NBS TECHNICAL NOTE 661

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Advances in the Measurement of rf Power and Attenuation Using SQUIDs

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[2] Part of the Center for Radiation Research.

[3] Located at Boulder, Colorado 80302.

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Advances in the Measurement of rf Power and Attenuation Using SQUIDs

R.A. Kamper
M.B. Simmonds
R.T.Adair
C.A. Hoer

Electromagnetics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

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Advances in the Measurement of rf Power and Attenuation Using SQUIDs*

R. A. Kamper, M. B. Simmonds, R. T. Adair, and C. A. Hoer

This report covers the progress made in the application of Superconducting QUantum Interference Devices (SQUIDs) to the measurement of rf power and attenuation during the year from July 1973 to June 1974. The earlier work on this project was reported in NBS Technical Note 643†, which contains a detailed introduction to the principles involved. We will assume the reader to be familiar with the material we presented there, since we do not repeat it in this report. In order to make the connection as smooth as possible, we have retained our earlier chapter titles as far as possible.

During the year we have developed stable SQUIDs with preset junctions which survive thermal cycling and mechanical shock. Further work is required to arrive at a version suitable for precise rf measurements. We have assembled a "breadboard" system capable of measuring rf power at levels down to 10^{-15}W in the range of frequency from 100 MHz to 1 GHz. We have extended the dynamic range of our system to measure rf attenuation to 60 dB, and developed the hardware to partially automate its operation and to accommodate step attenuators. We have tested a portable version of this system, and are in process of designing an improved version based on what we learned from the first one.

Key words: Josephson effect; quantum interference; rf attenuation; rf measurement; rf power; superconductivity.

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† Technical Note 643 will be referred to as TN 643 throughout the text.

1. MICROWAVE SQUIDS

The design of quantum interference devices which can be biased (or pumped) at 1 GHz and above presents many new problems, but the improvements available in bandwidth and signal strength make the effort worthwhile.

We have two new SQUID offerings to describe in this report:

1) An X-Band pumped parametric receiver. This device can be tuned from 100 MHz to 1 GHz (in two ranges) and has a very low noise temperature.

2) An L-Band pumped SQUID for use in our 30 MHz attenuation measurement program. This SQUID distinguishes itself by its ability to fit into a helium storage dewar through a 9/16 inch diameter access. This device also uses replaceable cartridge junctions which we will discuss in section 1.3.

1.1. The SQUID Receiver

This device is shown in figures 1 and 2. It is similar in signal coil configuration to the toroidal X-Band SQUID described in TN 643. However, the microwave cavity is three wavelengths long at 9 GHz, and has three functionally separate regions, each being one wavelength long. The first is a 0.25 mm high region where the point and the signal coil are located. This height gives a characteristic impedance of 10 Ω, which approximately matches the point's impedance at this frequency. The next region is a tapered transition which widens from this 0.25 mm height to 1.25 mm. The last region, which ties on smoothly to the wide end of the taper, provides the waveguide-to-coax conversion. This 1.25 mm high length of the cavity has a characteristic impedance of 50 Ω, so that a decent match to the 50 Ω coaxial line can be effected by simply running the center conductor across the waveguide one quarter wave-length back from the end of the cavity.

The signal coil lies in a toroidal groove cut around the Josephson point contact. The coil, in one version of this SQUID, has three spaced turns of #38 copper wire and is only 1 mm in diameter. This coil is connected in parallel with a variable piston capacitor. This capacitor can be adjusted with a control rod from the top of the cryostat. The signal is coupled into this tuned circuit through another variable capacitor. This second capacitor is adjusted so that a perfect match is achieved between the 50 Ω signal line and the resonant circuit; all the signal power is dissipated in the SQUID. The circuit, with typical values, is shown in figure 3. This figure also shows a range switch which enables us to span the decade from 100 MHz to 1 GHz with a changeover at about 350 MHz. However, the additional stray inductance introduced by the switch on the high frequency range caused a 10 dB loss in sensitivity. This was apparently due to a reduction in the tank circuit Q combined with an effective decoupling of the coil from the junction. For other tests (see section 2) this switch was removed and the three turn coil, mentioned previously, was installed. With this coil our tuning range was from 250 MHz to 800 MHz.

1.2. The L-Band SQUID

The Josephson junction cartridge (which we report on in section 1.3) has made possible a reduction in SQUID complexity, since one no longer needs an adjusting rod or the associated guides, levers and springs. It has thus become feasible to design a SQUID for the measurement of attenuation at 30 MHz which can be inserted directly into a helium storage dewar. The body of this device is 1.3 cm in diameter and 4 cm long. The principle of operation is identical to the L-Band SQUID described in section 2.2 of TN 643. The differences are that the cavity has been folded up into a cylindrical form, and the integral point contact has been replaced by a plug-in cartridge. (see section 1.3).

Figure 4 shows an exploded view of the unit. The manner in which the cavity has been folded makes its visualization less than obvious. The main capacitive region of the cavity is the hemi-cylindrical region insulated by polyimid film. The grooves around the cartridge, axially down the side of the babbitt insert, and radially across the end of the header provide the inductance for the cavity. The characteristic impedance of the cavity is about 2 Ω so that the coupling to the 50 Ω pump coax is weak. This arrangement results in equal loading of the cavity by the point contact and by the pump circuit, giving optimum performance. The current sensitivity of this SQUID, through the signal coil, is about 10 mA/φ_o.

1.3 Cartridge Mounted Junctions

We have been using stabilized point contacts (TN 643, p. 29) mounted in niobium cartridges to create a new generation of quantum interference devices. These units are interchangeable and can be "plugged in" to almost any type of quantum interference device. A cross-section of a cartridge mounted junction is shown in figure 5. The cartridges are made by bonding together two "pucks" of niobium to form a cylinder 0.250 in. in diameter and 0.25 in. long. The two halves are electrically insulated. The point and the leaf spring (mounted on the end of a stud) are screwed in from opposite ends until they touch, thus creating the junction.

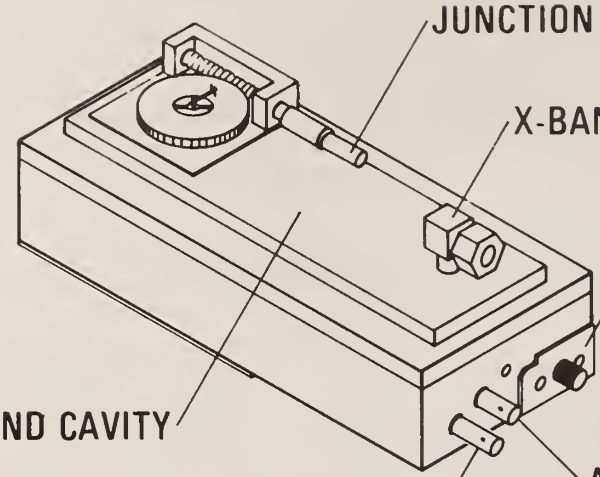
Our technique for preparing the contact surfaces has evolved somewhat since the description in TN 643 was written. The leaf spring of niobium, as well as the sharpened screw point, is electropolished. The screws and springs are then sputter coated with about 100 Å of silicon. This provides a barrier to the flow of supercurrent. About 50 Å of gold is then sputtered on top of the silicon to provide a reliable metallic contact between the point and the spring. The gold is thin enough that it does not significantly decrease the supercurrent density. Since there is no oxide to break through, the critical current is roughly proportional to the contact area. A spring contact is used since it keeps a fairly constant force on the contact in the face of thermal expansions and shocks. The contact is set by loading the spring with the niobium screw so that the microscopically sharp point is deformed into a 2 μm diameter disc. A 0.1 cm x 0.2 cm x 0.002 cm niobium spring, when displaced about 0.002 cm, gives the desired contact area. Details of the contact are shown in figure 6.

The room temperature resistance of these junctions ranges from 0.1 Ω to 0.3 Ω. This resistance drops to between 0.02 Ω and 0.06 Ω in the normal state at 4 K. Typical critical currents are in the 5 to 50 μA range for useable devices. As shown in figure 7, the critical current versus temperature behavior of these coated contacts is essentially exponential. This precludes their use in such applications as millikelvin thermometry, but variations of a degree or two around 4 K can easily be tolerated. The exceptionally low normal state resistance of these junctions tends to suppress multiple quantum transitions, consequently they are able to operate over a wider range of critical currents than conventional point contact junctions.

This extremely low normal state resistance has caused one serious problem in the measurement of attenuation at 30 MHz. The high rate of change of flux caused by the large input signal induces large shunt currents to flow through the junction. Any asymmetries in the current-voltage characteristic of the junction will thus generate harmonics or d.c. components from the 30 MHz signal. By direct four-terminal measurements of the junctions themselves we have found that a 5% difference between forward and reverse resistance is typical for a 30 mΩ (normal state resistance) junction. The L/R time constant for a SQUID using such a junction is long enough that a few quanta of 30 MHz signal produce a significant fraction of a quantum of d.c. For the specific values we have mentioned, $\frac{1}{4}\,\phi_o$ of d.c. will be generated by the rf level corresponding to the 10th zero of the rf response; this is intolerable. If we could raise the normal state resistance of the junction to 1 Ω while holding the asymmetry to 5%, then one could go to the 300th zero of rf response before accumulating $\frac{1}{4}\,\phi_o$ of d.c. offset; this would be acceptable. We are now attempting to design junctions with these characteristics.

