NBS TECHNICAL NOTE

373

Radio-Frequency Measurements in the NBS Institute for Basic Standards

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in four broad program areas. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Measurement Services and the following technical divisions:

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> Office of Standard Reference Data—Clearinghouse for Federal Scientific and Technical Information —Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.

[2] Located at Boulder, Colorado 80302.

[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

UNITED STATES DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
NATIONAL BUREAU OF STANDARDS • A. V. Astin, Director

NBS TECHNICAL NOTE 373

ISSUED JUNE 1969

Nat. Bur. Stand. (U.S.), Tech. Note 373, 116 pages (June 1969)
CODEN: NBTNA

RADIO-FREQUENCY MEASUREMENTS IN THE NBS INSTITUTE FOR BASIC STANDARDS

EDITED BY ROBERT S. POWERS
AND WILBERT F. SNYDER

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

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ABSTRACT

This volume is a collection of diagrams, tables, and text material, which has been assembled to show the interrelationships between various radio frequency measurements made by the Institute for Basic Standards (IBS). In particular, the measurements are those which lead to services provided to the public or to other government agencies. These services include not only calibrations made for fees, but the broadcast services of the four NBS radio stations. Measurements made as part of the IBS research and development program are not included.

The information included is designed to give the users and potential users of the radio frequency services a clearer understanding of the origins of the measurement output of IBS in this field.

Key words: accuracy; calibration services; measurements; measurement techniques; radio frequency; uncertainties of measurement.

RADIO-FREQUENCY MEASUREMENTS IN THE NBS INSTITUTE FOR BASIC STANDARDS

Edited by Robert S. Powers
and Wilbert F. Snyder

INTRODUCTION

This volume is being published to give users of the National Bureau of Standards calibration services at radio frequencies a collection of information about the uncertainties given in Report of Calibration. It is a collection of diagrams, tables, and text material which shows the interrelationships among various radio frequency measurements made by the Institute for Basic Standards (IBS). In particular, the measurements are those which lead to services provided to the public or to other government agencies. These services include not only calibrations made for fees, but also the broadcast services of the four NBS radio stations. Measurements made as part of the IBS research and development program are not included.

It is hoped that this information will give the users and potential users of the radio-frequency services a clearer understanding of the origins of the measurement output of IBS in this field.

Generally, the sequence of measurements which leads to an output calibration or other service is shown by measurement flow charts. The notations of these charts are explained on page 5.

Each measurement may have errors arising from many sources. Typical values of these errors are given in one of two ways. In most cases, known or suspected sources of bias error are listed along with typical values of the random errors (or imprecision). In addition, in many instances, Error Flow Diagrams have been included to show more explicitly the way the various sources of uncertainty enter the measurement chain.

The study that led to these charts and tables was initiated to provide the management of the Institute and its divisions with a fairly detailed analysis of how the elements of the NBS part of the national system of radio measurements relate to each other. This was to help identify those parts of the "NBS subsystem of radio measurement" which could make the greatest contributions to improving the output of the subsystem as a whole, if given the limited funds that are available. The principal suggestion arising from the study was that significant gains in the overall performance of the IBS system could result from improvement in the treatment and reporting of the known error sources. At this time, a program to improve the reporting of uncertainties is under way.

This information is current as of approximately January, 1969. It serves to update, and present in a different form, some of the information in NBS Technical Note 262.*

The term "error" means the difference between the value actually measured and some "true value" which would have been obtained from a hypothetical "perfect" experiment.** The term "uncertainty" refers to the range within which the metrologist believes the actual error, as defined above, does fall. Thus, an error does have a particular value, although the metrologist does not know that value; the uncertainty is a range of values specified by the metrologist to indicate his best knowledge about the likely value of the error.

The phrase "bias uncertainties" has been used rather than the more commonly used "systematic errors" to express the uncertainty about the sources of error listed. If the error itself could be evaluated, a correction would be made. The phrase "random error" is used to represent observed deviations of measurements from the mean of a set of measurements.

In perusing these pages, the reader will observe that the values for errors are sometimes shown with plus and minus signs (±) and sometimes without the signs. There is no significant difference between the two designations, it being mostly a matter of personal choice. Prepared material for this volume came from a number of sources, and no particular effort was made to bring the use of plus and minus signs into uniformity. To do so would have required extensive redrafting and retyping.

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* NBS Technical Note 262, Accuracy in measurements and calibrations, 1965, edited by W. A. Wildhack, R. C. Powell, and H. L. Mason, issued June 15, 1965.

** The concept of "true value" is discussed in some detail by Churchill Eisenhart in his paper, Realistic evaluation of the precision and accuracy of instrument calibrating systems, J. Res. NBS 67C, 161 (1963).

Bias Uncertainties:

The uncertainties shown in these tables are typical values and in general may vary somewhat, depending on the range of frequency, the magnitude of the measurand (the quantity being measured), or the nature of the particular device being calibrated. Sometimes the magnitude is given as a single typical value and sometimes as a range of values. More details can be obtained from the person(s) listed under Personnel.

Where error flow diagrams were available, they were used in place of tables.

Random Errors:

In general, the number given for the random error represents approximately three times the estimated standard deviation (3σ) for a representative set of measurements.

Total Uncertainty:

The total uncertainty figure represents the sum of the estimated bias uncertainties and the 3σ random errors. Note that in a rather large number of the radio frequency measurements the random errors are quite negligible with respect to the bias uncertainties. The terms "limits of uncertainty" and "limits of error" are often used interchangeably with "total uncertainty."

Uncertainty quoted customer:

The uncertainty quoted to the customer is not always equal to the total uncertainty as described above. It is sometimes larger due to round-off, and sometimes larger to include an additional margin of safety in the estimate of possible error. Reporting practice is tending more and more toward quoting the actual number obtained as above, rather than the larger figures.

Notes:

The notes include information and comments which are intended to clarify the diagrams and charts or otherwise help the reader to understand some aspect of the measurement.

References:

The lists of references are not intended to be complete, but rather to supply the reader with at least one source of published information concerning the measurement, as made by NBS. Sometimes no such sources are available. Where references are given, they often include extensive bibliographies on the subject measurement. Unpublished information can often be obtained from the personnel whose names are listed.

Personnel:

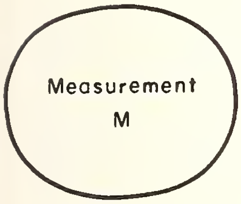
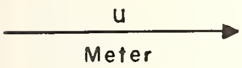
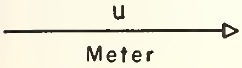
The name of the person(s) responsible for each measurement is given. Anyone requiring more detailed information about any of the measurements is invited to write to the appropriate person at

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

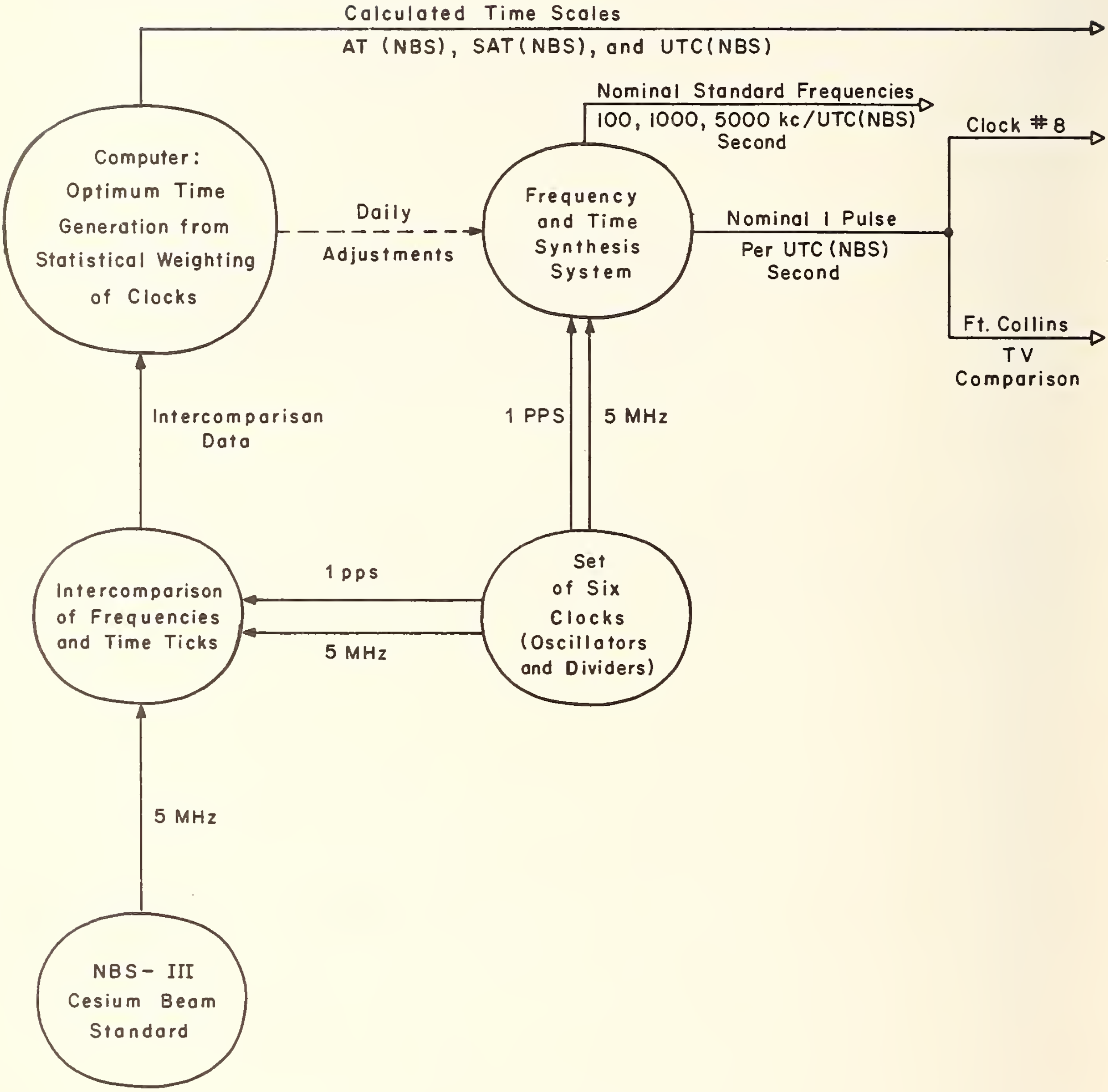
or telephone (303) 447-1000 and ask for the person named.

These names are also listed to give credit to those who helped to prepare the charts and other information on the various measurements.

MEASUREMENT REPRESENTATION

The Symbol :	Represents :
	A measurement technique or device
	The output of one measurement and input to other measurements; e.g., a calibrated meter having uncertainty u. The uncertainty is expressed either as a percentage, as a fraction, or as a quantity with dimensions; e.g. "5%", "3×10^{-7}", or "10μsec". These outputs are usually available to NBS customers.
	A measurement output available to NBS customers.

TIME AND FREQUENCY STANDARDS



Bias Uncertainties:

Source of Uncertainty	Fractional Uncertainty	
Magnitude of $\overline{H(x)}$ (3σ limits)	0.3	(parts in 10^{12})
Overlap of neighboring transitions	1.0	
Use of $\overline{H(x)}^2$ for $\overline{H^2(x)}$	0.1	
Distortion arising from C-field nonuniformity	0.5	
Cavity mistuning	0.1	
Uncertainty in magnitude of cavity phase shift	3.0	
Doppler shifts	1.0	
Microwave power level	1.0	
Spectral purity of excitation	2.0	
Second harmonic distortion of servo modulation	0.5	
Miscellaneous servo system effects	2.0	
Multiplier chain transient phase shifts	1.0	
Random Errors (one hour averaging, 3σ):	0.5	
Total Uncertainty (square root of sum of squares):	4.7	(parts in 10^{12})

Notes: Error sources listed here contribute to the uncertainty in determining the frequency of a particular atomic state separation of the free cesium atom. The fractional uncertainty is given as 3σ limits for statistically determined quantities and by estimated extreme limits for other quantities.

The random error given above refers to the random variations between successive frequency comparisons (with one hour averaging time) between the NBS-III cesium beam machine and another highly stable oscillator. The contribution of NBS-III to the relative fluctuation between the pair of signals generated can be identified (approximately) because the stability of the second signal generator is known from comparisons with still other oscillators.

NBS-III cannot be operated continuously -- the NBS time scale is actually computed from the data obtained by daily intercomparisons between NBS-III and the signals from five sources (two crystal and three cesium) which do operate continuously. Data obtained from these intercomparisons may be used to adjust the frequencies of the five working sources, when necessary, as shown on page 6.

The standard signals used to control the NBS broadcast stations are generated from one of the working oscillators. The AT (NBS) time scale is derived directly from the frequency of the cesium atom, as realized by NBS-III. The UTC (NBS) scale is generated from a signal having a frequency offset which has been promulgated by the Bureau International de l'Heure to make the time scale correspond approximately to the UT2 time scale.

USNO and NBS Time Coordination

On 1 October 1968 the epochs of the UTC (NBS) and the UTC (USNO) time scales were within one microsecond of each other. Since there was a slight rate difference between the master clocks at these two institutions, this time coincidence would not have continued. Hence, the USNO and the NBS agreed to each change their rates by nominally half the difference on 1 October 1968, and from thenceforth coordinate the rates so that the master clock at the USNO and the master clock at the NBS would remain near synchronous. It was initially felt and agreed upon that the time difference could be kept less than 5 μs.

In the figure (page 6), the abbreviation "pps" means "pulses per second."

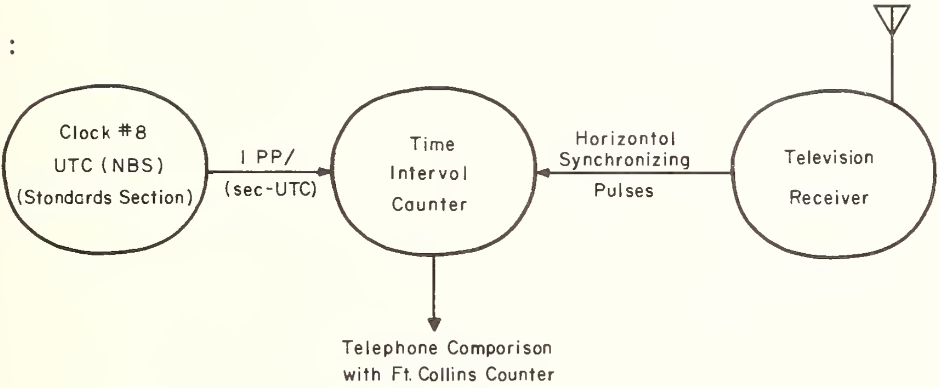
Reference: R. E. Beehler and D. J. Glaze, The performance and capability of cesium beam frequency standards at the National Bureau of Standards, IEEE Trans. Instr. Meas., IM-15, 48 (1966).

