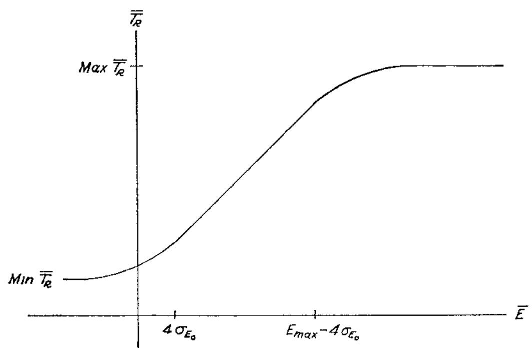

Fig. 4—Noise source characteristic with a noisy input voltage.

A similar effect will occur as the input voltage approaches the value for the maximum noise source temperature. The net result is to reduce the linear range of the variable noise source as shown in Fig. 4. If values of $\overline{E}=4\sigma_{E_0}$ and $\overline{E}=E_{\max}-4\sigma_{E_0}$ are chosen as determining the linear region of the noise source, then, using the relationship that $K_2\sigma_{E_0}=\sigma_{T_R}$, the noise source will be linear for the region

$$4\sigma_{T_R} < \overline{T}_R < \max \overline{T}_R - 4\sigma_{T_R} .$$

The 4σ value was chosen arbitrarily. The probability of exceeding the 4σ value is 63×10^{-6}.

II. Variable Noise Sources

As pointed out in section I, the variable noise source and its transfer function K_2 determine directly the stability of the output of the system. With this in mind, several variable noise sources were considered. They fall into three classes: standard noise sources with variable attenuators, continuously variable noise sources, and standard noise sources with variable duty cycle.

In the centimeter wavelength region, the argon gas discharge tube is the generally accepted standard noise reference. This device has a thermal output 15.28 db above T_0 (290°K). It is very insensitive to ambient temperature and the discharge current through the tube. This noise source used with a suitable precision attenuator can provide a variable noise source dependent only on the variable attenuator characteristics.

Precision variable attenuators have three basic configurations: waveguide beyond cutoff piston attenuators, metallicized glass vane attenuators and rotary vane attenuators. All of these types of attenuators are quite nonlinear; ranging from exponential for the waveguide beyond cutoff to a $\cos^4$ law for the rotary vane type. This would cause gain variations in the system but as long as the open loop system gain remained large, the only effect would be a nonlinear output. Faraday rotational ferrite attenuators were also considered, but were rejected because of nonlinearity and hysteresis which would prevent accurate calibration of this type of device.

Variable noise sources in the form of temperature-limited diodes provide a convenient noise source at frequencies up to about 1000 Mc. Above that frequency, the only other variable noise source capable of high equivalent noise temperatures is a reverse biased microwave semiconductor diode. Several investigators[4,5] have measured the noise output of these diodes, and discussed the mechanism of noise generation. In general, it has been found that these diodes can produce noise temperatures comparable to argon discharge tubes with reverse currents that do not exceed the diode rating. The linearity of such a noise source varies considerably from diode to diode, and therefore measurement of several diodes to find one with sufficient linearity is necessary and then the unit would require calibration.

Several diodes were measured, and found to be linear up to about 5000°K output. This included both point contact types and junction varactor diodes. Fig. 5 is a plot of the diode characteristics measured. Of the diodes tested, it was found that the varactor diodes gave the most repeatable results.

Another possible variable noise source is the argon discharge tube with a variable duty cycle. The average temperature of such a noise source is

$$T_{AV} = (T_{NS} - T_\alpha)\delta + T_\alpha,$$

where

T_{AV} = average temperature of the noise source
T_α = ambient temperature
δ = duty cycle.

Therefore, if the duty cycle is varied over the range $0\leq\delta\leq 1$, the average temperature will range from ambient to the full temperature of the noise source.