We are still in the process of obtaining long term data on the overall reliability of these cartridge SQUID systems, but so far we have found them to be quite convenient and predictable.

TOP VIEW



BOTTOM VIEW

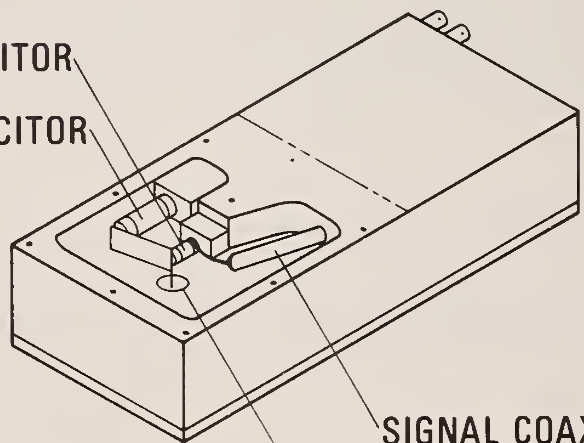


Figure 1. General view of the tunable SQUID designed for maximum sensitivity in the range 100 MHz-1 GHz. See section 1.1

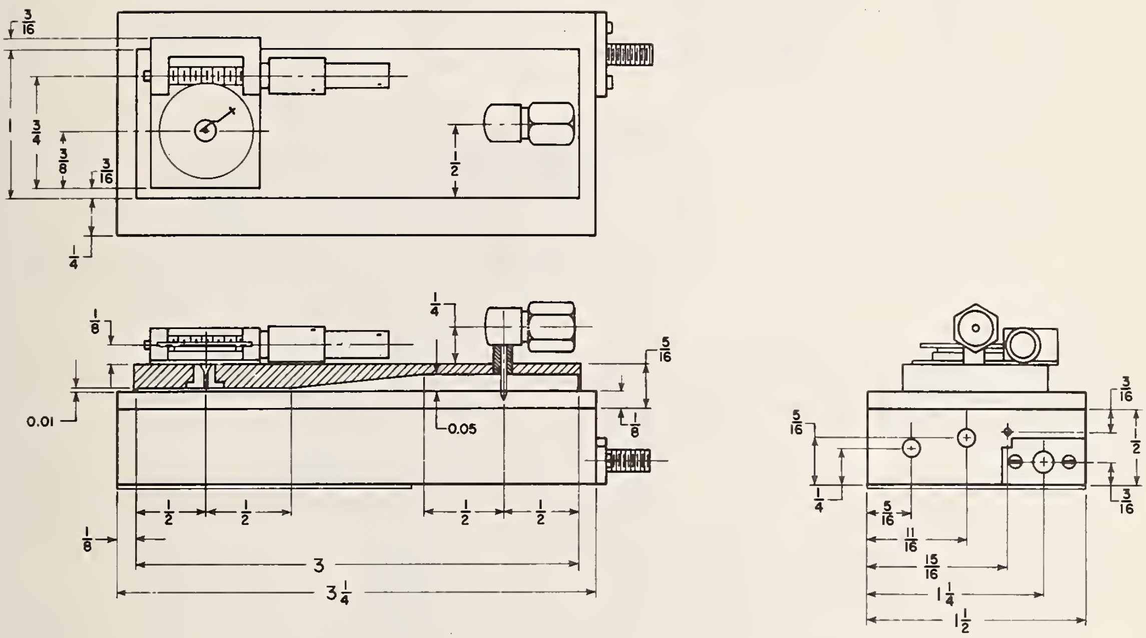


Figure 2. Essential dimensions (in inches) of the tunable SQUID shown in figure 1.

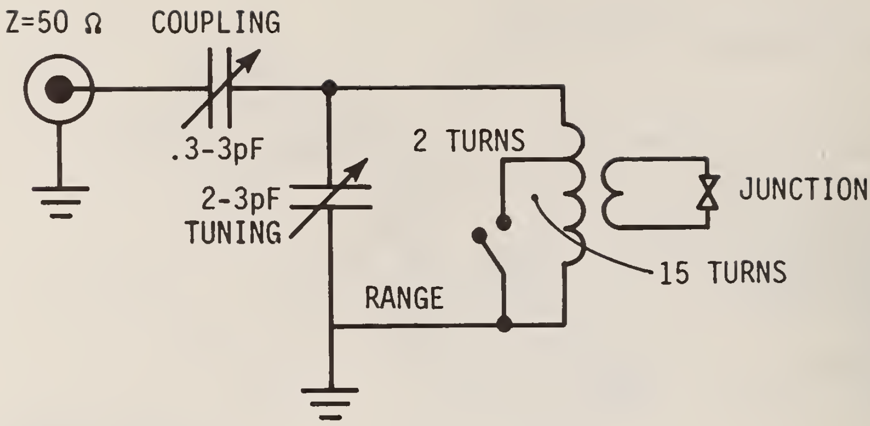


Figure 3. Coupling circuit for the tunable SQUID described in section 1.1.

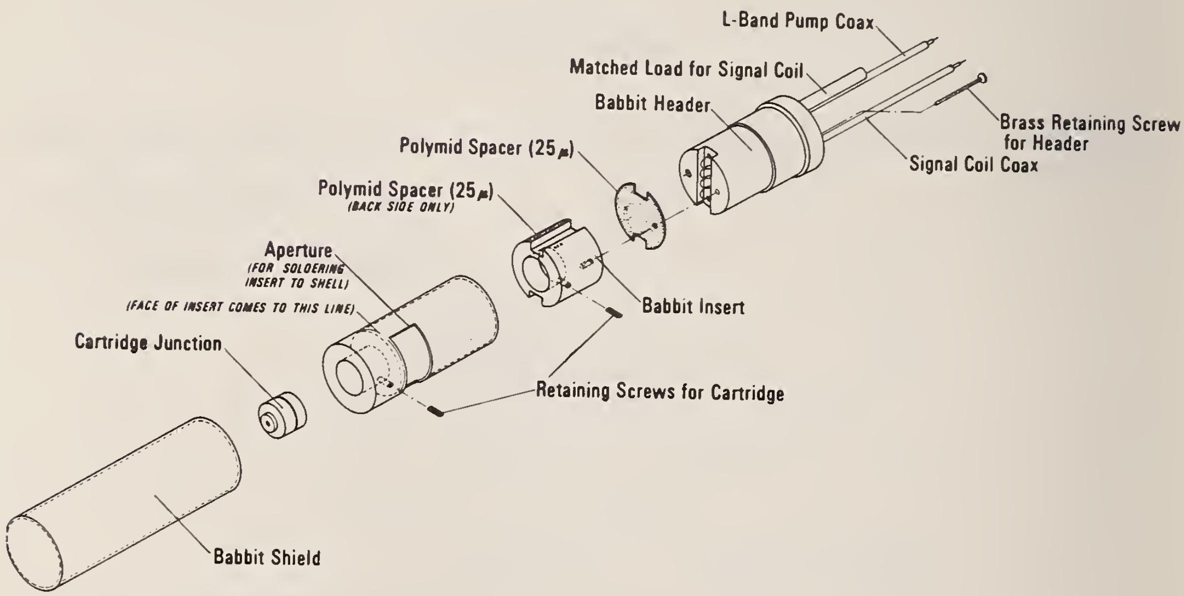


Figure 4. Exploded view of a SQUID using a cartridge-mounted Josephson junction (see section 1.2)