Personnel: D. Halford
D. W. Allan

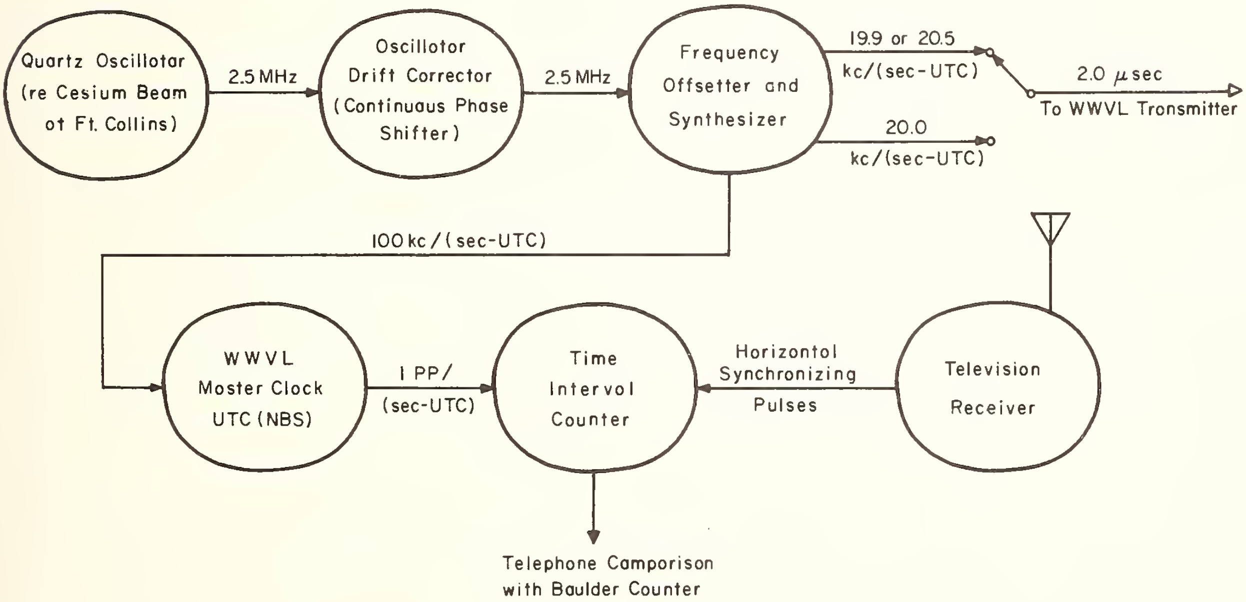
TIME AND FREQUENCY DISSEMINATION – WWVL

19.9 or 20.5 and 20.0 kc/(sec-UTC)
UTC (NBS) Time Scale

AT BOULDER:

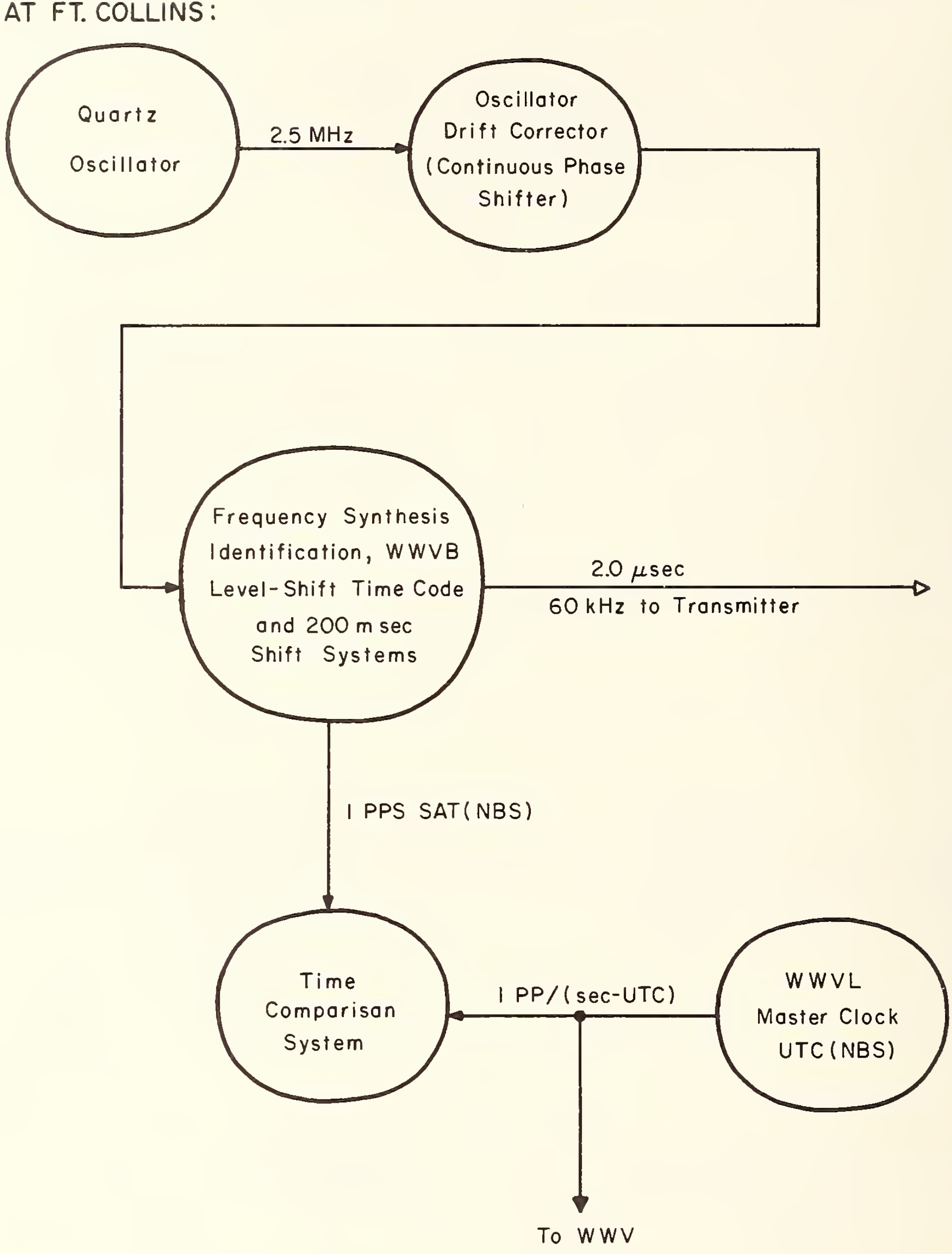


AT FT. COLLINS:



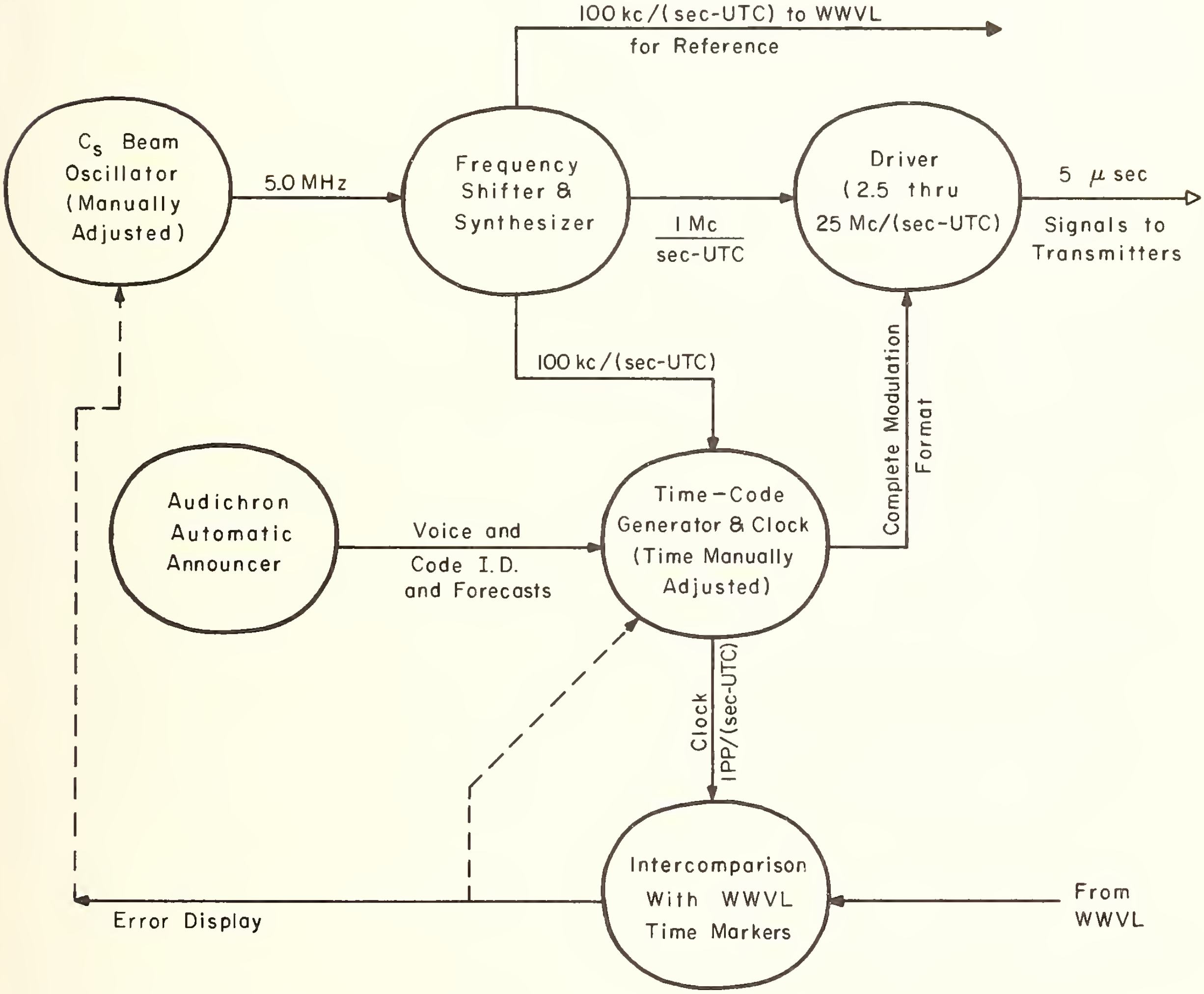
TIME AND FREQUENCY DISSEMINATION – WWVB

60 kHz SAT (NBS) Time Scale



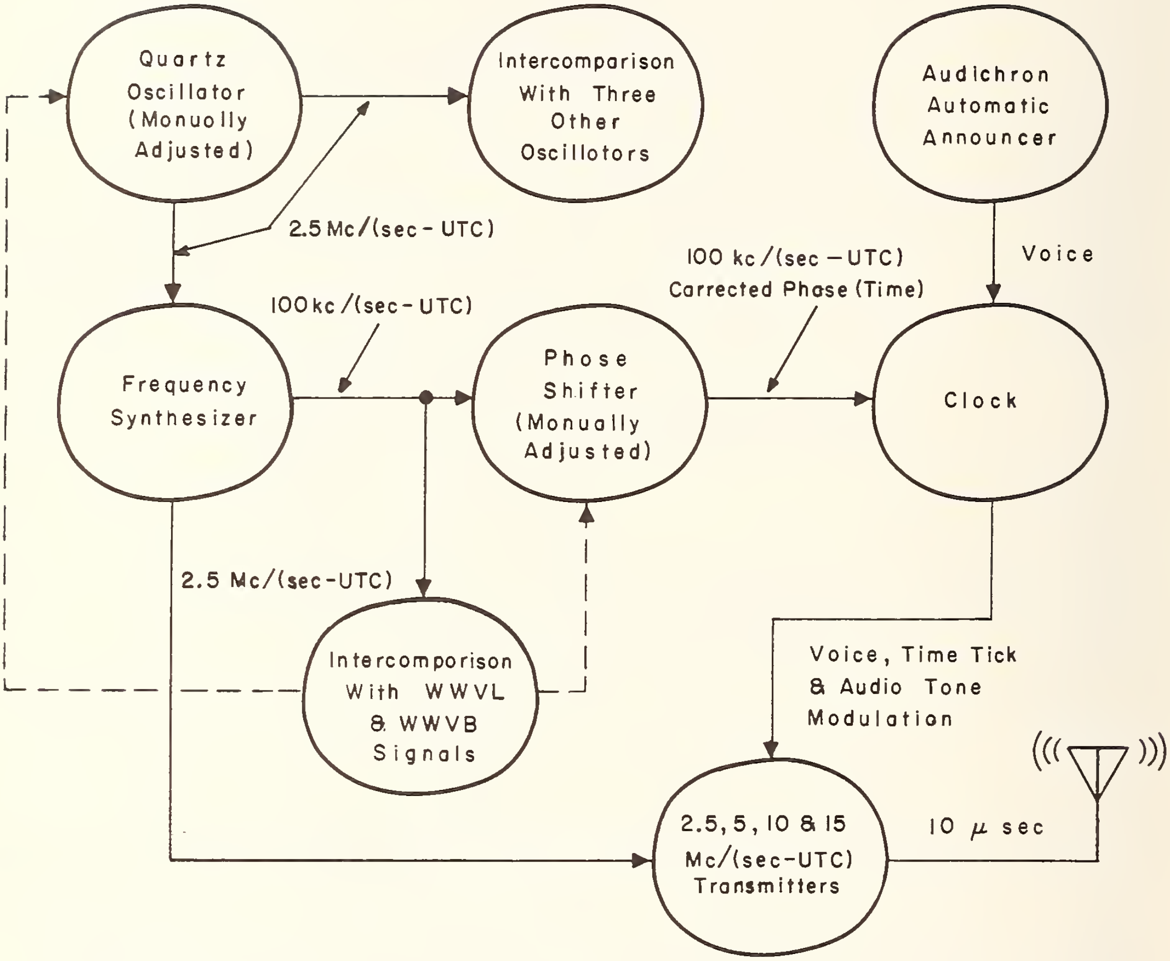
TIME AND FREQUENCY DISSEMINATION – WWV

2.5, 5, 10, 15, 20 & 25 Mc/(sec-UTC)
UTC (NBS) Time Scale



TIME AND FREQUENCY DISSEMINATION - WWVH

2.5, 5, 10 & 15 Mc/(sec-UTC)
UTC (NBS) Time Scale



Time and Frequency Dissemination

WWVL, WWVB, WWV, and WWVH:

Bias Uncertainties: Since the signals from all the stations are controlled by the standards in Boulder, as shown on pages 7-10, there is no significant long-term bias in the phase of the broadcast signals relative to the NBS time scales.

Random Errors: The phase (time) uncertainties given below are random fluctuations due to weather-caused changes in antenna impedance and to operator and equipment limitations.

Station	Maximum Phase Error [re SAT(NBS) or UTC(NBS)] (microseconds)
WWVL	2.0
WWVB	2.0
WWV	5.0
WWVH	10.0

Total Uncertainty: Same as Random Errors

Notes: Standard time and frequency signals are broadcast from four radio stations operated by the National Bureau of Standards. WWVL, WWVB, and WWV are located near Ft. Collins, Colorado; WWVH is on the island of Maui, Hawaii. For detailed description of the information available on each signal, see the reference below.

The unit of frequency, Hz, is used to denote one cycle per second, where the second is that defined internationally in terms of a transition in cesium. The unit, c/(sec -UTC), denotes one cycle per second where the second is derived from the UTC(NBS) time scale.

The frequency offset from the internationally defined atomic frequency required to generate the UTC(NBS) time scale is determined annually by the Bureau International de l' Heure (BIH) in Paris. At present the offset is -300 parts in 10^{10}.

SAT(NBS) is a Stepped Atomic Time scale based on the atomic frequency with periodic retardations to approximate UT-2.

Time synchronization between the NBS coordinated time scale UTC(NBS) and the clocks at the Ft. Collins transmitter sites is checked daily.

Reference: NBS Standard Frequency and Time Services, Special Pub. 236 (1968). (Revised annually).

Personnel: P. Viezbicke

DIRECT COMPARISON:

In addition to obtaining time information from the broadcast signals, one can also make direct comparisons between the NBS clocks at Boulder and a portable clock.

Bias Uncertainties: See Notes

Random Errors: See Notes

Total Uncertainty: See Notes

Uncertainty quoted customer: See Notes

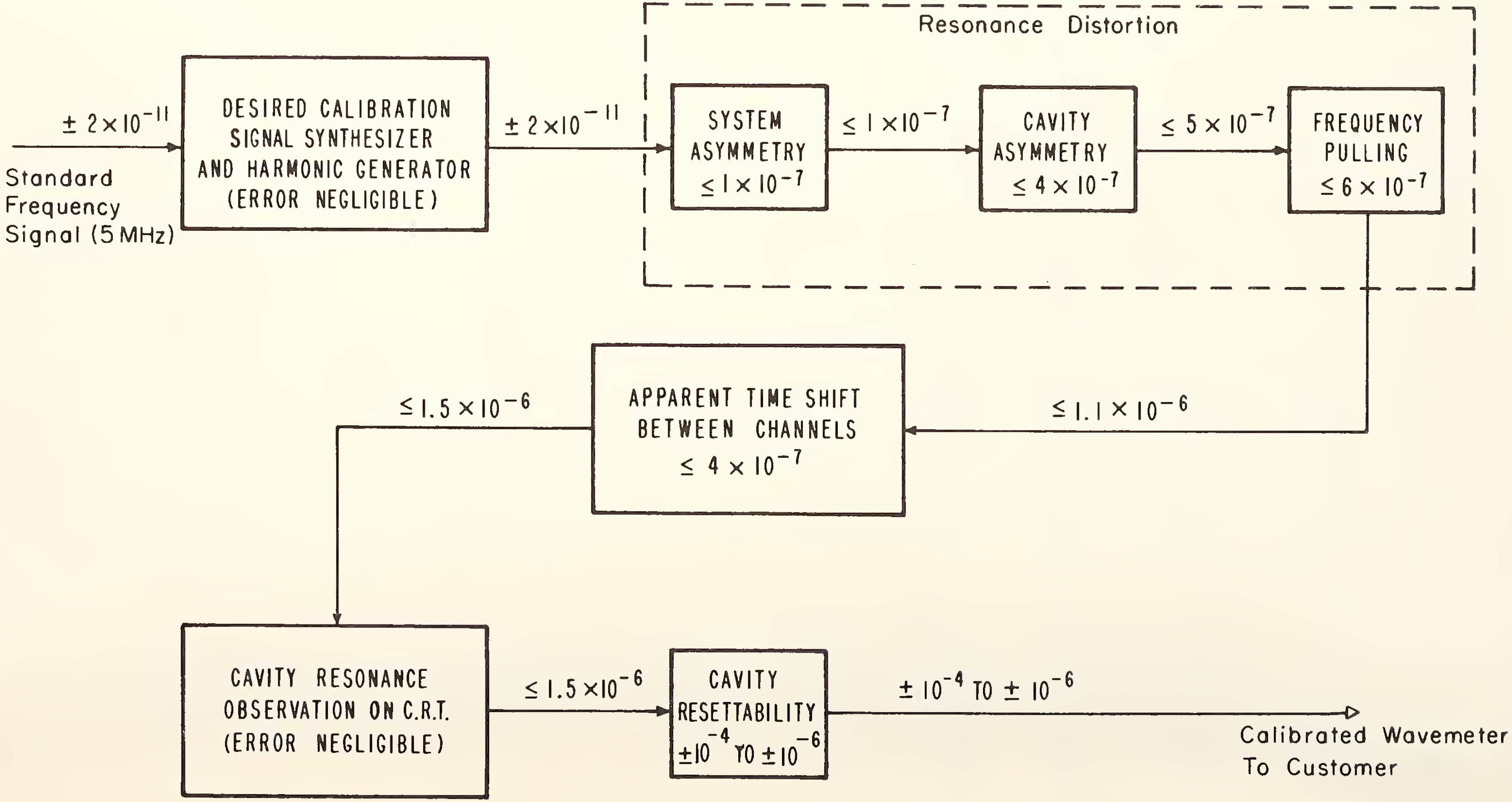
Notes: Comparison between AT(NBS) and the customer clock can be made with a precision of about 1 n sec. and an accuracy of about 100 n sec.