Pulsed operation of the noise source can be achieved by two methods: direct pulsed operation of the gas discharge tube, or the use of switched attenuators. Both of these methods can be used satisfactorily at low repetition rates, but as the repetition rate increases, difficulty can be experienced with either type of operation.

[4] H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 15, p. 186; 1948.

[5] G. R. Nicoll, "Noise in silicon microwave diodes," *Proc. IEE*, vol. 101, pt. III, p. 317; September, 1954.

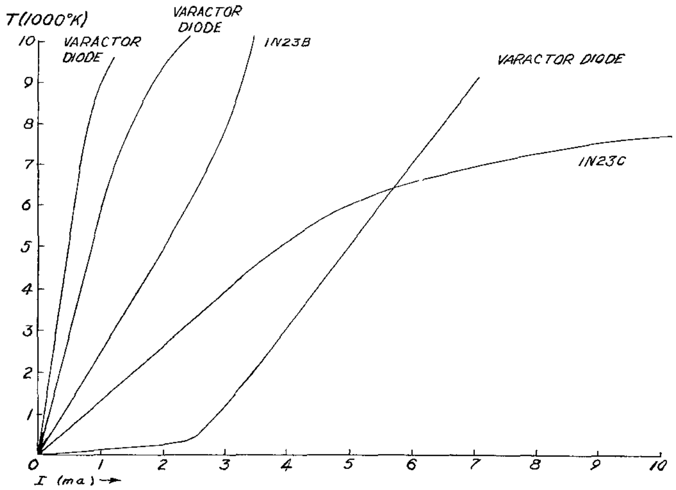

Fig. 5—Noise output of silicon microwave diodes vs current.

Pulsing of gas tubes in general is limited by the noise build up and decay which is on the order of 50 to 100 μsec.[6] Therefore, there is a limitation of minimum duty cycle at which the pulsed noise tube can be operated. In addition, to minimizing the effects of the rise and decay time, the repetition time must be long compared to the rise and decay time.

Ferrite or crystal diode switches may be used rather than pulsing the noise tube, but the isolation must be sufficiently large to prevent leakage of the noise power through the switch. In general, ferrite switches are obtainable with rise times on the order of 10 μsec or better which will permit operation over wider ranges of duty cycle and shorter repetition times than direct pulsing of the gas tube permits. Crystal diode switches are capable of even faster operation but do have the disadvantage of higher insertion losses.

III. Experimental System

To confirm the analysis made in this paper, an experimental X-band radiometer system was built. The system block diagram is shown in Fig. 6.

The test signal is an argon discharge tube with a rotary vane precision attenuator. The ferrite switch is a Faraday rotational type followed by a balanced mixer and IF amplifier. The detected output of the IF amplifier is amplified by a narrow-band (12 cps) amplifier followed by a chopper used as a phase sensitive demodulator. An operational amplifier connected as a current amplifier controls the current through a crystal diode noise source which acts as a variable comparison load. The current through the diode is then recorded as indicating the temperature of the input.

Overnight stability tests of this system were conducted, and no zero drift was detectable provided the diode had not been subjected to excess forward current or otherwise mishandled. The most serious problem in this particular system was the changes in crystal diode characteristics. It was found that if the system was allowed to saturate corresponding to a negative temperature demand, then K_2 was decreased by a factor of approximately two. This was not a permanent effect, but required several hours for the diode to return to original sensitivity.

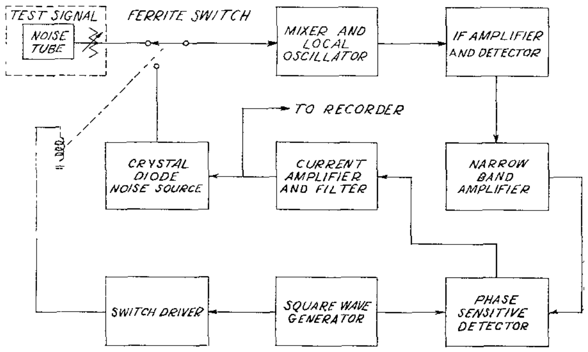

Fig. 6—Experimental system block diagram.