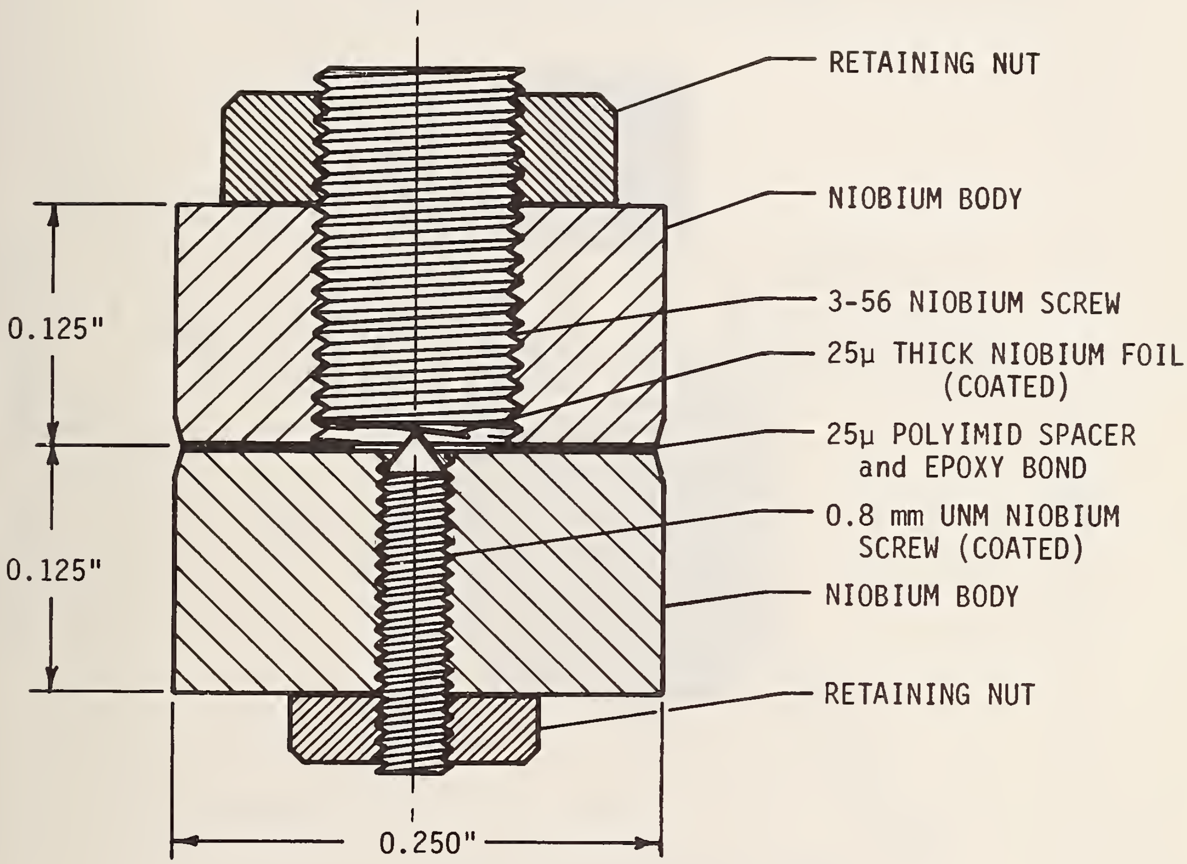
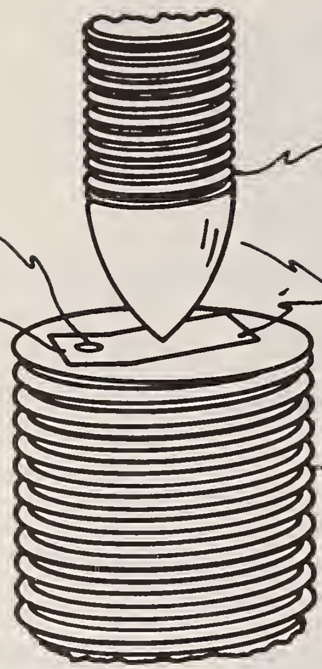


Figure 5. Cross section of cartridge-mounted Josephson junction.



CONFIGURATION OF COATED
CONTACT JUNCTION

Figure 6. Configuration of spring-loaded point contact for cartridge mounting.

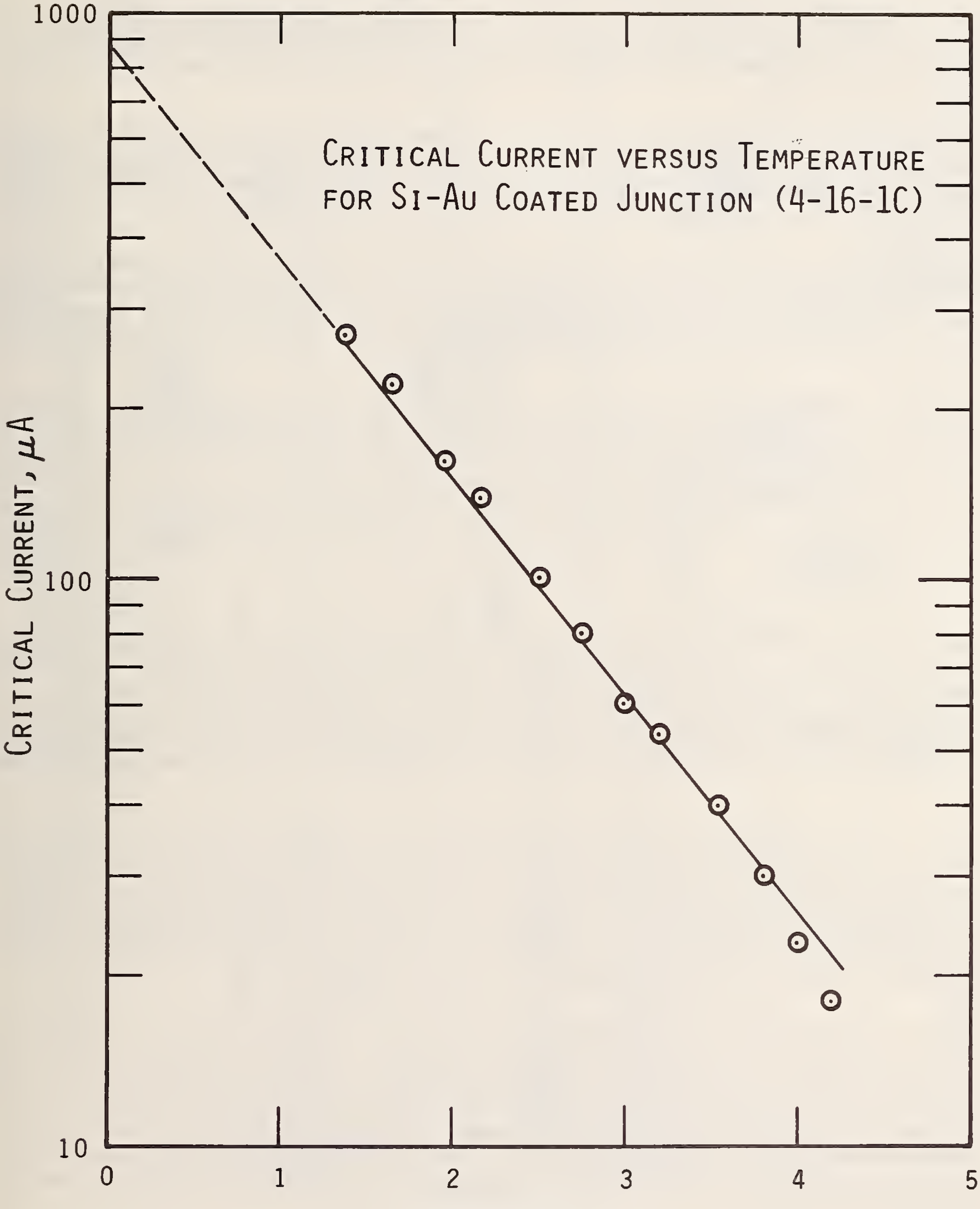


Figure 7. Variation of critical current with temperature for a typical cartridge-mounted Nb-Si-Au-Si-Nb junction.

2. MEASUREMENT OF RF POWER

In our previous report (TN 643) we described the use of a broadband SQUID to measure rf power at levels down to 10^{-9}W, and sketched a proposed scheme for extending that measurement down to 10^{-15}W using the same broadband SQUID for reference. Our more recent work has been directed towards realization of that scheme.

The resulting system is shown in figure 8. A broadband SQUID is used to prepare a reference signal of known power at some conveniently high level, and approximately the same frequency as the signal to be measured. This reference signal is attenuated by a measured amount and used to calibrate a very sensitive tuned SQUID with which the actual measurement is made.

The reference signal is generated by a stable (both in frequency and in power) signal generator, and is split into two equal parts by a 180°hybrid junction. One part is presented to a broadband SQUID which measures its power level exactly as described in section 3.1 of TN 643. This is shown on the left of figure 8. The other part of the signal power passes through a calibrated attenuator pad (70 dB in the test we conducted) to become the reference signal proper.

The actual low-level measurement is made with the SQUID described in section 1.1 of this report. It functions as a combination of mixer and parametric up-converter at the front end of what amounts to a narrow-band heterodyne receiver, shown on the right of figure 8. The frequency of the local oscillator is offset from that of the reference signal by 10 kHz. The microwave readout system for the SQUID operates at 9 GHz. The rectified voltage $\bar{V}$ at the first crystal microwave detector varies with the amplitude φ_{rf} of the magnetic flux induced in the SQUID by the rf signals according to the formula

$$\bar{V} = V_0 + V_1 J_o(2\pi\varphi_{rf}/\varphi_o)$$

where φ_o is the magnetic flux quantum. The level of the local oscillator is set on the first null of $J_o(2\pi\varphi_{rf}/\varphi_o)$, where $\partial\bar{V}/\partial\varphi_{rf}$ has its maximum value. The reference signal then mixes with the signal from the local oscillator to generate small excursions of the rf magnetic flux amplitude at the difference frequency, which cause a periodic variation in $\bar{V}$ at the difference frequency. This is amplified by an audio amplifier, rectified, and measured with a voltmeter. The bandwidth of the system is restricted to 1 kHz by a band-pass filter (centered on the difference frequency) preceding the audio amplifier.