Reference: D. W. Allan, R. L. Fey, H. E. Machlan, J. A. Barnes, An ultraprecise time synchronization system designed by computer simulation, Frequency 6, #1, 11 (1968).

Personnel: D. W. Allan

CAVITY WAVEMETERS

100 MHz – 90 GHz



Cavity Wavemeters

100 MHz - 90 GHz

Bias Uncertainties:

Random Errors:

Total Uncertainty:

Uncertainty quoted customer:

See Error Flow Diagram, page 11

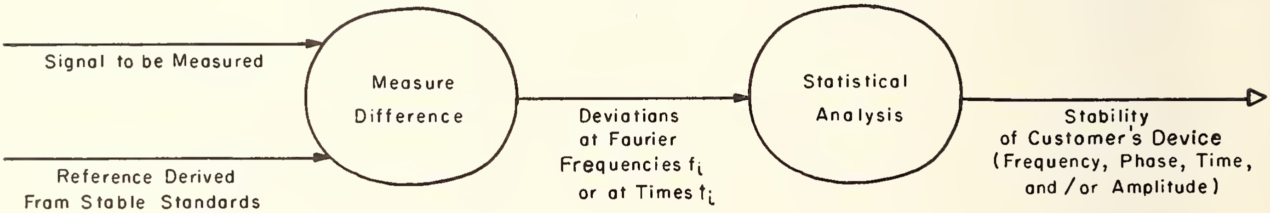
Notes: None

Reference: C. G. Montgomery, Techniques of microwave measurements, Radiation Laboratory Series, No. 11, pp. 291-293 (1947).

Personnel: R. E. Larson
C. K. S. Miller

STABILITY OF STABLE OSCILLATORS AND OTHER SIGNAL SOURCES: FREQUENCY, PHASE, TIME, AND AMPLITUDE STABILITY

Carrier Frequency : 0 Hz - 12.4 GHz
Frequency Domain: 10^{-6}Hz - 10^{6}Hz Fourier Frequency
Time Domain : 10^{-6}s - 10^{6} s Time Interval



Stability of Stable Oscillators and Other Signal Sources: Frequency, Phase, Time, and Amplitude Stability

Carrier Frequency: 0 Hz - 12.4 GHz
Frequency Domain: 10^{-6} Hz - 10^{6} Hz Fourier Frequency
Time Domain: 10^{-6} s - 10^{6} s Time Interval

Bias Uncertainties: Less than 3dB typical, to as low as 0.1dB

Random Errors: Less than 3 dB typical, to as low as 0.1 dB

Total Uncertainty: Less than 5 dB typical, to as low as 0.2 dB

Uncertainty quoted customer: Same as Total Uncertainty.

Notes: These calibrations can be performed on quartz crystal oscillators, atomic frequency standards, signal generators, frequency synthesizers, frequency multiplier chains, frequency dividers, amplifiers, buffers, phase shifters, and in general any device which generates or processes a frequency, phase, or time signal. Spectrum analysis can be done directly at Fourier frequencies f greater than 1 hertz, with an analyzer bandwidth as narrow as 1 hertz. The entire range of frequency domain stability can be obtained by Fourier transformation of time domain data.

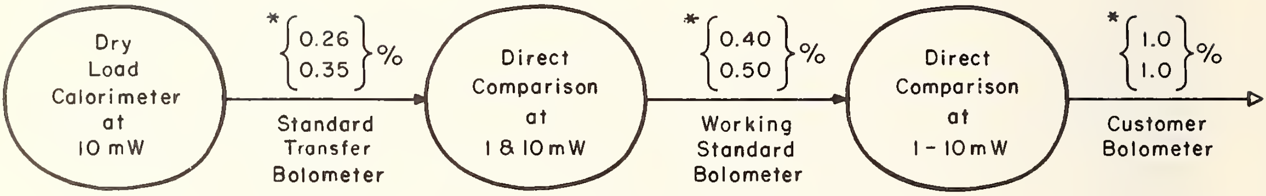
References: D. W. Allan, Statistics of atomic frequency standards, Proc. IEEE, 54, 221 (1966), and L. S. Cutler and C. L. Searle, Some aspects of the theory and measurement of frequency fluctuations in frequency standards, Proc. IEEE, 54, 136 (1966).

Personnel: J. H. Shoaf
D. Halford

RF POWER IN COAXIAL SYSTEMS

10 – 4000 MHz
1 – 10 mW Power Level

BOLOMETER CALIBRATION FROM
DRY LOAD CALORIMETRIC MEASUREMENT



* {10 to 1000 MHz
1000 to 4000 MHz}

DRY LOAD CALORIMETRIC MEASUREMENT:

10 - 4000 MHz
50 mW - 5W

Bias Uncertainties:

	10 - 1000 MHz	1000 - 4000 MHz
Calorimeter efficiency	0.04%	0.08%
VSWR mismatch	negligible	negligible
RF - dc substitution	0.05	0.10
dc power	0.02	0.02
Feedback loop error	0.15	0.15
Random Errors:	negligible	negligible
Total Uncertainty:	0.26%	0.35%

Uncertainty quoted customer: See Notes

Notes: Ordinarily this measurement is not offered to the public as a service, but is used for international comparisons and to calibrate standard transfer bolometers which are in turn used to calibrate working standard bolometers for the NBS Electronic Calibration Center.

Reference: M. L. Crawford, A new RF - dc substitution calorimeter with automatically controlled reference power, IEEE Trans. Instr. Meas. IM-17, 378 (Dec. 1968).

Personnel: P. A. Hudson

TRANSFER BOLOMETER CALIBRATION BY DIRECT COMPARISON:

At 10 mW power level

Bias Uncertainties:

The bias uncertainties are taken to be equal to the total error estimated for the calibration of the standard transfer bolometer by the dry load calorimeter. See page 13-1.

Random Errors: Random errors are less than 0.1%.

Total Uncertainty:

10 - 1000 MHz: 0.40%
1000 - 4000 MHz: 0.50%

Uncertainty quoted customer: See Notes

Notes: Ordinarily this measurement is not offered to the public as a service, but is used to calibrate working standard bolometer units for use in the NBS Electronic Calibration Center.

Reference: None

Personnel: P. A. Hudson

BOLOMETER CALIBRATION BY DIRECT COMPARISON:

At 1, 3, 10 mW power levels

Bias Uncertainties:

Bias uncertainties are taken to be the total estimated error in the calibration of the working standard bolometer. See page 13-2.

Random Errors: Random errors in calibration of customer units by direct comparison are less than 0.15%.

Total Uncertainty:

10 - 300 MHz: 0.50%
300 - 1000 MHz: 0.65%
1000 - 4000 MHz: 0.85%

Uncertainty quoted customer:

10 - 300 MHz: 1%
300 - 1000 MHz: 1%
1000 - 4000 MHz: 1%

References: P. A. Hudson, A precision RF power transfer standard, IRE Trans. Instr. I-9, 280 (1960).

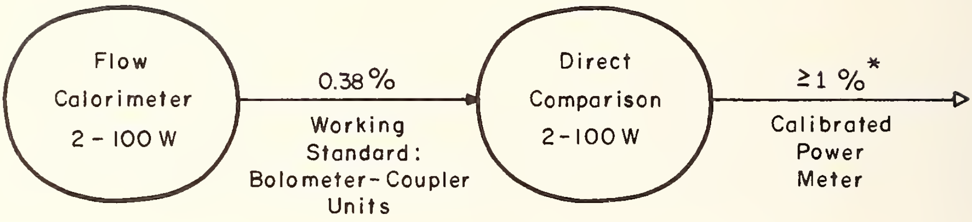
R. F. Desch and R. E. Larson, Bolometric microwave power calibration techniques at the National Bureau of Standards, IEEE Trans. Instr. Meas. IM-12, 29 (1963).

Personnel: F. X. Ries

RF POWER IN COAXIAL SYSTEMS

dc — 4000 MHz
2 - 100 W Power Level

FLOW CALORIMETER MEASUREMENT



* Error Limits Are Often Quoted As Greater Than 1 %, Since Many Meters Calibrated Are Inherently Less Accurate Than 1 %.

RF Power in Coaxial Systems
dc - 4000 MHz
2 - 100 W Power Level

FLOW CALORIMETRIC MEASUREMENT:

2 - 100 watts

Bias Uncertainties:	
dc power	0.02%
RF - dc substitution	0.10
Calorimeter efficiency	0.05
Thermal drift and flow rate variations	0.15
Random Errors: See Notes	0.06
Total Uncertainty:	0.38%

Uncertainty quoted customer: See Notes

Notes: Ordinarily this measurement is not offered to the public as a service, but is used only for international comparisons and to calibrate working standard bolometer-coupler units for use in the NBS Electronic Calibration Center.

The random error given here is the maximum observed variation.

Reference: None

Personnel: P. A. Hudson

FLOW CALORIMETRIC MEASUREMENT, DIRECT COMPARISON:

2 - 100 watts

Bias Uncertainties:	
Uncertainty of working standard	0.5%
VSWR mismatch and errors in meter to be calibrated	0.3
Random Errors:	0.2
Total Uncertainty:	1.0%

Uncertainty quoted customer: 1%

Notes: Errors inherent in the meter to be calibrated can be more than the allowance made here, that is 0.3%. Thus, occasionally the uncertainty quoted the customer is greater than 1%.

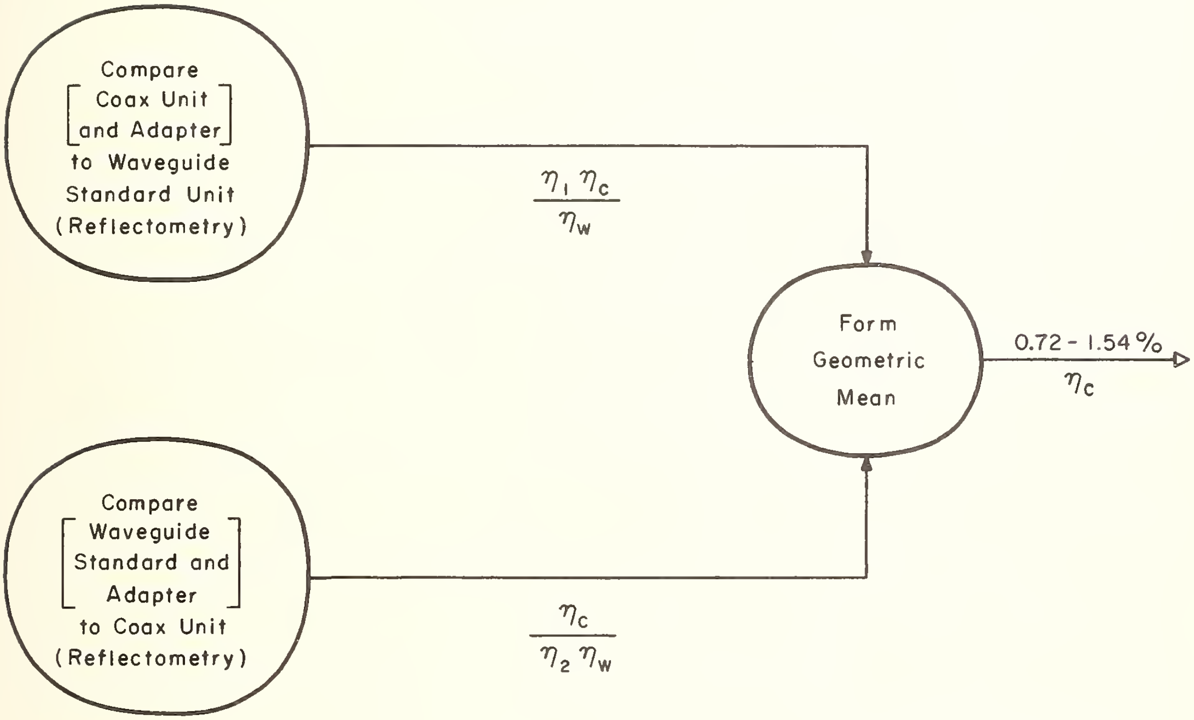
Reference: None

Personnel: F. X. Ries

MICROWAVE POWER: COAXIAL BOLOMETER UNITS

Type N Connector, Male : 4 – 10 GHz
Precision Connector (GPC – 14) : 4 - 8.5 GHz
1 – 10 mW Power Level

ADAPTER METHOD OF MEASUREMENT



η_c: Effective Efficiency of Coaxial Unit
η_w: Effective Efficiency of Waveguide Standard Unit
$\eta_{\frac{1}{2}}$: Efficiency of Adapter as Used In Step ($\frac{1}{2}$)

Microwave Power: Coaxial Bolometer Units
Type N Connector, Male: 4 - 10 GHz
Precision Connector (GPC-14): 4 - 8.5 GHz
1 - 10 mW Power Level

ADAPTOR METHOD OF MEASUREMENT:

Bias Uncertainties:

Random Errors: See Error Flow Diagrams, pages 15-2 and 15-3

Total Uncertainty:

Uncertainty quoted customer: 0.8% to 1.8%

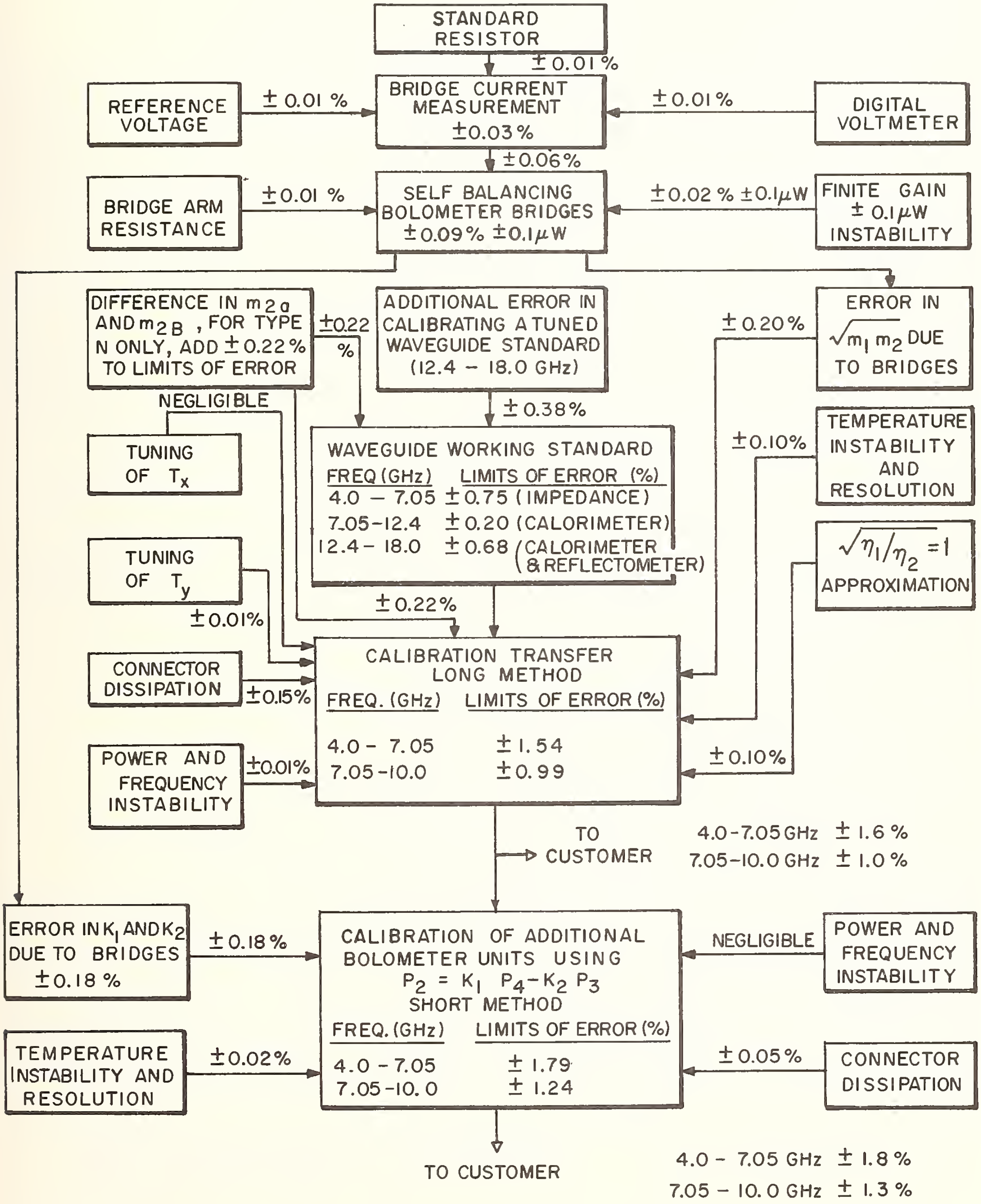
Notes: This measurement permits the comparison of a coaxial bolometer unit directly with a waveguide standard bolometer unit. Thus, it is not necessary to develop a calorimetric technique for calibrating working standard coaxial bolometer units in this frequency range. See reference. The uncertainty in the waveguide standard in the frequency range 4 to 7.05 GHz (where the impedance method of measurement is used) is 0.75%. In the frequency range 7.05 to 10 GHz (where the calorimetric method of measurement is used), the uncertainty in the waveguide standard is 0.2%.

Symbols appearing in the error flow diagrams are defined in the reference below.