The gain of the system was varied and no error was measurable if the decrease in gain was not greater than 5 db. Beyond that point, the error increased with decreasing gain, to about 25 per cent for a gain reduction of 13 db.

The diode noise spectrum was measured from 8600 Mc to 9600 Mc at 100 Mc intervals and was found to be "flat" across this 1000 Mc interval. This required retuning the diode waveguide mount at each frequency, and if a broad-band diode source is required, a suitable waveguide mount would be required to match the diode over the desired band.

IV. Applications

In using a variable noise source with a radiometer feedback control systems, two cases need be considered: that of a low noise system such as a maser, and a relatively high noise system such as TWT receivers or superheterodyne receivers. In the maser system, a helium-cooled reference load is desirable. The variable noise source can be coupled to the helium-cooled reference load through a directional coupler and the temperature of the comparison arm will be

$$T = T_H + \frac{T_{NS}}{\alpha_{DC}},$$

where

T_H = temperature of the helium-cooled load
T_{NS} = temperature of variable noise source
αD_C = attenuation of the directional coupler.

If a helium-cooled reference load is unavailable, it would probably be necessary to inject the variable noise source into the antenna transmission line. Under

[6] J. Minck and M. Negrete, "Continuous Monitoring of Radar Noise Figures," Hewlett-Packard Company, Palo Alto, Calif. Application Note No. 43; 1960.

these conditions,

$$T_A = T_\alpha - \frac{T_{NS}}{\alpha_{DC}},$$

where T_α is the temperature of the reference load. This of course would increase the system noise temperature by T_α. This method could be used quite well with high noise system since the addition of noise to the antenna signal will not degrade the system performance noticeably.

In the application of variable duty cycle noise sources, two modes of operation can be considered: nonsynchronous and synchronous. For the nonsynchronous case it is necessary that the repetition period of the noise source be sufficiently shorter than the comparison period of the radiometer. This restriction is necessary to minimize the quantizing effect of the comparison period. Care must also be exercised so that no cross products of the radiometer switching frequency and the noise source repetition frequency and their associated harmonics fall within the signal spectrum.

In the synchronous mode of operation, the noise source switching is synchronized by the radiometer switching frequency. The noise source is turned on at the beginning of the comparison period and turned off at the proper time for the required average temperature. This method can ease the rise time requirement on the noise source since the noise source can be turned on before the start of the comparison period.

Control of the duty cycle can be accomplished by conventional pulse timing circuits such as linear sweep clippers or other voltage comparators. In this manner, the duty cycle can be varied with an applied voltage to an accuracy of one per cent or better. This type of variable noise source can be made to respond exponentially by using an exponential sweep instead of a linear sweep in the voltage comparator. The main requirement is that the system gain be sufficiently large so that as the noise source transfer function varies exponentially, errors are not introduced by the change in gain. Measurement of incremental changes in temperature in the presence of a high ambient noise level can be readily made with a feedback radiometer system by adding a fixed amount of noise to the variable noise source. The incremental sensitivity and range is still a function of the variable noise source. This type of radiometer also lends itself well to applications requiring a large dynamic range.

In using a variable duty cycle noise source in a radiometer, the post detector filtering and phase detector must be revised. If narrow-band filtering is applied directly to the signal, the phase as well as the average amplitude of the fundamental of the detected output will vary with the noise source. Therefore, the detected complex waveform must be amplified without distortion and a square wave reference signal used. Alternately, the reference portion of the detected waveform must be averaged prior to narrow-band amplification.

In summary, a method of making radiometer measurements has been described that is relatively independent of system gain fluctuations, and is capable of operating over wide ranges with good linearity, providing an instrument which should improve the reliability and accuracy of radiometer measurements. Also, a method of providing a precision variable noise source for radiometric measurement has been described.

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