Figure 9 shows a calibration curve for the tuned SQUID, measured at 420 MHz using the broadband SQUID (itself calibrated with DC, as explained in TN 643) for reference. It is a plot of the rectified voltage at the second detector against incident rf power at the port of the SQUID. It requires a correction of a few percent to take account of reflections in various parts of the system. We did not evaluate these reflections for this test. In a separate test, we found we could reset the system at the same power level with an rms scatter of ±0.15 dB at 3×10^{-15}W, or ±0.05 dB at 10^{-13}W. The test frequency could be chosen anywhere within the tuning range of the SQUID.

After this internal calibration, the system would be ready to measure power incident on the input port (top right, in figure 8). The overall system bandwidth of 1 kHz places severe requirements on the frequency stability of signals that may be measured with it. This is unavoidable with any signal source that operates at ambient temperature and must be matched to the system to measure power at this very low level. An operational version of this system must have provision for selecting a bandwidth commensurate with the level of the signal to be measured, so that the inconvenience of a very narrow bandwidth need be tolerated only so far as is necessary to separate the signal to be measured from background thermal noise.

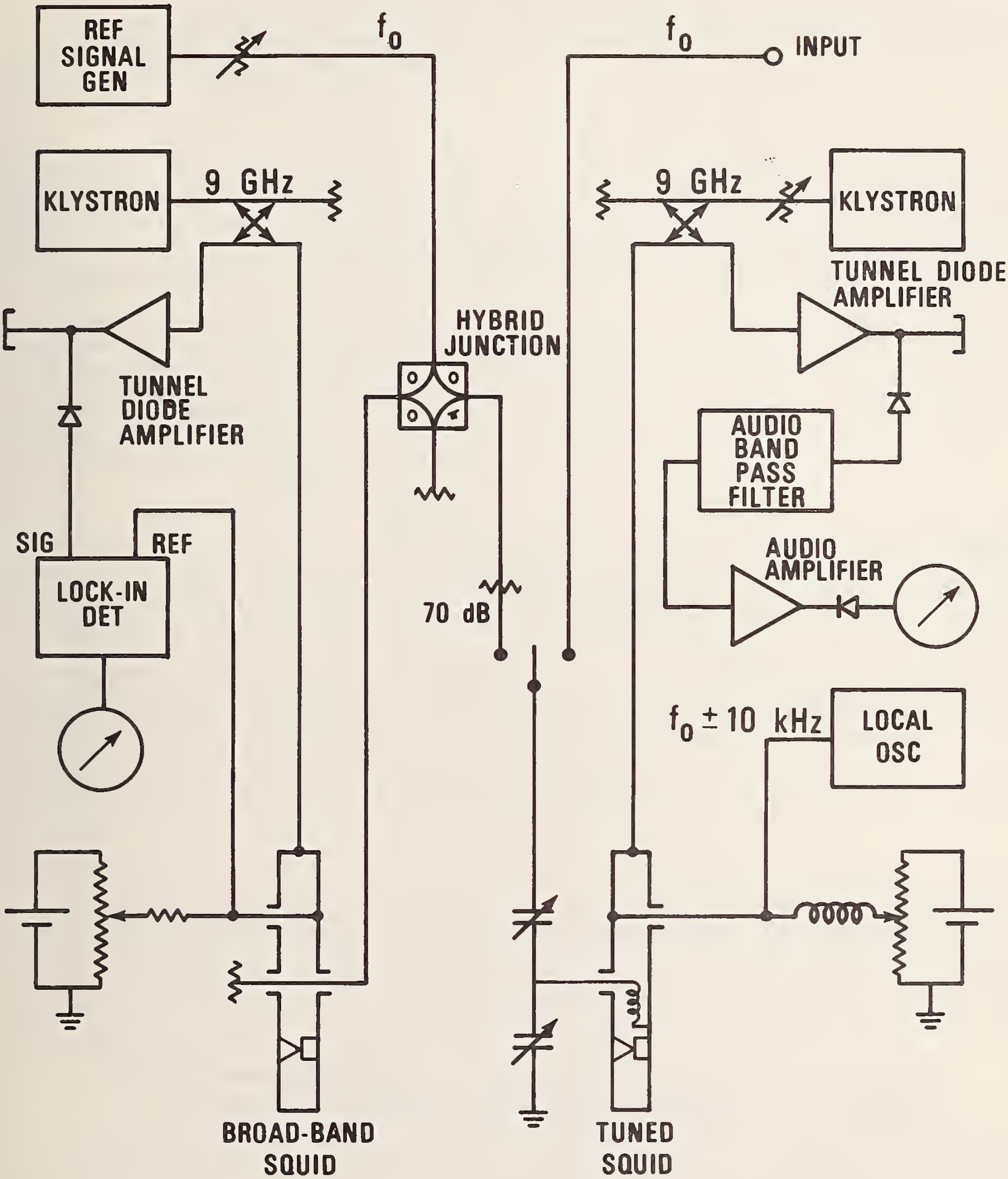


Figure 8. System for measuring rf power at very low level.

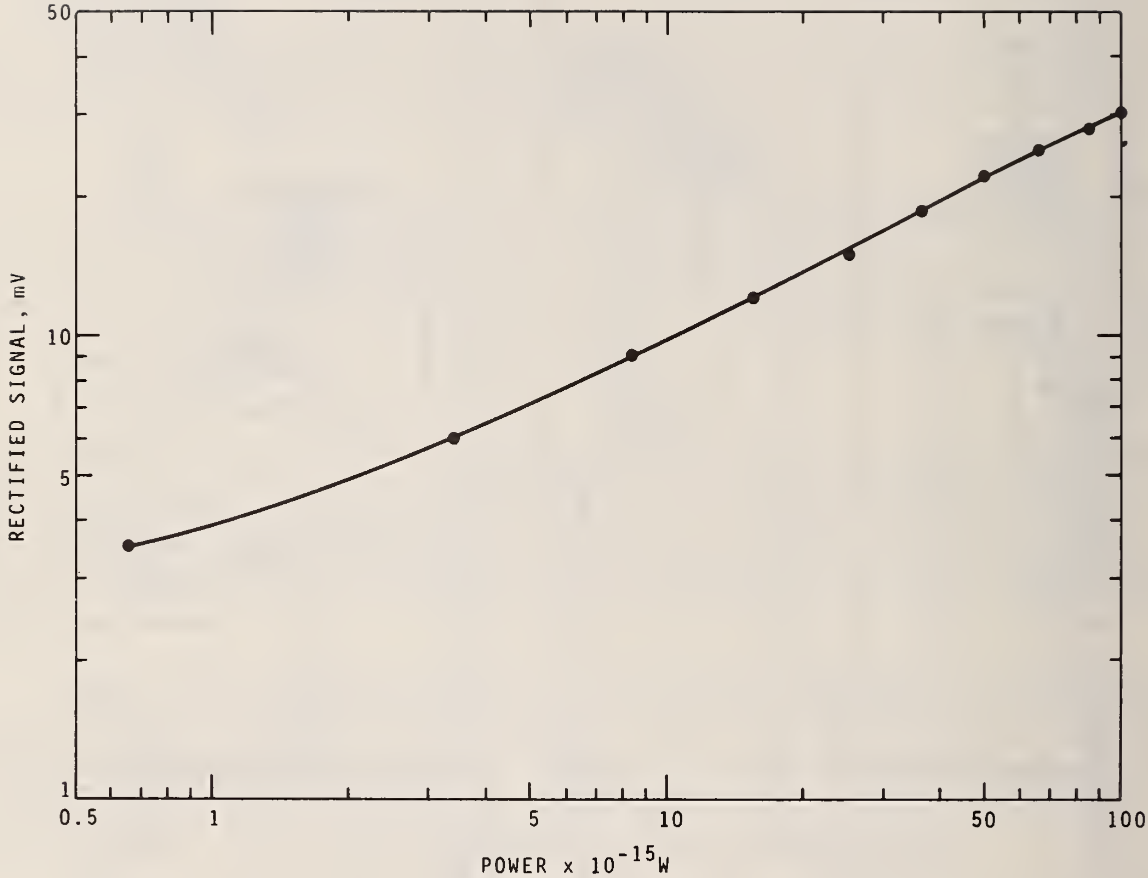


Figure 9. Calibration curve for the tuned SQUID described in section 1.1, obtained with the system shown in figure 8.

3. MEASUREMENT OF ATTENUATION

The principle of measuring attenuation with a SQUID is discussed at length in TN 643. Briefly, the response of a SQUID and its readout system to the amplitude I of the rf current of an incoming signal can be converted to a voltage $\overline{V}$ where

$$\overline{V} = V_1 J_o(2\pi I/I_o)$$

where I_o is the direct current required to induce one quantum of magnetic flux in the SQUID. The nulls of the Bessel function $J_o(2\pi I/I_o)$ define a series of signal amplitudes with known ratios to one another. If the signal comes from a stable generator via a variable attenuator under test, then the change in attenuation between the settings of the attenuator at the nulls of the response function may be compared with the ratios of signal levels computed with the aid of a table of Bessel functions.

The system we described in TN 643 to test this principle was assembled using versatile test equipment to evaluate the attainable performance over a range of 42 dB (using the first 100 nulls of the response function), and to determine the optimum operating conditions. The advances we report here are: extension of the dynamic range to 61 dB by using the first 900 nulls of the response function; development of hardware to count nulls automatically, interpolate between them, and accommodate step attenuators; and assembly and testing of a first portable version of the system using more specialized (and therefore cheaper) components.