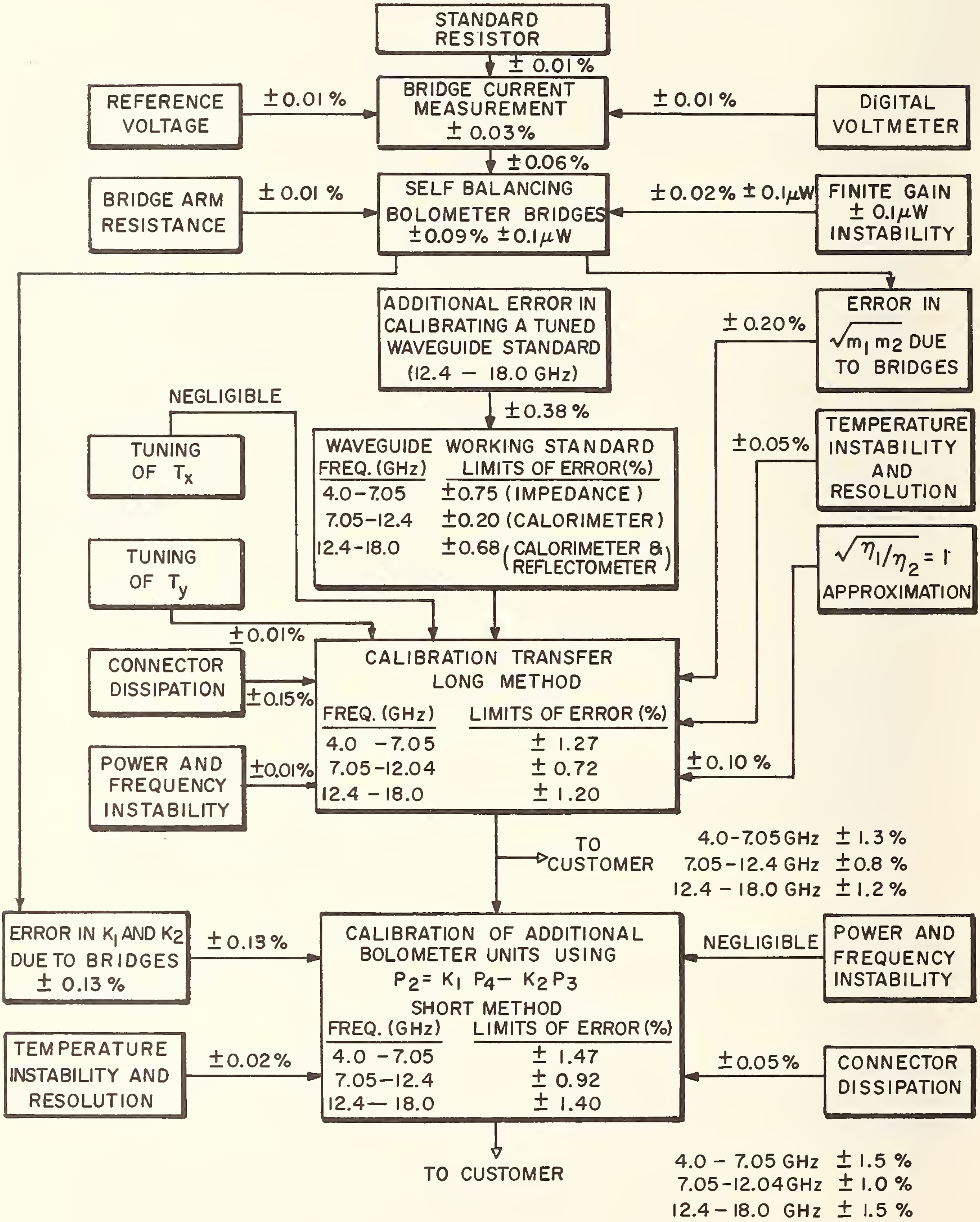
Reference: G. F. Engen, Coaxial power meter calibration using a waveguide standard, J. Res. NBS 70C, 127, (1966).

Personnel: R. F. Desch

MICROWAVE POWER: COAXIAL BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR CALIBRATION TRANSFER SYSTEM
FOR TYPE N CONNECTORS
ADAPTOR METHOD



MICROWAVE POWER: COAXIAL BOLOMETER UNITS ERROR FLOW DIAGRAM FOR CALIBRATION TRANSFER SYSTEM FOR PRECISION CONNECTORS (GPC-14 STOPS AT 8.5 GHz) ADAPTOR METHOD

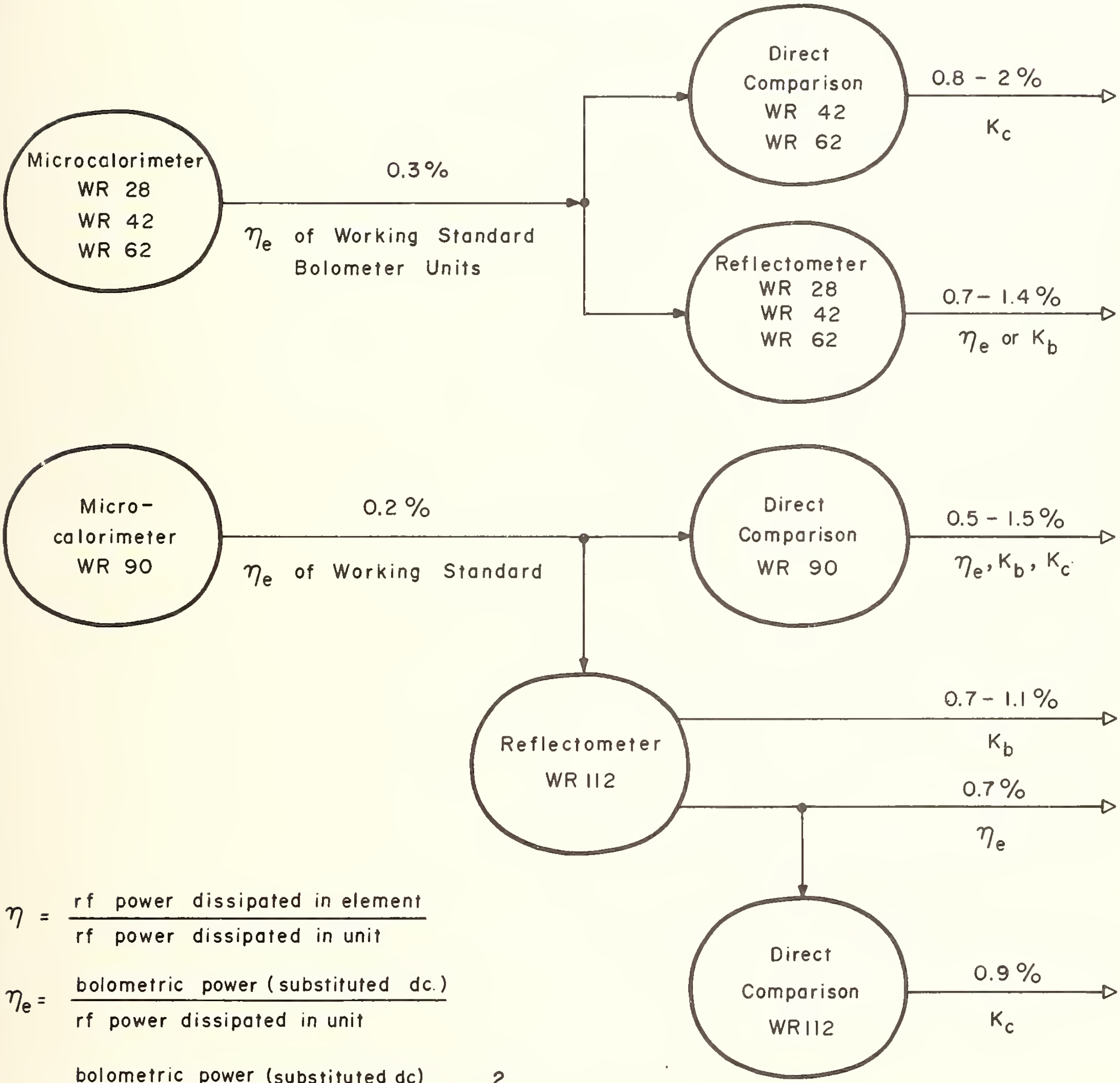


MICROWAVE POWER : WAVEGUIDE BOLOMETER UNITS

WR 28 : 26.5 - 40.0 GHz
WR 42: 18.0 - 26.5GHz
WR 62: 12.4 - 18.0GHz
WR 90: 8.2 - 12.4GHz
WR 112: 7.05 - 10.0GHz

10 mW Power Level

MICROCALORIMETRIC MEASUREMENT



$$\eta = \frac{\text{rf power dissipated in element}}{\text{rf power dissipated in unit}}$$

$$\eta_e = \frac{\text{bolometric power (substituted dc.)}}{\text{rf power dissipated in unit}}$$

$$K_b = \frac{\text{bolometric power (substituted dc)}}{\text{rf power incident on unit}} = (1 - |\Gamma|^2)\eta_e$$

$$K_c = \frac{\text{bolometric. power in sidearm (substituted dc)}}{\text{rf power incident on non-reflecting main-arm load}}$$

Microwave Power

WR 28: 26.5 - 40 GHz
WR 42: 18.0 - 26.5 GHz
WR 62: 12.4 - 18.0 GHz
WR 90: 8.2 - 12.4 GHz
10 mW Power Level

MICROCALORIMETRIC MEASUREMENT:

Bias Uncertainties:

Random Errors: See Error Flow Diagram, p. 16-2

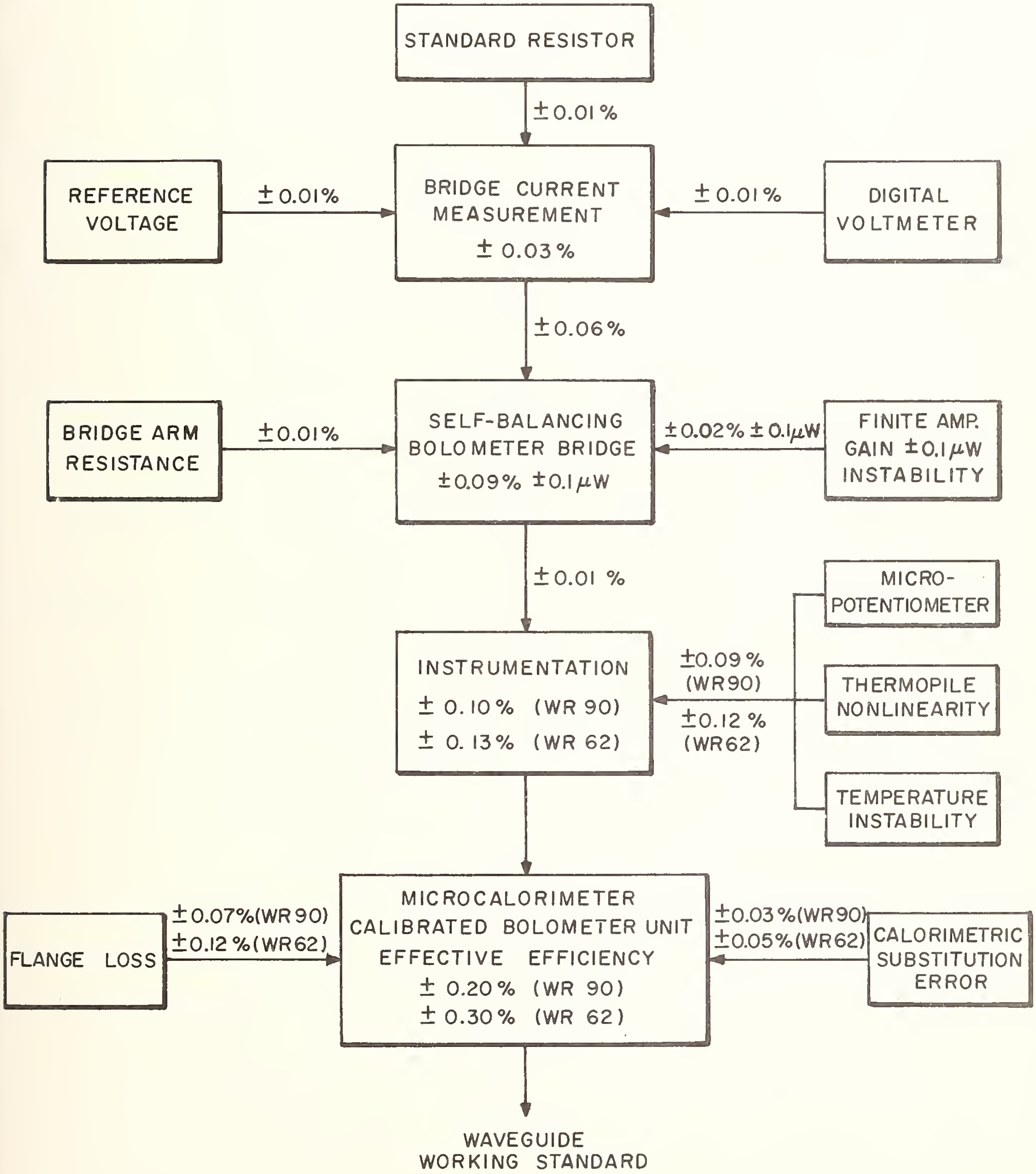
Total Uncertainty:

Uncertainty quoted customer: See Notes

Notes: Ordinarily this measurement is not offered to the public as a service, but is used only for international comparisons and to calibrate working standard bolometer units for use in the NBS Electronic Calibration Center.

Reference: G. F. Engen, A refined X-band microwave microcalorimeter, J. Res. NBS 63C, 77 (1959).

MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR REFERENCE STANDARD MICROCALORIMETRIC MEASUREMENT
WR90 AND WR62



MICROCALORIMETRIC MEASUREMENT, DIRECT COMPARISON METHOD:

Bias Uncertainties:

Calorimetric measurement of working standard	0.2 to 0.3%
RF power, temperature, and frequency stability	0.02
dc power	0.1
Flange dissipation and misalignment	0.05 to 0.1
VSWR mismatch (for $0.01 < \lvert\Gamma\rvert < 0.20$)	0.03 to 1.23
Random Errors: Typical value	0.04
Total Uncertainty: (for $0.01 < \lvert\Gamma\rvert < 0.20$)	0.40 to 1.75%

Uncertainty quoted customer: 0.5 to 1.8%

Notes: This measurement method is used for K_c only. (See definition below.)

$|\Gamma|$ is the absolute value of the complex reflection coefficient of the bolometer unit.

An error flow diagram for the measurement in the WR 90 waveguide size is given on page 16-5.

In this document the term "bolometer element" will refer to the thermoelement in which the RF power is detected. "Bolometer mount" will refer to the waveguide in which the element is mounted, and "bolometer unit" will refer to the combination. A "bolometer-coupler unit" is a bolometer unit mounted on an arm of a directional coupler.

The definitions of efficiency (η), effective efficiency (η_e), and calibration factor (K_b) of bolometer units are as follows:

$$\eta = \frac{\text{RF power dissipated in bolometer element}}{\text{RF power dissipated in bolometer unit}}$$

$$\eta_e = \frac{\text{bolometer power (substituted dc in the bolometer unit)}}{\text{RF power dissipated in bolometer unit}}$$

$$K_b = \frac{\text{bolometer power (substituted dc)}}{\text{RF power incident on unit}} = (1 - |\Gamma|^2)\,\eta_e$$

The calibration factor (K_c) for a bolometer-coupler unit is:

$$K_c = \frac{\text{bolometer power in the sidearm (substituted dc)}}{\text{RF power incident on a non-reflecting main-arm load}}$$

The nominal 10 mW power level is for direct incidence on the unit attached to the main arm.

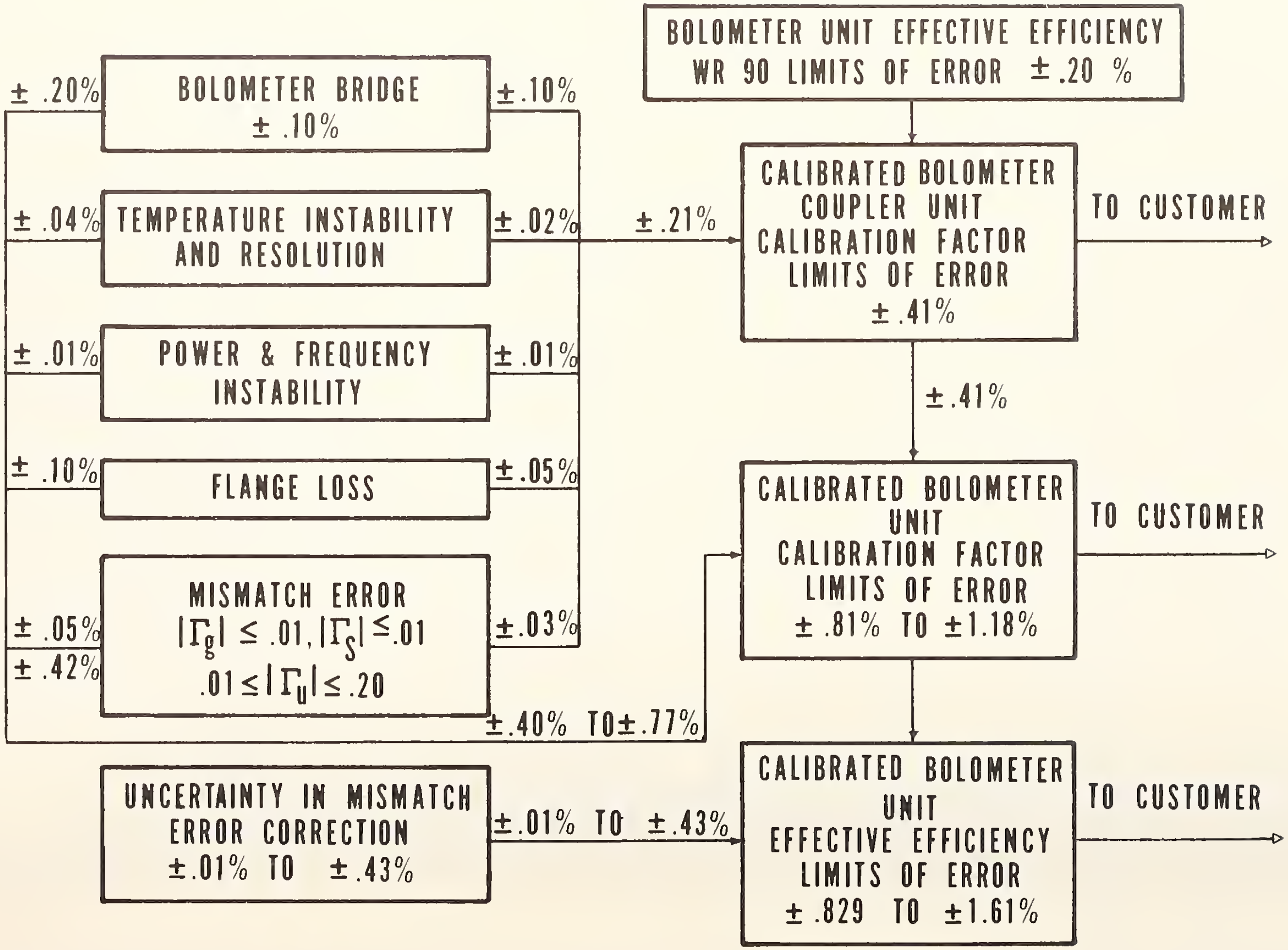
Bolometer-coupler units are calibrated at the power level appropriate to the coupler.

Symbols appearing in the error flow diagram are defined in the reference below.

Reference: R. F. Desch and R. E. Larson, Bolometric microwave power calibration techniques at the National Bureau of Standards, IEEE Trans. Instr. Meas., IM-12, 29 (1963).

Personnel: R. F. Desch

MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM
MICROCALORIMETRIC MEASUREMENT, DIRECT COMPARISON METHOD
WR 90 WAVEGUIDE



MICROCALORIMETER MEASUREMENT, REFLECTOMETER METHOD:

Bias Uncertainties:

Random Errors:

Total Uncertainty:

Uncertainty quoted customer:

See Error Flow Diagram, page 16-7

Notes: See notes for Direct Comparison method (see p. 16-3).

This measurement method is used for η_e and K_b only. (See definitions on p. 16-3.)

The estimated uncertainty in a measurement of K_b is actually about 0.1% higher than that for η_e, because reflection at the waveguide junction has an effect in that case. The uncertainty is still considerably less than 1%, however.

Symbols appearing in the Error Flow Diagram are defined in the reference below.

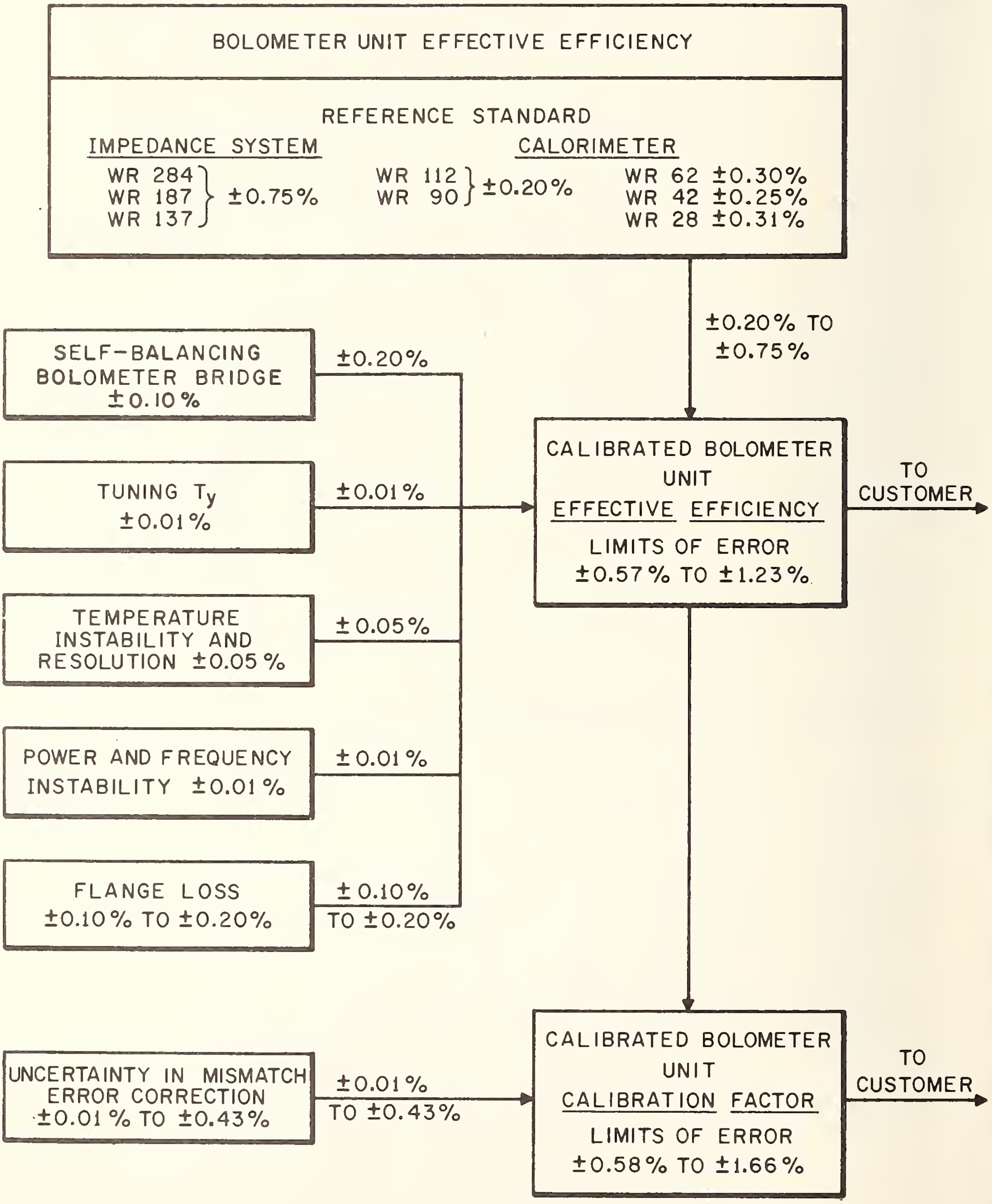
The self-balancing bolometer bridge (see p. 16-7) with an uncertainty at 0.10% contributes 0.20% to the total uncertainty because the bridge is used more than once in the power measurement.

Reference: G. F. Engen, A transfer instrument for the intercomparison of microwave power meters, IRE Trans. Instr., I-9, 203 (1960).

Personnel: N. T. Larsen
R. F. Desch

MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM
MICROCALORIMETRIC MEASUREMENT, REFLECTOMETER METHOD

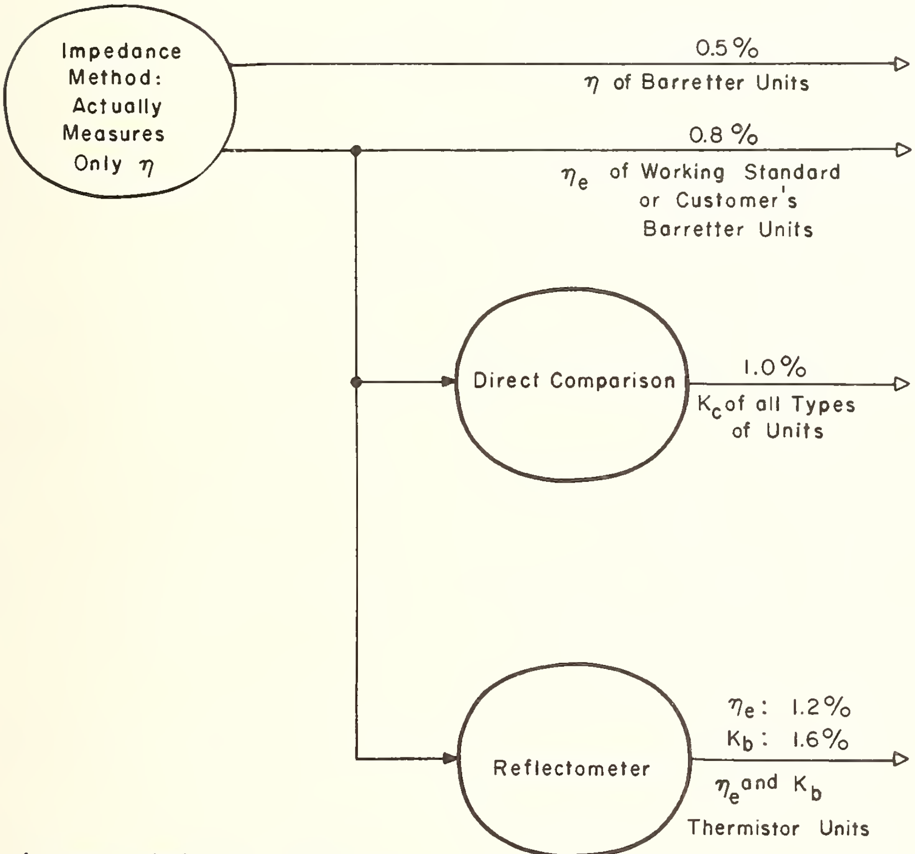
WR 284, WR 187, WR 137, WR 112, WR 90, WR 62, WR 42, WR 28



MICROWAVE POWER : WAVEGUIDE BOLOMETER UNITS

WR 137 : 5.85 – 8.20 GHz
WR 187 : 3.95 – 5.85 GHz
WR 284 : 2.60 – 3.95 GHz
10 mW Power Level

IMPEDANCE METHOD OF MEASUREMENT



$$\eta = \frac{\text{rf power dissipated in element}}{\text{rf power dissipated in unit}}$$

$$\eta_e = \frac{\text{bolometric power (substituted dc)}}{\text{rf power dissipated in unit}}$$

$$K_b = \frac{\text{bolometric power (substituted dc)}}{\text{rf power incident on unit}} = (1 - |\Gamma|^2)\eta_e$$

$$K_c = \frac{\text{bolometric power in sidearm (substituted dc)}}{\text{rf power incident on non-reflecting main-arm load}}$$

Microwave Power

WR 137: 5.85 - 8.20 GHz
WR 187: 3.95 - 5.85 GHz
WR 284: 2.60 - 3.95 GHz
10 mW Power Level

IMPEDANCE METHOD OF MEASUREMENT:

Bias Uncertainties:
Random Errors: See Error Flow Diagram, page 17-2
Total Uncertainty:

Uncertainty quoted customer: 1%

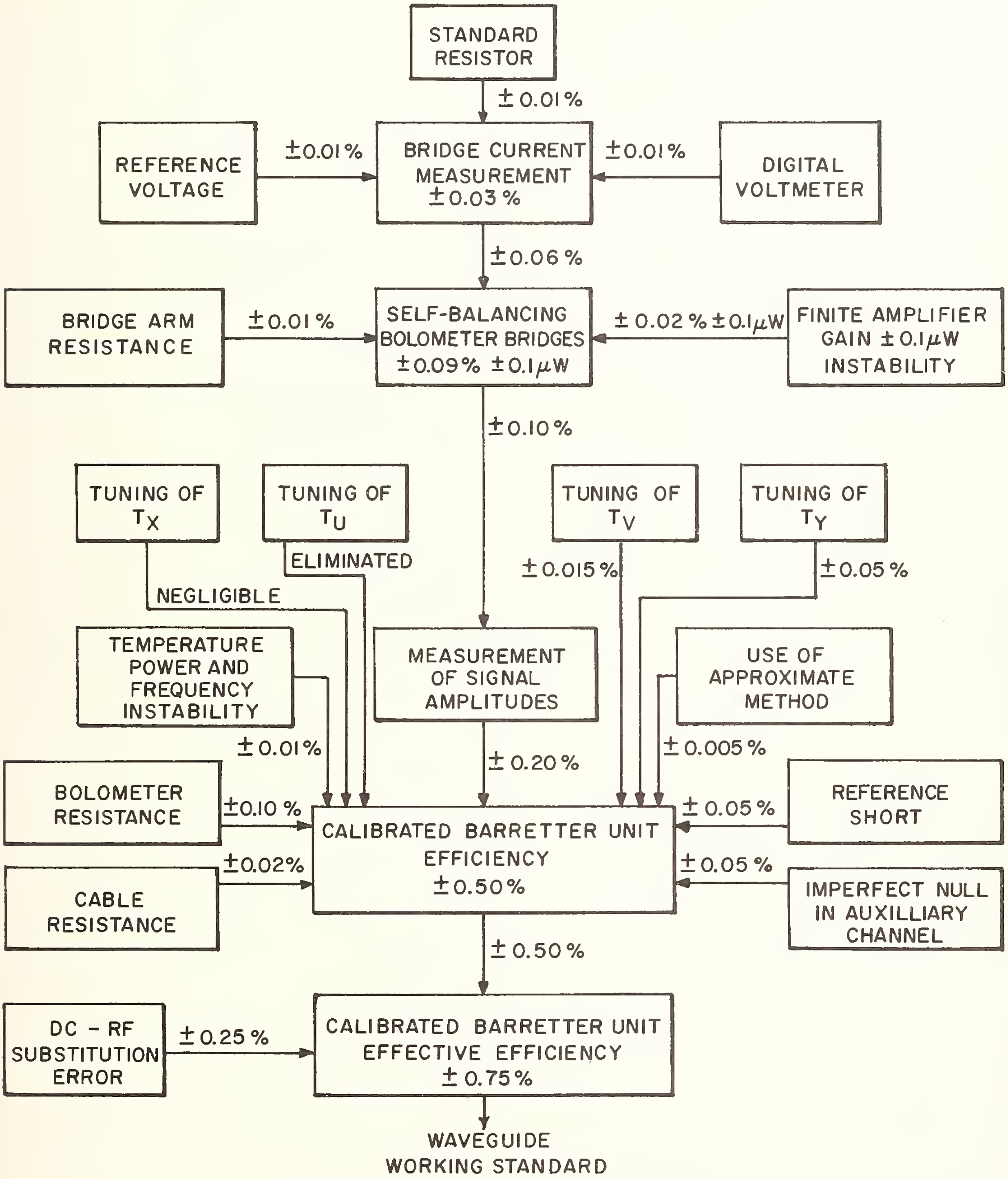
Notes: The impedance method actually measures only η, the efficiency of a bolometer unit. The limits on the effective efficiency of the working standard are obtained from the measured efficiency, η, and an estimate of the RF-dc substitution error. The standard is then used, as shown on page 17, to calibrate the customer's units when η_e, K_b, or K_c is desired.

Symbols appearing in the Error Flow Diagram are defined in reference below.

Reference: G. F. Engen, A bolometer mount efficiency measurement technique, J. Res., NBS, 65C, 113 (1961).

Personnel: R. F. Desch

MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR WORKING STANDARD
IMPEDANCE METHOD
WR284, WR187, WR137



IMPEDANCE METHOD OF MEASUREMENT, DIRECT COMPARISON METHOD:

Bias Uncertainties:

Random Errors:

Total Uncertainty:

} See Error Flow Diagram, page 16-5

Uncertainty quoted customer: 1.5%

Notes: This measurement is used to obtain K_c for bolometer-coupler units with any type of element.

Reference: None

Personnel: R. F. Desch

IMPEDANCE METHOD OF MEASUREMENT, REFLECTOMETER METHOD:

Bias Uncertainties:

Random Errors: See Error Flow Diagram, page 16-7

Total Uncertainty:

Uncertainty quoted customer: η_e for $|\Gamma| < 0.01$: 1%
K_b for $|\Gamma| < 0.2$: 1%

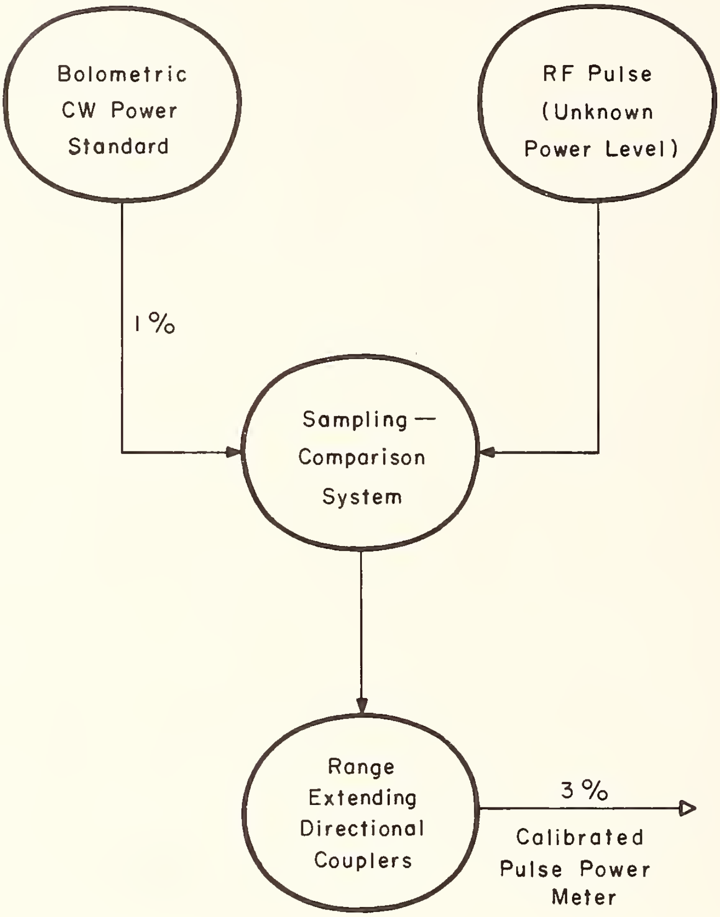
Notes: This measurement is used to obtain η_e and K_b for bolometer units with thermistor-type elements.