3.1. Extension of the Dynamic Range

Figure 10 shows a comparison between an NBS Model VII transfer standard attenuator and the SQUID system, using the first 900 nulls of the latter's response to cover a dynamic range of 61 dB. A calibration of the Model VII against the national standard over the same range showed that the measurements with the SQUID deviated from the national standard of attenuation by less than ±0.002 dB rms.

In order to relieve the tedium of counting nulls in the response of the SQUID system by eye, an electronic counter was employed. Details of the required triggering circuit are given in section 6.1 of TN 643. The mode of operation was to drive the dial of the Model VII attenuator at a constant speed from one measured setting to the next, using the counter to record the number of nulls traversed in between. It was necessary to use a slow speed (approximately one count per second) in order to accommodate the post-detection time constant of the SQUID system. We would not recommend this mode of operation for routine work: it was merely the simplest way to test the performance of the system.

This increase in dynamic range also called for an improvement in the computer program we use to analyze our measurements. Our old program is presented in section 4.2 of TN 643. Our new program (also in "basic" language) is listed in table 1 of this report. Instead of storing the arguments of the Bessel function nulls obtained from published tables, the new program computes the required arguments as needed from a simple power series expansion. This avoids the need to store an arbitrarily large amount of information. Also, a simple routine is incorporated so that a standard printer can present the results of a run in graphical form. A typical plot generated by this program is shown in figure 11.

3.2. Automatic Counting and Interpolation

We discussed several ideas for automatic counting of the nulls in the response of the SQUID system in TN 643. The one we finally settled on is shown schematically in figure 12. When a measurement is to be made, the power supplied to the system from the 30 MHz signal generator is slowly reduced to a very low level at a rate permitting the nulls in the response of the SQUID to be electronically counted as they are traversed. After restoring the power to its original level, interpolation between nulls is accomplished by closing a servo loop controlled by the SQUID to lock the power level to the nearest null of suitable parity. A measurement of servo voltage can then be used to determine the resulting increment in power level after calibration of this part of the system.

The heart of this system is a voltage-controlled attenuator, which must have: a small, stable, repeatable insertion loss in the "on" condition; an attenuation versus voltage characteristic which enables nulls to be traversed at a constant rate with a reasonably simple shape for the voltage ramp; and 60 dB dynamic range. After trying several commercially available devices, which all proved deficient in one or other of these requirements, we developed the device shown in figure 12. It consists of a well-balanced 180° hybrid junction, which has the property that the transmitted signal is the difference between the reflections from the two side ports. When they carry identical terminations their reflections exactly cancel and the device transmits only the very small leakage power. When one side port is open circuit and the other is short circuit, the reflections are in anti-phase and combine to transmit power with very little insertion loss. We therefore terminate one side port with the source connection of a field-effect transistor with grounded drain, and terminate the other side port with a small capacitor to ground to match the source-to-gate capacitance of the transistor. When the transistor is biased "on", the hybrid junction has very little insertion loss. When it is biased "off" we can obtain over 60 dB of attenuation. Over quite a large segment of the intermediate range there is an almost linear relationship between transmitted rf voltage and bias voltage, permitting a simple linear ramp function to be used for null counting. We thank Mr. C. M. Allred for his suggestion to use a field-effect transistor for this purpose.

For the servo loop required for interpolation we use the output of the lock-in detector in the read-out circuit for the SQUID (figure 12) to drive the field-effect transistor controlling the transmission of the hybrid junction. A buffer amplifier is required to avoid direct perturbation of the lock-in detector by the rf signal. A digital voltmeter is used to measure the servo voltage applied to the transistor. Ultimately, the computer used to analyze the measurements will "read" this digital voltmeter and the null counter directly.

The overall function of the system described in this section is to determine the power reaching the SQUID from the 30 MHz generator at any desired time. Measurements of a change in attenuation will then be accomplished by going through the procedure we have described before and after the change, and taking the ratio. Clearly this can be used to measure step attenuators and the insertion loss of fixed pads just as well as the continuously variable attenuators to which the primitive form of our system was restricted.

3.3. The Portable System

Figure 13 shows a photograph of our first portable version of the system to measure attenuation at 30 MHz. The NBS Model VII attenuator is placed to show where an attenuator would be connected for test. It is not a part of the system.

Figure 14 shows a schematic diagram of the layout. It is arranged in three plug-in modules in a common case. This proved to be a mistake, because the resulting multiple ground connections caused an intolerable leakage between parts of the circuit carrying high and low level signals. We were able to make the system function acceptably by "unpacking" some of the components. We are presently designing an improved version of this system in the light of what we learned from it. The components we chose to use are satisfactory, but the new system will be built in a compartmented box with massive aluminum walls.

All the components of this system use solid-state devices exclusively. The power supplies, the 30 MHz generator and amplifier, and the L-band microwave components are all commercial items. The audio-frequency components were all developed by Mr. Nolan V. Frederick for general use in readout circuits for SQUIDs. With these components mounted to eliminate leakage of signals we have been able to match the performance of our earlier system assembled with test instruments.

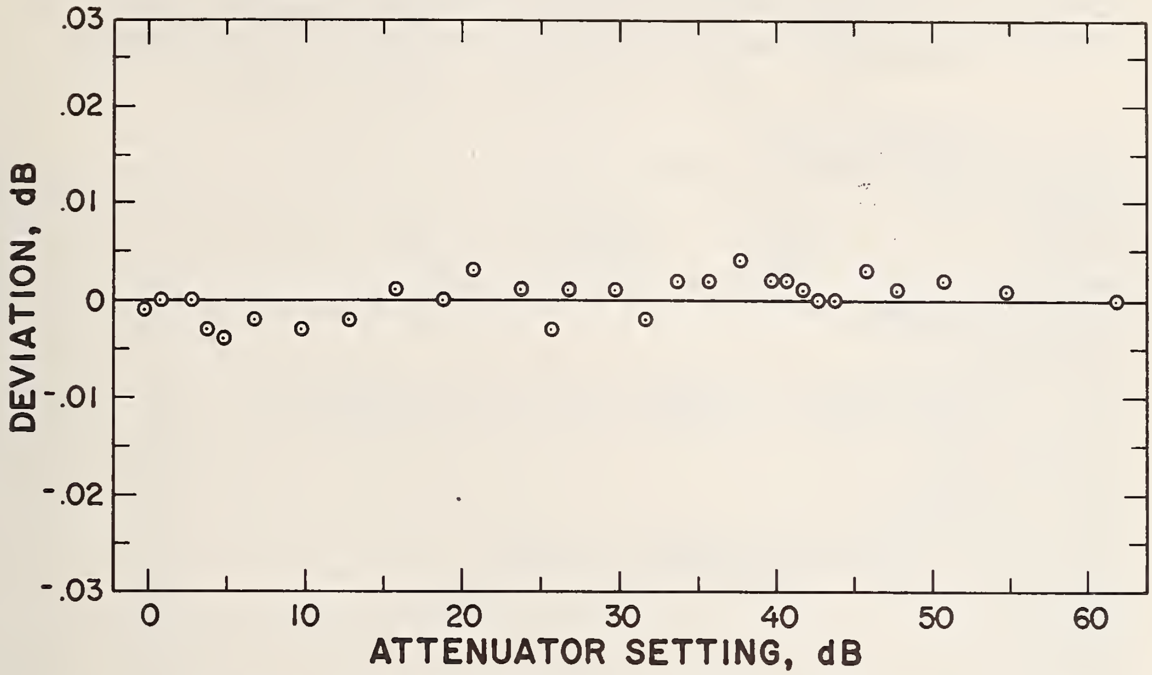


Figure 10. Measurement of Attenuation at 30 MHz with a SQUID. This plot shows the deviation between the dial setting of an accurate transfer standard attenuator and the corresponding variation in attenuation measured by the SQUID. 900 nulls of the response were used to cover a dynamic range of over 60 dB.