Reference: None

Personnel: R. F. Desch

RF PEAK-PULSE POWER IN COAXIAL SYSTEMS

300 - 500 MHz
950 - 1200 MHz
Pulse Duration : 2 - 10 μsec
Pulse Repetition Rate : 100-1600 pps
Maximum Duty Factor : 33 x 10^{-4}
Peak - Pulse Power : 1.0 mW - 3.0 kW



Peak-Pulse Power in Coaxial Systems

300 - 500 MHz
950 - 1200 MHz
Peak-Pulse Power: 1.0 mW - 3.0 kW

Bias Uncertainties:

RF power measurement

a. signal level (CW)	1%
b. direction coupler calibration	1
c. comparison system	1

Random Errors: negligible

Total Uncertainty: 3%

Uncertainty quoted customer: 3%

Notes: This measurement can be made with the uncertainties stated only on the following conditions:

1. Pulse duration must be between 2 and 10 microseconds.
2. Pulse repetition rate range: 100 to 1600 pps.
3. The duty factor (duty cycle) must be less than 33×10^{-4}.
4. The peak-pulse power range must be between 1.0 mW and 3.0 kW.

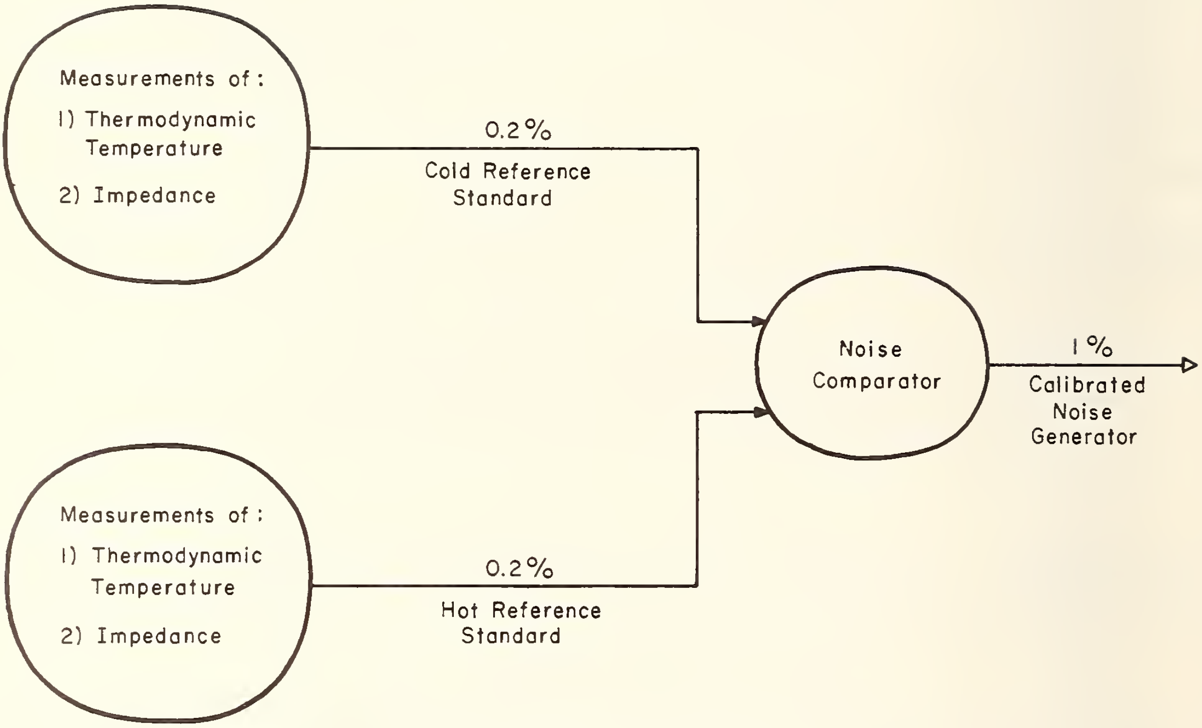
References: P. A. Hudson, W. L. Ecklund and R. A. Ondrejka, Measurement of RF peak-pulse power by a sampling-comparison method, IRE Trans. Instr., I-11, 280 (1962).

Peak-pulse power calibrations initiated, NBS, RSL, Engineering Division, IEEE Trans. Microwave Theory and Tech., MTT-14, 47 (1966).

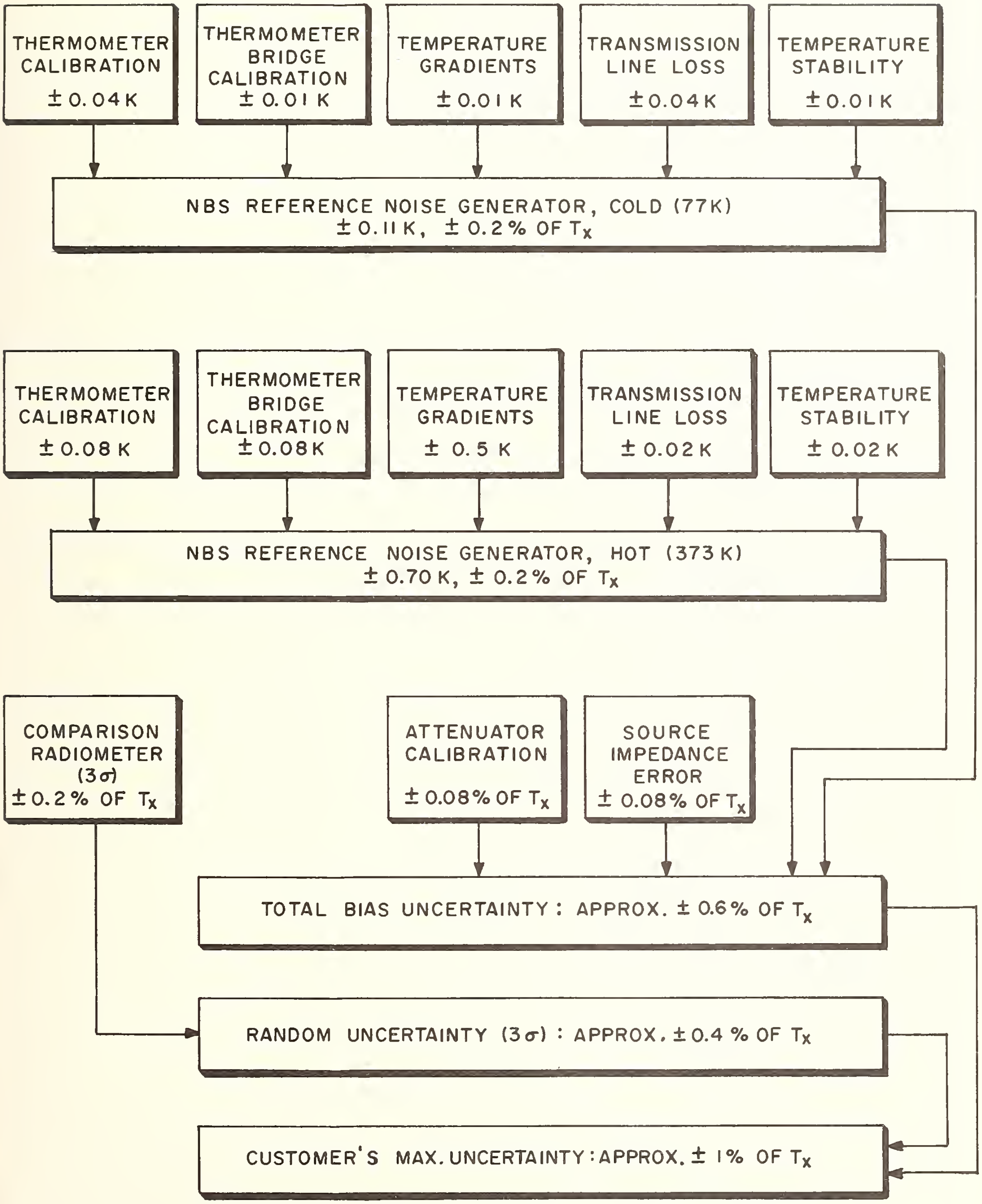
Personnel: P. A. Hudson
P. A. Simpson

NOISE TEMPERATURE

Coaxial Noise Generator at 3 MHz
75 K to 30,000 K



NOISE TEMPERATURE
COAXIAL NOISE GENERATOR AT 3 MHz
75 K TO 30,000 K



Noise Temperature
Coaxial Noise Generator at 3 MHz
75 K to 30,000 K

Bias Uncertainties: Approximately ±0.6%

Random Errors: Approximately ±0.4%

Total Uncertainty: Approximately ±1%

Uncertainty quoted customer: Actual total uncertainty as computed from the measurement data, using the error equation for the measurement process.

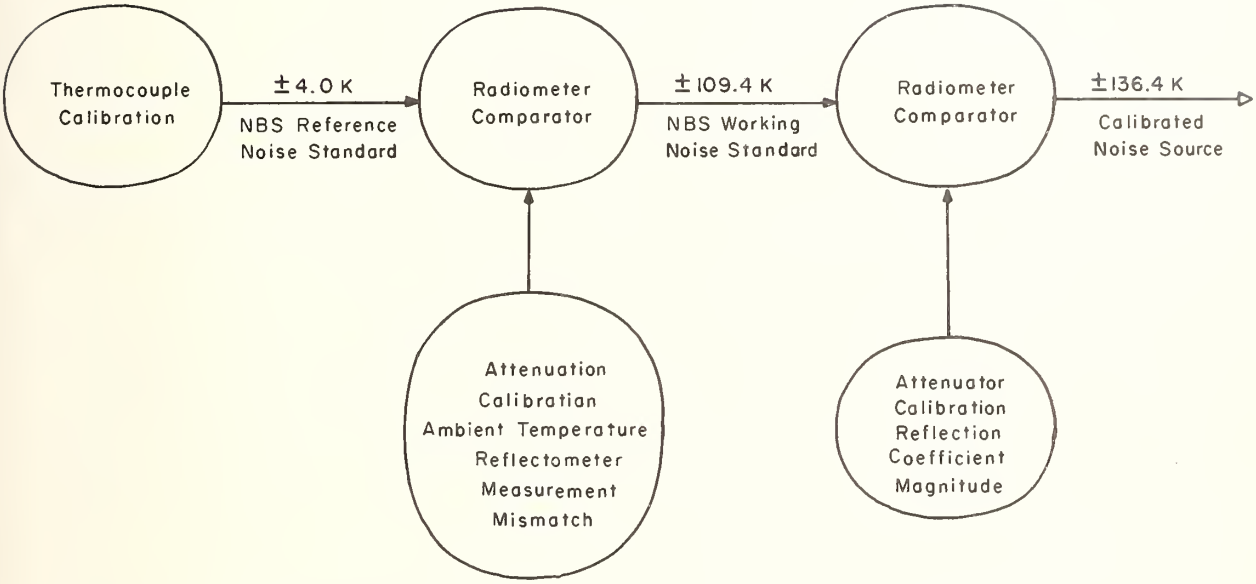
Notes: The uncertainties on the diagram (page 19-1) are typical values. Two values are given for each reference generator. The first is the actual uncertainty in the noise temperature of the reference generator; the second is the contribution by that reference generator to the total uncertainty in the measured value of the unknown noise temperature, T_x.

Reference: M. G. Arthur, C. M. Allred, and M. K. Cannon, A precision noise-power comparator, IEEE Trans. Instr. Meas., IM-13, 301 (1964).

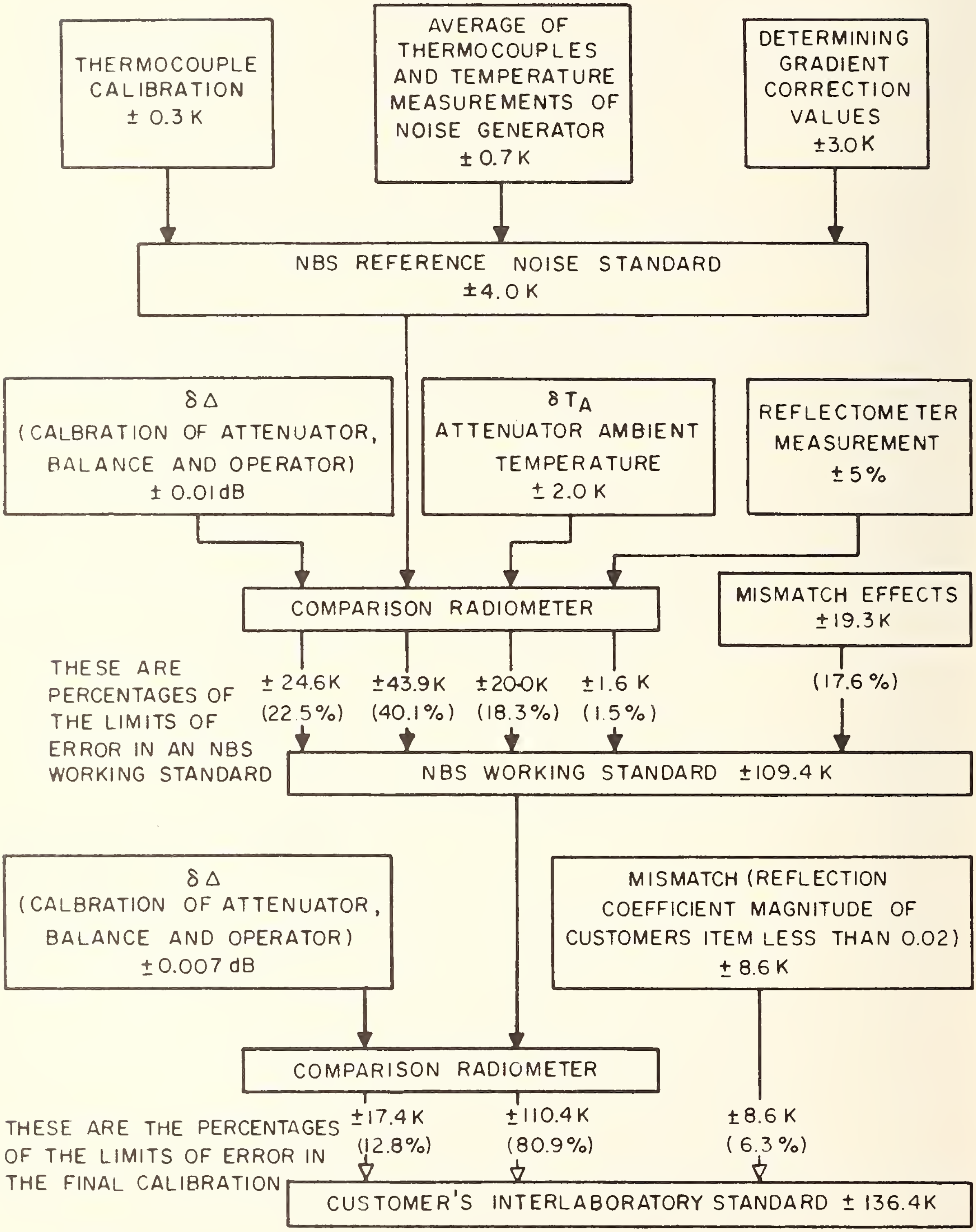
Personnel: M. G. Arthur

EFFECTIVE NOISE TEMPERATURE
WAVEGUIDE NOISE SOURCE AT 9 GHz

11, 000 K



EFFECTIVE NOISE TEMPERATURE FOR ARGON NOISE SOURCE, OR WAVEGUIDE NOISE SOURCE AT 9 GHz OPERATING AT 11,000 K



Effective Noise Temperature For Argon Noise Source, or Waveguide Noise Source at 9 GHz
11,000 K

Bias Uncertainties:

Random Errors: See page 20-1

Total Uncertainty:

Uncertainty quoted customer: Same as Total Uncertainty.

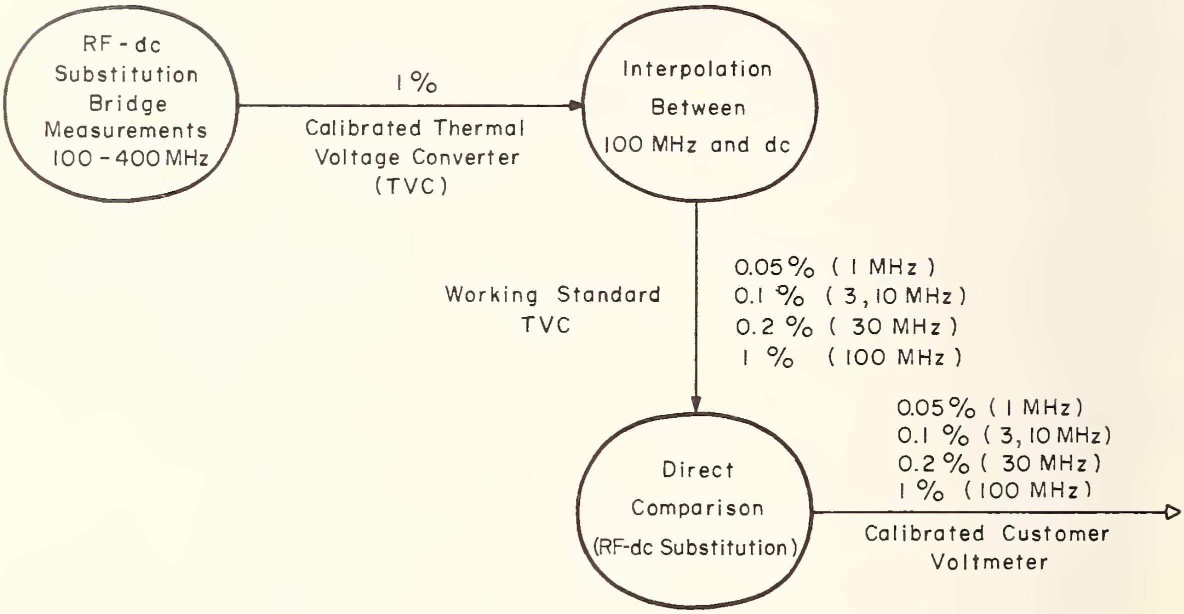
Notes: The uncertainties on the diagram (page 20-1) are typical values of systematic error at 9.0 GHz. The error limits depend in a very complicated way on several parameters.

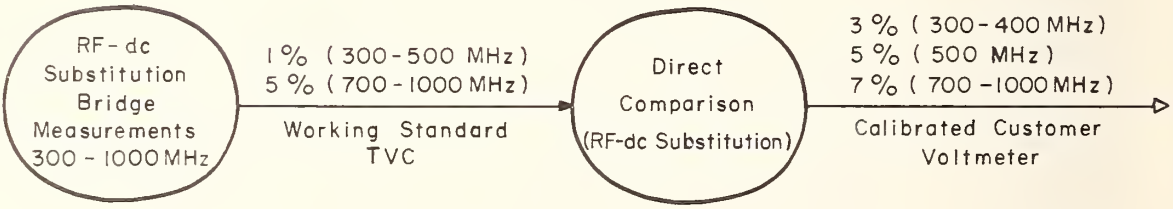
Reference: J. S. Wells, W. C. Daywitt and C. K. S. Miller, Measurement of effective temperatures of microwave noise sources, IEEE Trans. Instr. Meas., IM-13, 17 (1964).

Personnel: C. K. S. Miller

RF VOLTAGE, COAXIAL SYSTEMS

30 kHz - 1000 MHz
0.1 - 300 Volts





RF Voltage (cw) in Coaxial Systems
30 kHz - 1000 MHz
0.1 - 300 Volts

BOLOMETER BRIDGE MEASUREMENT:

A. Frequencies 30 kHz - 100 MHz

Bias Uncertainties:

dc voltages and resistances	0.061%
RF source drift	0.020
Galvanometer noise	0.050
Stability of interlaboratory standard resistor	0.010
Short time thermal effects on standard resistor	0.005
Random Errors (3σ):	0.251
Total Uncertainty:	0.397%

B. Frequencies 100 - 1000 MHz

Analysis similar to the above yields the following estimated error limits:

Frequency (MHz)	Total Uncertainty (%)
100	1
300, 500	1
700, 1000	5

Uncertainty quoted customer: See Notes

Notes: Ordinarily this measurement is not offered to the public as a service, but is used only for international comparisons and to calibrate working standards for use in the NBS Electronic Calibration Center.

Reference: M. C. Selby and L. F. Behrent, A bolometer bridge for standardizing radio-frequency voltmeters, J. Res. NBS, 44, 15 (1950).

Personnel: M. C. Selby

THERMAL VOLTAGE CONVERTERS at frequencies 30 kHz - 100 MHz

At frequencies below 100 MHz the uncertainties involved in using thermal voltage converters (TVC's) to compare directly dc and ac voltage, without calibration of the converter on a bridge, have been shown by Hermach and Williams to be generally less than the bridge uncertainties (See p. 21). The most important error in this direct procedure is the ac-dc substitution error, which has been investigated theoretically by Hermach and Williams (see Reference p. 21-3). They checked their theoretical results by making measurements of the ac-dc difference on the bolometer bridge at frequencies up to 400 MHz, and found satisfactory agreement. In particular, the theory was verified at frequencies above 100 MHz, where the ac-dc substitution error is greatest and the bridge uncertainties are less than that error. On the basis of this verification of the theory, the converters are used as devices (working standards) to compare ac voltages to dc standards without the use of a bridge. The uncertainty in the TVC as a working standard is taken to be just the substitution error, as follows:

Frequency (MHz)	Uncertainty (%)
1	0.05
3, 10	0.1
30	0.2
100	1.0

RF Voltage (cw) in Coaxial Systems

DIRECT COMPARISON of customer voltmeters with NBS working standard TVC's:

Bias Uncertainties: In addition to the substitution error considered on page 21-2, other possible sources of error in an actual comparison of ac voltage with dc are:

Measurement of the dc voltage
Mismatch
Determination of the reference plane

It is felt that these errors are negligible with respect to the uncertainty of the working standard at frequencies up to 100 MHz, and that they add between two and four percent to the uncertainties of the working standard at frequencies between 300 and 1000 MHz.

Random Errors: Negligible

Total Uncertainty:

Frequency (MHz)	Uncertainty (%)
1	0.05
3, 10	0.1
30	0.2
100	1
300, 400	3
500	5
700, 1000	7

Uncertainty quoted customer: Same as Total Uncertainty above.

Notes: None

References: F. L. Hermach and E. S. Williams, Thermal voltage converters for accurate voltage measurements to 30 megacycles per second, Trans. AIEE, Communication and Electronics, No. 49, 200 (July 1960).

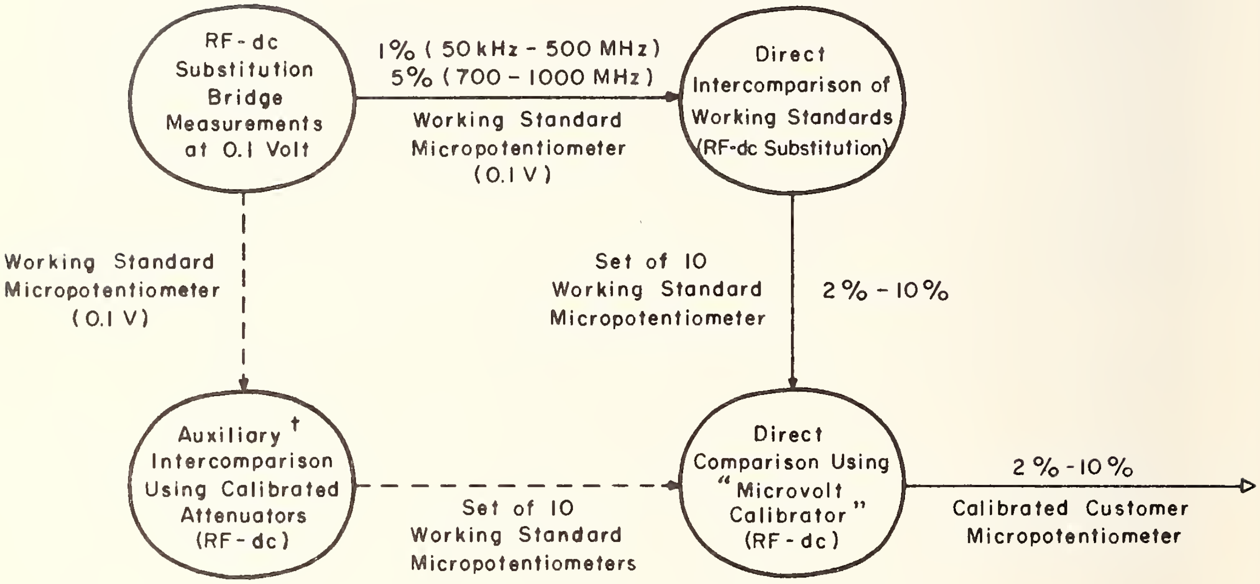
M. C. Selby and L. F. Behrent, A bolometer bridge for standardizing radio frequency voltmeters, J. Res. NBS, 44, 15 (1950).

M. C. Selby, Voltage measurement at high and microwave frequencies in coaxial systems, Proc. IEEE, 55, 877 (1967).

Personnel: M. C. Selby, F. X. Ries

RF MICROVOLTAGE

1 - 100 Microvolts, 50 kHz - 500 MHz
100 - 100,000 Microvolts, 50 kHz - 900 MHz



[†] Each Set of 10 Working Standards is Intercompared by Two Different Techniques as an Internal Check.

RF Microvoltage
1 - 100 Microvolts; 50 kHz - 500 MHz
100 - 100,000 Microvolts; 50 kHz - 900 MHz

MICROPOTENTIOMETER CALIBRATION:

Bias Uncertainties:

Uncertainty of the standard (thermal voltage converter)
dc voltage measurement
dc current measurement
attenuation measurement
RF leakage
ground currents (dc)
transfer instrument (RF receiver) sensitivity
determination of voltage reference plane

The largest of these is the uncertainty of the thermal voltage converter.

Random Errors: Negligible

Total Uncertainty:

Frequency MHz	Voltage Range microvolts	Uncertainty %
0.05 - 300	1 - 100	5
300 - 500	1 - 100	10
0.05 - 10	100 - 100,000	2
10 - 300	100 - 100,000	3
300 - 900	100 - 100,000	5

Uncertainty quoted customer: Same as Total Uncertainty, above.

Notes: None

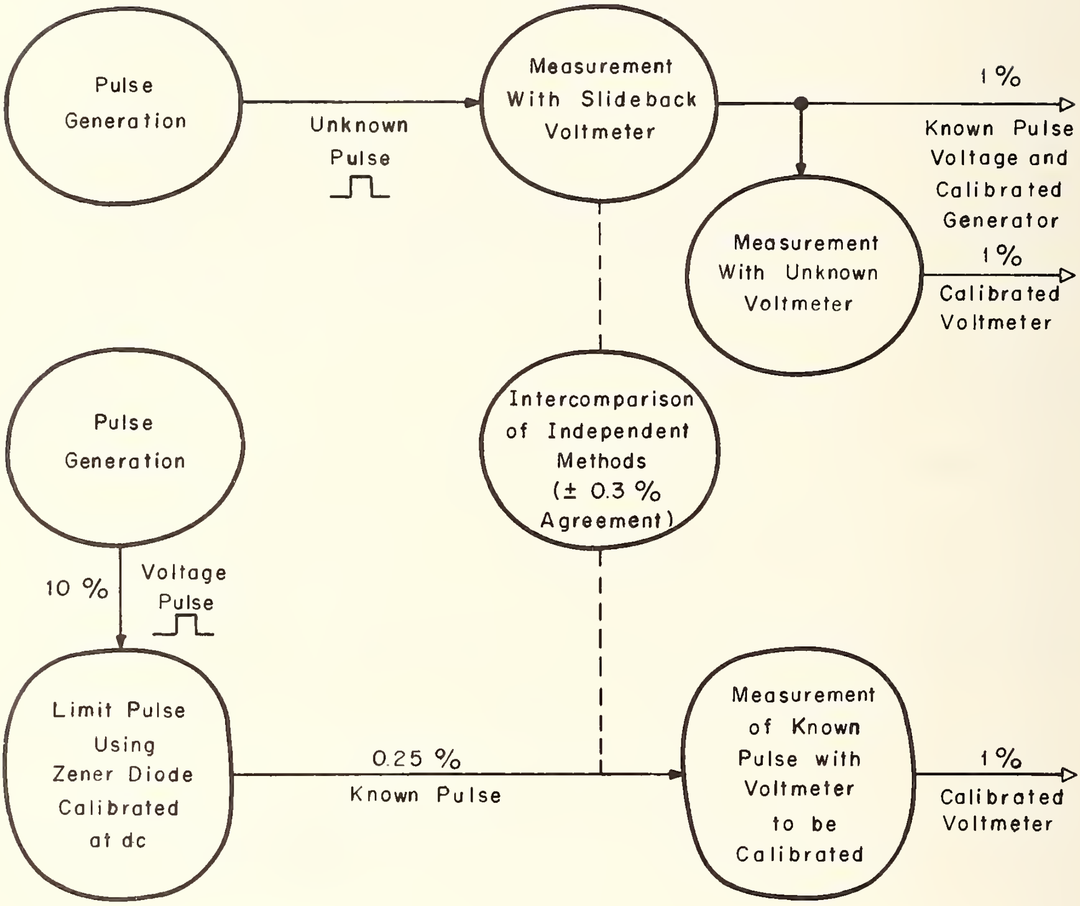
Reference: M. C. Selby, Accurate radio-frequency microvoltages, Trans. AIEE, Communication and Electronics, No. 6, 158-164 (May 1953).

Personnel: M. C. Selby
F. X. Ries

PULSE VOLTAGE

5 - 1000 Volts

Pulse Length : ≥ 10 Nanoseconds



Pulse Voltage
5 - 1000 Volts
Pulse Duration: ≤10 Nanoseconds

SLIDEBACK VOLTMETER METHOD:

Bias Uncertainties:

Thermal effects	10 mV
Detector null sensitivity	10 mV
dc voltage	0.05 %
Random Errors:	0.1 %
Total Uncertainty:	0.15 % ± 20 mV

Uncertainty quoted customer: 1%

Notes: This measurement is made only for pulses longer than 10 nanoseconds.

Measurement agreement between this slideback voltmeter method and the standard pulse generator method is 0.3 %. See page 23-2.

Reference: A. R. Ondrejka and P. A. Hudson, Measurement standards for low and medium peak-pulse voltages, J. Res. NBS, 70C, 13 (1966).

Personnel: P. A. Hudson
P. A. Simpson

STANDARD PULSE GENERATOR (ZENER DIODE) SYSTEM:

Bias Uncertainties:

Thermal effects	0.1 %
10% uncertainty in input pulse voltage	0.1
dc voltage	0.05
Random Errors:	negligible
Total Uncertainty:	0.25%

Uncertainty quoted customer: 1%

Notes: This measurement is made only for pulses longer than 10 nanoseconds.

The 10% uncertainty in input pulse voltage can be either an amplitude variation of the flat top of an individual pulse or an amplitude modulation in a series of pulses, or a combination of both.

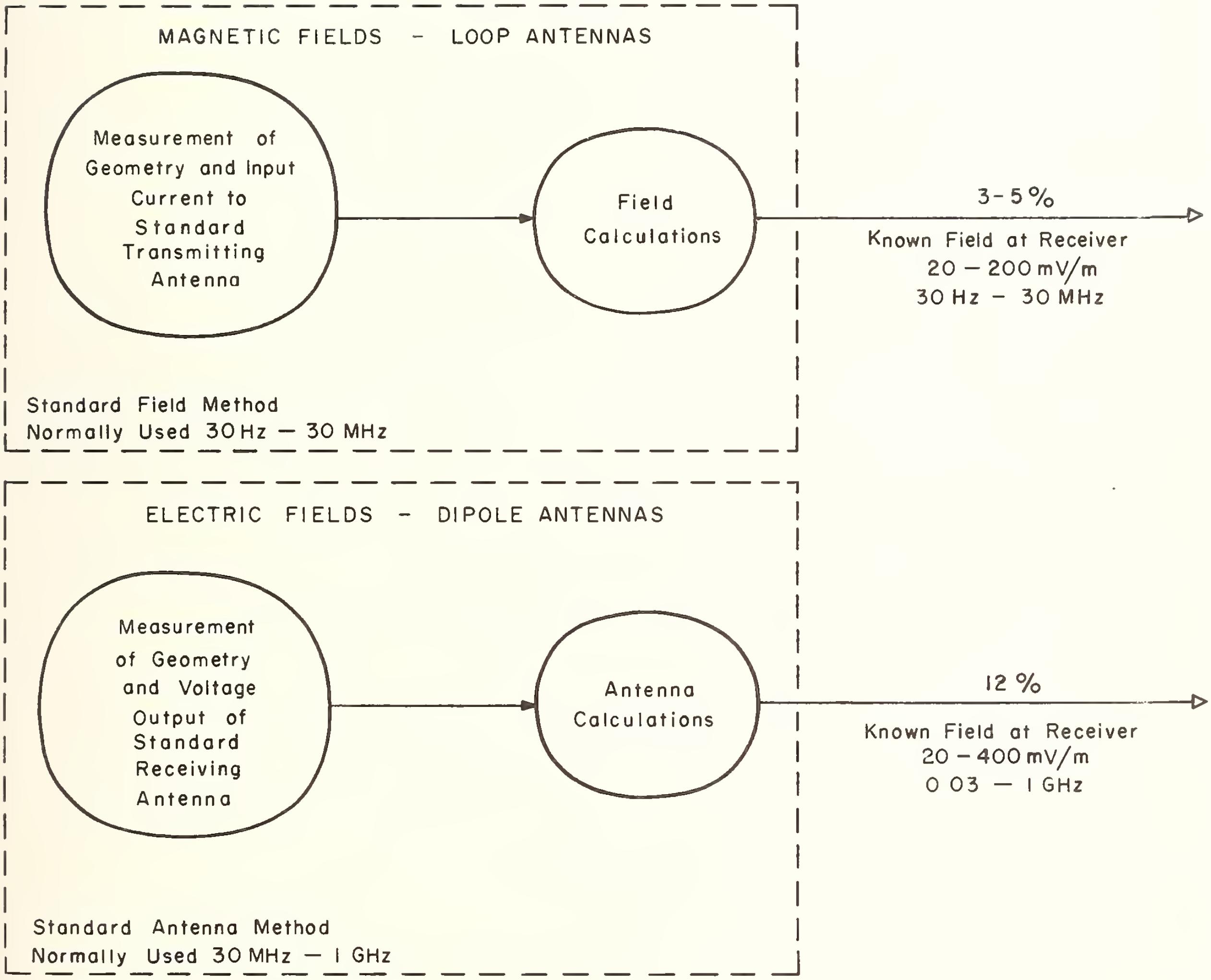
Measurement agreement between this standard pulse generator system and the slideback voltmeter system is 0.3%. See page 23-1.