Table 1. Computer program in basic language to generate a deviation plot for an attenuator from measurements performed with a SQUID. A typical set of experimental results are inserted in lines 500-532.

```
10 DIM N[50],M[50],T[50]
20 DISP "TYPE IN NUMBER OF DATA POINTS";
50 INPUT N0
60 PRINT
70 PRINT "   I       THEORY       MEASURED      T-M"
80 PRINT "   -       ------       --------      ---"
90 PRINT
100 FOR K=1 TO N0
110 READ N[K],M[K]
120 I=N[K]
130 J1=2.40483
140 J=I*3.14159265358-0.78540566+0.0405529/I+0.00808324/I↑2
150 T[K]=20*LGT(J/J1)
160 NEXT K
170 A=T[6]+M[6]
180 FOR K=1 TO N0
190 T[K]=A-T[K]
200 FORMAT F4.0,F13.4,F11.3,F13.4
210 WRITE (15,200)N[K];T[K];M[K];T[K]-M[K]
220 NEXT K
230 PRINT
240 PRINT
250 PRINT
260 PRINT
270 PRINT "                   DEVIATION IN DB VERSUS ATTENUATOR SETTING IN DB"
280 PRINT
290 PRINT
300 PRINT
310 PRINT "           -0.025 DB "TAB34" 0.000"TAB59"+0.025 DB"
320 PRINT "             +----+----+----+----+----0----+----+----+----+----+"
330 PRINT
340 I=INT(T[N0])
350 FOR L=1 TO N0
360 K=N0+1-L
370 IF I+0.5>T[K] THEN 410
380 PRINT TAB5,I,TAB36".",TAB64,I
390 I=I+1
400 GOTO 370
410 IF ABS(T[K]-M[K])>0.0005 THEN 440
420 PRINT TAB5,I,TAB36"*",TAB64,I
430 GOTO 480
440 IF T[K]-M[K]<0 THEN 470
442 IF T[K]-M[K]<0.025 THEN 450
444 M[K]=T[K]-0.025
450 PRINT TAB5,I,TAB36"."TAB(36+1000*(T[K]-M[K]))"*"TAB64,I
460 GOTO 480
470 PRINT TAB5,I;TAB(36+1000*(T[K]-M[K]))"*"TAB36"."TAB64,I
480 I=I+1
490 NEXT L
500 DATA 1,61.799,2,54.582,3,50.679,4,47.995,5,45.941,6,44.285,7,42.894
510 DATA 8,41.695,9,40.637,10,39.701,12,38.078,15,36.104,20,33.57,25,31.615
520 DATA 30,30.009,40,27.495,50,25.546,60,23.954,80,21.447,100,19.503
530 DATA 150,15.972,200,13.473,300,9.946,400,7.447,500,5.508,600,3.922
532 DATA 700,2.582,800,1.421,900,0.399
540 PRINT
550 PRINT "             +----+----+----+----+----0----+----+----+----+----+"
560 PRINT "           -0.025 DB "TAB34" 0.000"TAB59"+0.025 DB"
570 PRINT
580 PRINT
590 PRINT
600 PRINT
610 STOP
```

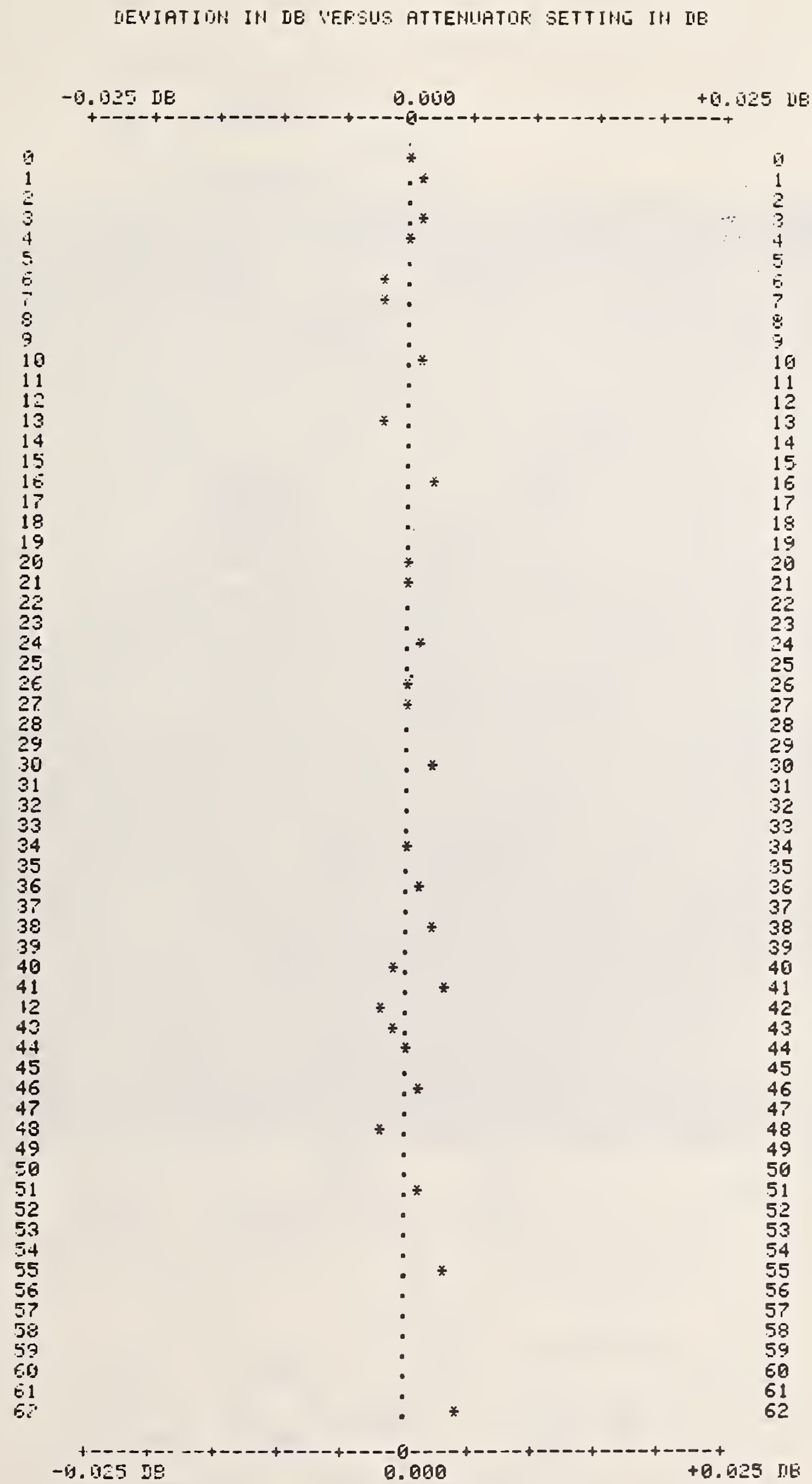


Figure 11. Typical plot generated by the program listed in table 1.

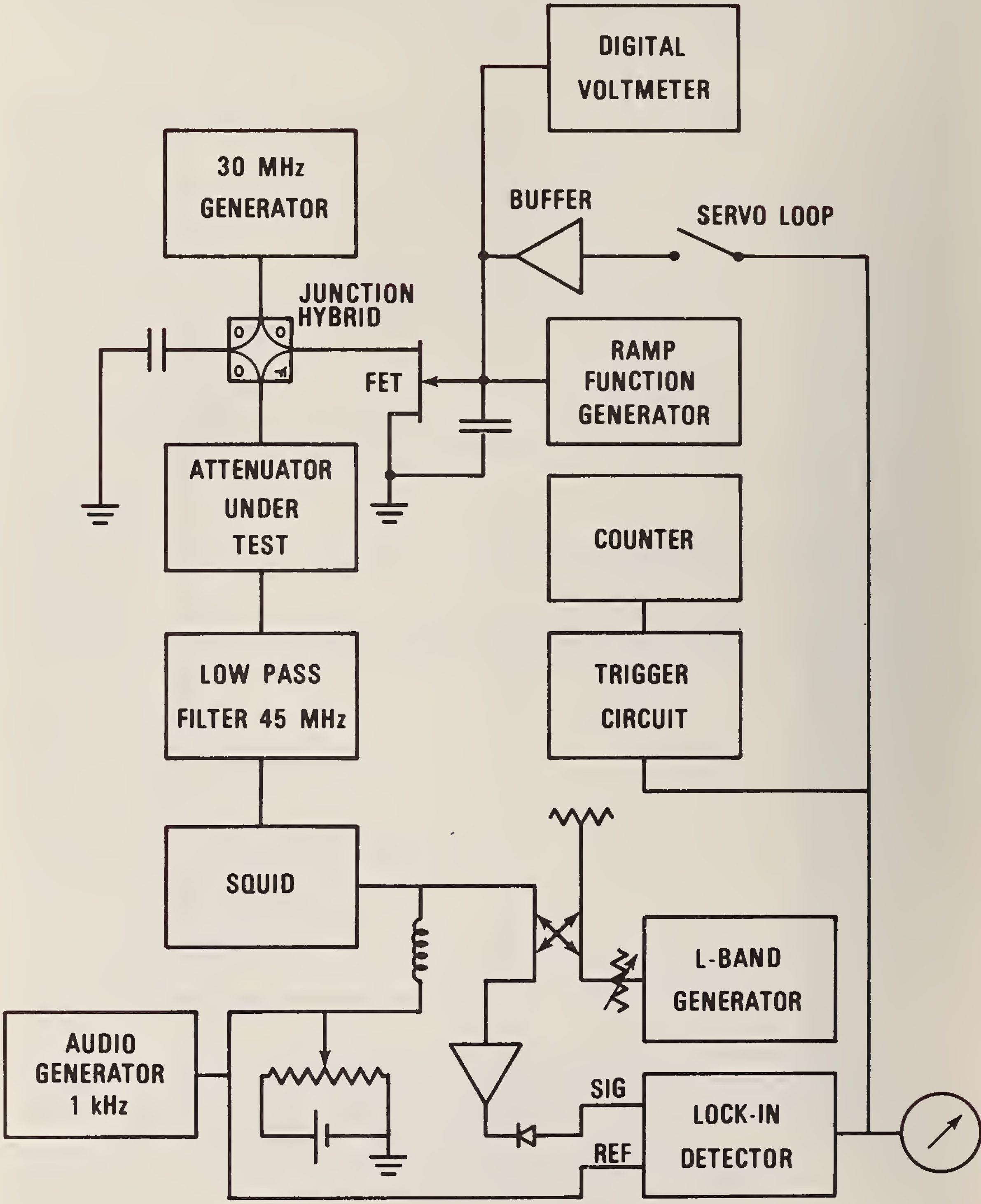


Figure 12. System for automatic counting of Bessel function nulls and interpolation between them.

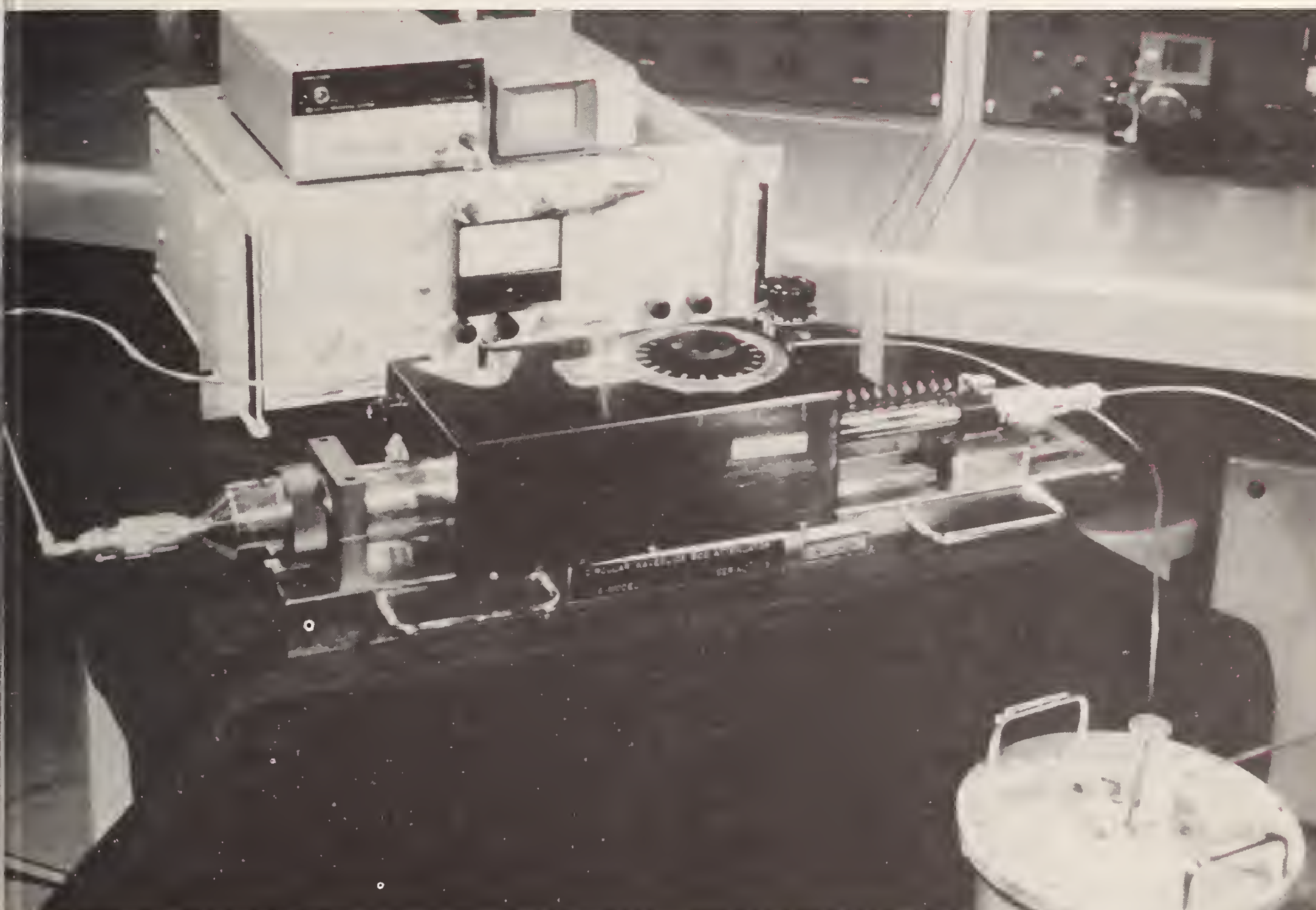


Figure 13. Portable system for calibrating attenuators. The system comprises the rack-mounting box in the center of the picture and cryostat at lower right. The piston attenuator in the foreground is connected for a calibration. It is not part of the measuring system.

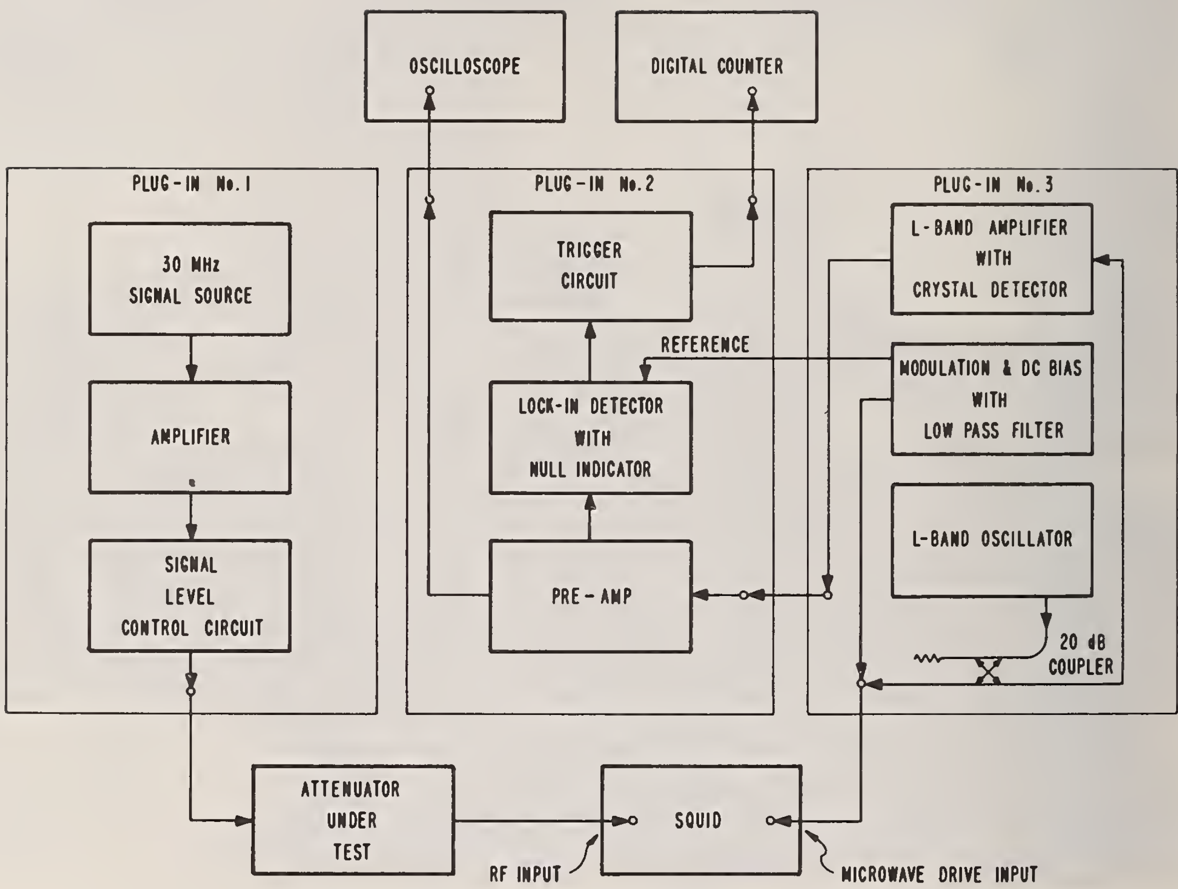


Figure 14. Block diagram of the portable system for measuring attenuation.

4. SYSTEMATIC ERRORS

We analyzed the systematic errors in rf measurements with a SQUID, arising from harmonic distortion of the functional form of its basic response to magnetic flux, in chapter 5 of TN 643. Subsequent experience has emphasized the importance of third harmonic distortion, and rf leakage and interference, which we did not discuss in detail there. This brief chapter rectifies that omission. The definition of the symbols we use follows chapter 5 of TN 643.

4.1. Third Harmonic Distortion

If the response function of the SQUID system takes the form

$$V \sim J_o(X) + \alpha J_o(3X),$$

where X is the amplitude of the rf current, then to first order the arguments of the zeros are displaced by an amount

$$\delta X = \alpha J_o(3j_o)/J_1(j_o),$$

where j_o is the argument at the undisplaced zero:

$$J_o(j_o) \equiv 0.$$

A trivial numerical computation shows that, at all the first ten zeros,

$$J_o(3j_o)/J_1(j_o) = +0.58.$$

Thus, a perturbation of this type displaces all the sensitive zeros by the same amount δX with respect to current. The displacement in dB is $20 \, \mathrm{Log}_{10}(1 + \delta X/j_o)$, which diminishes with increasing order number (and hence increasing j_o).

The error caused by this distortion is compared with the experimental points taken in a typical bad run in figure 15. It can be either positive or negative, depending on the sign of the coefficient α.

The settings of bias level and modulation depth chosen to maximize the wanted signal and null out second harmonic distortion also, unfortunately, maximize third harmonic distortion. Third harmonic distortion may be nulled out by choosing a modulation depth of one third of the amount which brings V_M (the signal recorded by the lock-in detector) to its first null.

4.2. rf Leakage

Since rf signals travelling by different paths from a common source combine coherently, this source of error also causes a constant offset with respect to current. The errors measured in dB therefore vary with order number in exactly the same way as the error caused by third harmonic distortion, as shown in figure 15. Once again, this error has arbitrary sign depending on the phase of the leakage signal.

4.3. External rf Noise

Let us assume that an external rf signal of amplitude X_1 is interfering with the signal of amplitude X_o which is being measured. The approximate form of the resulting signal X is then

$$X = X_o + X_1 \cos \omega t$$

where ω is the angular beat frequency. The functional form of the response of the SQUID system is then

$$V \sim \omega \int_0^{1/\omega} J_o(X_o + X_1 \cdot \cos \omega t) \cdot dt$$

using the integral form of J_o, and inverting the order of integration, we find

$$V \sim \frac{1}{\pi}\int_0^{\pi} J_o(X_1 \sin\varphi) \cdot \cos(X_o \sin\varphi) \cdot d\varphi$$

making the approximation

$$J_o(X) \approx 1 - \tfrac{1}{4}X^2$$

we find

$$V \sim J_o(X_o) - \frac{X_1^2}{8}\left[J_o(X_o) - J_2(X_o)\right].$$

At the zeros of J_o:

$$J_o(X_o) = J_o(j_o) = 0$$

and

$$V \sim X_1^2 \cdot J_2(j_o)/8.$$

Since

$$J_2(j_o) = 2 \cdot J_1(j_o)/j_o$$

we find

$$V \sim \frac{X_1^2}{4j_o} \cdot J_1(j_o).$$

Hence, to first order, the displacement δX of the zeros of the response by this perturbation is

$$\delta X = -V/\frac{dV}{dX_o} \approx X_1^2/4j_o.$$

Hence, the displacement in dB is $20 \operatorname{Log}_{10}(1 + X_1^2/4j_o^2)$. Note that this error is always positive. Paradoxically, in the presence of rf interference more power (less attenuation) is needed to set on the nulls. The error affects the first null strongly, and the others very little. Typical errors from this source are also shown on Figure 15.

4.4. Procedure to Minimize Errors.

The errors due to rf leakage and interference can only be eliminated at their source. Our experience with harmonic distortion has led us to formulate the following set of rules for setting up the system described in section 4.1 of TN 643 for accurate measurements.

1) Adjust the contact pressure at the Josephson junction until the optimum microwave power level does not exceed -80 dBm at the SQUID.

2) Adjust the DC bias level and make fine adjustments to the microwave power level until the reflected microwave signal appears exactly symmetrical on an oscilloscope display. Tests with a spectrum analyzer have shown that this has the effect of eliminating even-order (i.e.: second, fourth, etc.) harmonic distortion.

3) With a digital AC voltmeter, observe the modulation depth which just nulls out the desired signal, and set the modulation depth at exactly one third of that level. This nulls out the effect of third harmonic distortion.

After using this procedure, the systematic errors in measurements with the system are usually: less than ±0.01 dB at the first null; less than ±0.005 dB at the second null; less than ±0.003 dB at the third null; and negligibly small (compared with random setting errors) thereafter. Errors exceeding these amounts can usually be traced either to external interference or to violation of one of the rules in the setting-up procedure. Random errors have been consistently less than ±0.002 dB rms.

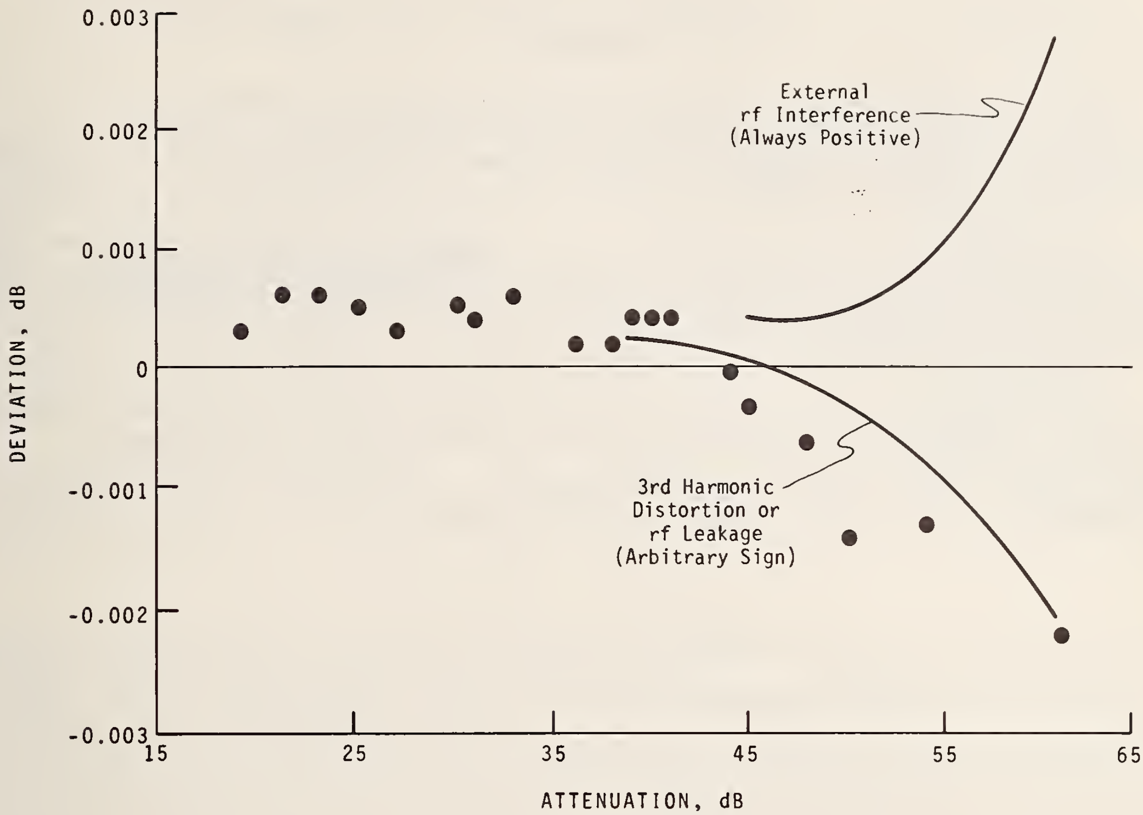


Figure 15. The calculated effects of various sources of systematic error compared with the experimental results of a typical "bad" run.

5. SUMMARY

We have demonstrated the feasibility of a system to measure rf power at levels down to 10^{-15}W and frequency in the range 100 MHz to 1 GHz, using SQUIDs both for the low-level sensor and the device to transfer calibration from DC to the signal frequency. Much remains to be done to put this system into a form suitable for routine use.

We have extended to 60 dB the dynamic range of our system for measuring attenuation at 30 MHz. We have developed the hardware required to automate the operation of this system and to accommodate step attenuators and fixed pads in addition to continuously variable attenuators. We have constructed and tested a portable version of this system, and are in process of designing an improved model for use in a calibration laboratory.

We have developed a permanently set Josephson junction mounted in a replaceable cartridge. Its characteristics need to be modified before it can be used for precise rf measurements.

Acknowledgment. We would like to thank our colleagues N. V. Frederick. J. E. Zimmerman, D. B. Sullivan, and C. M. Allred for their contributions to this work.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report covers the progress made in the application of Superconducting QUantum Interference Devices (SQUIDs) to the measurement of rf power and attenuation during the year from July 1973 to June 1974. The earlier work on this project was reported in NBS Technical Note 643† which contains a detailed introduction to the principles involved. We will assume the reader to be familiar with the material we presented there, since we do not repeat it in this report. In order to make the connection as smooth as possible, we have retained our earlier chapter titles as far as possible.

During the year we have developed stable SQUIDs with preset junctions which survive thermal cycling and mechanical shock. Further work is required to arrive at a version suitable for precise rf measurements. We have assembled a "breadboard" system capable of measuring rf power at levels down to 10^{-15}W in the range of frequency from 100 MHz to 1 GHz. We have extended the dynamic range of our system to measure rf attenuation to 60 dB, and developed the hardware to partially automate its operation and to accommodate step attenuators. We have tested a portable version of this system, and are in process of designing an improved version based on what we learned from the first one.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Josephson effect; quantum interference; rf attenuation; rf measurement; rf power; superconductivity.

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