Reference: A. R. Ondrejka and P. A. Hudson, Measurement standards for low and medium peak-pulse voltages, J. Res. NBS, 70C, 13 (1966).

Personnel: P. A. Hudson
P. A. Simpson

FIELD STRENGTH

30 Hz — 1 GHz
20 — 400 mV/m



LOOP ANTENNAS, STANDARD FIELD METHOD:

30 Hz - 30 MHz
20 - 200 mV/m

Bias Uncertainties:

Antenna dimensions
Input current
Output voltage (RF)
Effect of earth and other objects
Attenuation measurement

Random Errors: Not reported.

Total Uncertainty: 3% (See Notes)

Uncertainty quoted customer: 3%

Notes: The uncertainty of calibration is determined from two independent measurement methods: (1) the standard-field method, (2) the standard-antenna method. The standard-field method is used to calibrate loop antennas. The loop is calibrated in terms of a quasi-static magnetic field and converted to the equivalent electric field based on free space calibrations.

References: F. M. Greene, NBS field-strength standards and measurements (30 Hz to 1000 MHz), Proc. IEEE, 55, 970 (June 1967).

H. E. Taggart, Field-strengths and RFI standards at the National Bureau of Standards, 1968 IEEE Electromagnetic Compatability Symposium Record, IEEE 68CIZ-EMC, 149-158.

Personnel: F. M. Greene
H. E. Taggart

DIPOLE ANTENNAS, STANDARD ANTENNA METHOD:

30 - 1000 MHz
20 - 400 mV/m

Bias Uncertainties:

Antenna dimensions
Output voltage (dc or RF)
Effect of earth and other objects
Attenuation measurements

Random Errors: Not reported.

Total Uncertainty: 12% (See notes)

Uncertainty quoted customer: 12%

Notes: The uncertainty of calibration is determined from two independent measurement methods: (1) the standard-field method, (2) the standard-antenna method. The standard-antenna method is used to calibrate dipole antennas. The dipole antenna is calibrated by placing it in a known field at a specified height above ground.

References: F. M. Greene, NBS field-strength standards and measurements (30 Hz to 1000 MHz), Proc. IEEE, 55, 970 (June 1967).

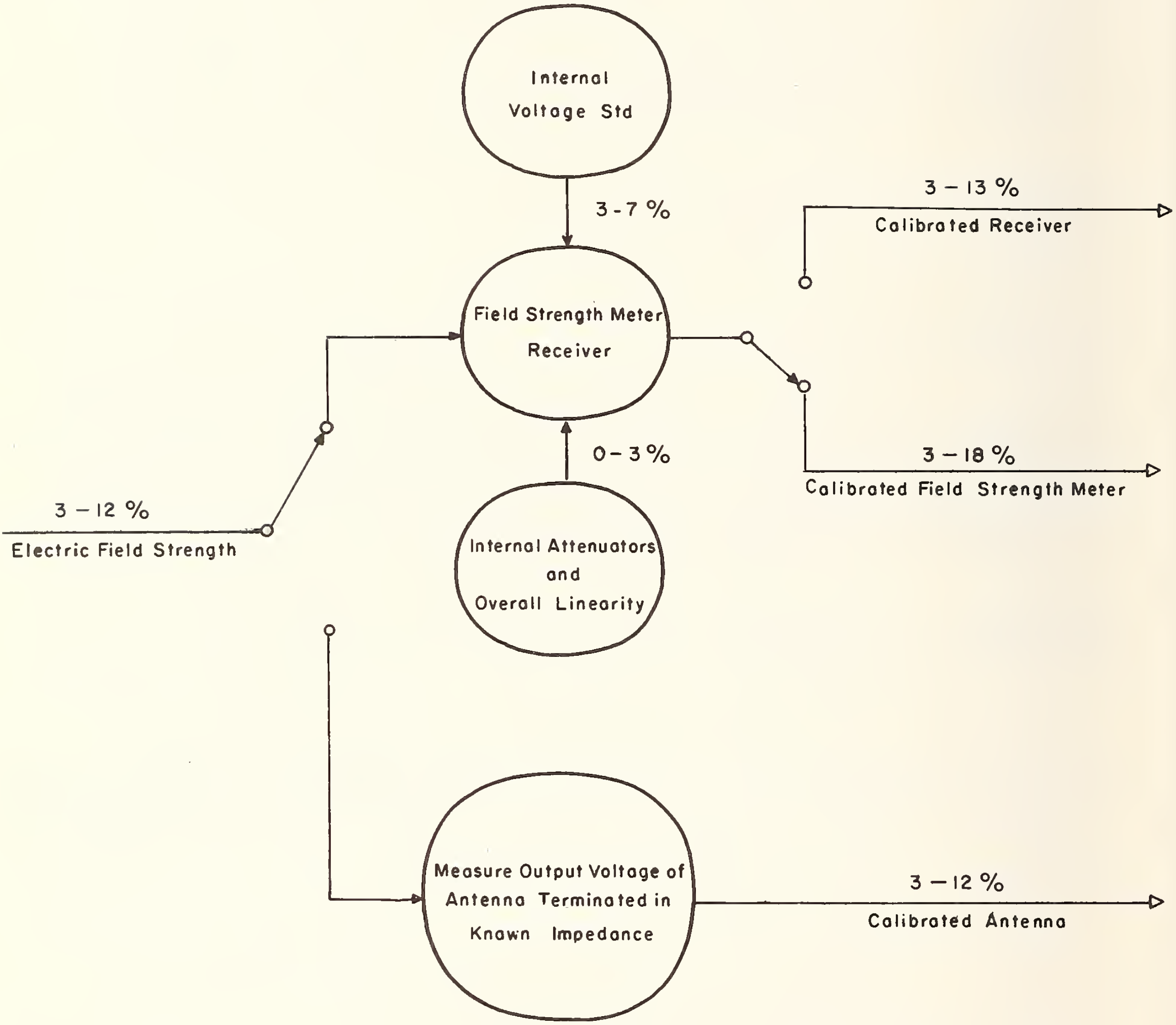
H. E. Taggart, Field-strengths and RFI standards at the National Bureau of Standards, 1968 IEEE Electromagnetic Compatability Symposium Record, IEEE 68CIZ-EMC, 149-158.

Personnel: F. M. Greene
H. E. Taggart

FIELD STRENGTH METER

30 Hz - 1 GHz

(20 - 400mV/m)



Field Strength Meter
30 Hz - 1 GHz
20 - 400 mV/m

RECEIVER CALIBRATION: (See Notes)

Bias Uncertainties:

Voltage measurement	30 Hz - 100 MHz	3%
	100 - 500 MHz	5%
	500 - 900 MHz	7%
Calibration of attenuators and overall linearity of receiver	30 Hz - 400 MHz	0.1dB+0.03dB/10dB
	400 - 1000 MHz	0.1dB+0.05dB/10dB

Random Errors: Not reported.

Total Uncertainty: 3% + 0.1dB + 0.03dB/10dB to
7% + 0.1dB + 0.05dB/10dB

Uncertainty quoted customer:

30 Hz - 100 MHz	5%
100 - 500 MHz	7%
500 - 1000 MHz	10%

Notes: As shown on page 25, a field strength meter consisting of an antenna and a receiver (which itself consists of a detector, internal attenuators and a voltmeter) can be calibrated as a unit (the "switch" is shown in that position), or the receiver and the antenna can be calibrated separately (the other "switch" position). When calibrated as a unit, the uncertainties are those as given on pages 24-1 and 24-2. When calibrated separately, the uncertainties are as given on pages 25-1 and 25-2.

Reference: None

Personnel: F. M. Greene
H. E. Taggart

ANTENNA CALIBRATION:

Loop antennas: 30 Hz - 30 MHz
Dipole antennas: 30 - 1000 MHz

Bias Uncertainties: See Notes.

Random Errors: Not reported.

Total Uncertainty: Loop antennas, 3%; dipole antennas, 12%.

Uncertainty quoted customer: Loop antennas, 3%; dipole antennas, 12%.

Notes: As shown on page 25 the calibration of an antenna by itself is done by placing the antenna in a known field, terminating it in a known impedance, and measuring its output voltage. The total uncertainty is taken to be equal to that of the uncertainty in the field itself, which is obtained as on pages 24, 24-1, and 24-2.

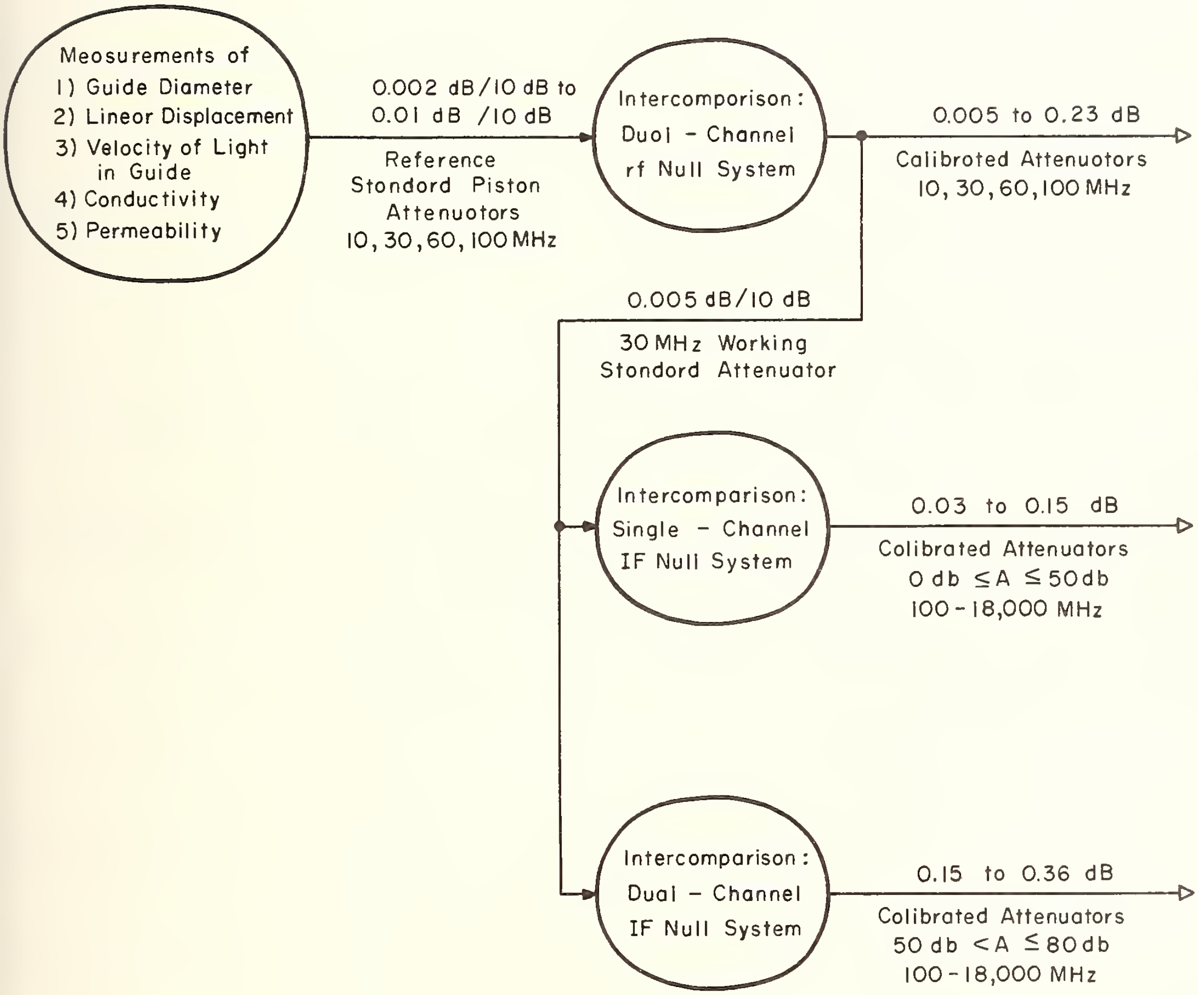
References: F. M. Greene, NBS field-strength standards and measurements (30 Hz to 1000 MHz), Proc. IEEE, 55, 970 (June 1967).

H. E. Taggart, Field-strengths and RFI standards at the National Bureau of Standards, 1968 IEEE Electromagnetic Compatability Symposium Record, IEEE 68CIZ-EMC, 149-158.

Personnel: F. M. Greene
H. E. Taggart

ATTENUATION: COAXIAL SYSTEMS

10 - 18,000 MHz
0 - 140 dB



PISTON ATTENUATION:

10, 30, 60, 100 MHz
0 - 140 dB

Bias Uncertainties:

Coaxial waveguide diameter	0.0003dB/10dB
Linear displacement of receiving coil	0.001dB/10dB-0.01dB/10dB
Velocity of electromagnetic waves in medium inside guide	negligible
RF conductivity of guide	0.00026dB/10dB
RF permeability of guide	negligible

Random Errors: negligible

Total Uncertainty: 0.002dB/10dB-0.01dB/10dB

Uncertainty quoted customer: See Notes.

Notes: Lower limits of these measurements are not available to customers,but are used only to establish the uncertainty in the National Bureau of Standards reference standard piston attenuators.

Reference: C. M. Allred and C. C. Cook, A precision RF attenuation calibration system, IRE Trans. Instr. I-9, 268 (1960).

Personnel: R. T. Adair

DUAL-CHANNEL RF NULL SYSTEM:

10, 30, 60, 100 MHz
0 - 140dB

Bias Uncertainties:

Reference standard piston attenuator	0.002dB/10dB-0.01dB/10dB
Mismatch errors	0.001dB/10dB
Leakage	0.001dB/10dB

Random Errors: See Notes. 0.001 - 0.06dB

Total Uncertainty: 0.005 - 0.23dB

Uncertainty quoted customer: Uncertainty is estimated for each individual case and those estimates are reported directly to the customer.

Notes: The random errors are reported to the customer as 3 times the standard error, which is defined on the calibration report. Typical standard errors range from about 0.001dB at low attenuations up to about 0.06dB at high attenuations.

Explicit numbers for mismatch errors and leakage errors are estimated for each individual case.

The maximum range of the standard piston attenuators is 140dB at 30 MHz and 100dB at 10, 60, and 100 MHz.

The numbers quoted for bias uncertainties are typical values, and may not apply to a particular calibration.

Reference: C. M. Allred and C. C. Cook, A precision RF attenuation calibration system, IRE Trans. Instr., I-9, 269 (1960).

Personnel: R. T. Adair

SINGLE-CHANNEL IF NULL SYSTEM:

100 - 18,000 MHz
0 - 50dB

Bias Uncertainties:

Mismatch errors	0.01dB/10dB
Mixer non-linearity	0.005dB/10dB
Noise, as a systematic error	0.005dB/10dB
Leakage	0.005dB/10dB
Working standard piston attenuator uncertainty	0.005dB/10dB

Random Errors: See Notes.

Total Uncertainty: 0.03 - 0.15dB

Uncertainty quoted customer: Reported as estimated in each individual case.

Notes: The random errors include such effects as connector precision, generator and detector fluctuations, and noise or instability in the unknown attenuator. They are reported to the customer as 3 times the standard error, with a sample size usually 6, giving about a 96% confidence limit. These random errors are generally negligible.

Explicit numerical entries for the bias uncertainties are estimated in each individual case.

Reference: David H. Russell, An unmodulated twin-channel microwave measurement system, ISA Trans., 4, 162 (1965).

Personnel: R. T. Adair

DUAL-CHANNEL IF NULL SYSTEM:

100 - 18,000 MHz
50 - 80dB

Bias Uncertainties:

Mismatch errors	0.01dB/10dB-0.02dB/10dB
Mixer non-linearity	0.005dB/10dB-0.01dB/10dB
Noise, as a systematic error	0.005dB/10dB
Leakage	0.005dB/10dB
Working standard piston attenuator	0.005dB/10dB

Random Errors: See Notes, page 26-3.

Total Uncertainty: 0.15 - 0.36dB

Uncertainty quoted customer: Reported as estimated in each individual case.

Notes: Explicit numerical entries for the bias uncertainties are estimated in each individual case.

References: D. Russell and W. Larson, RF attenuation, Proc. IEEE, 55, 942 (1967).

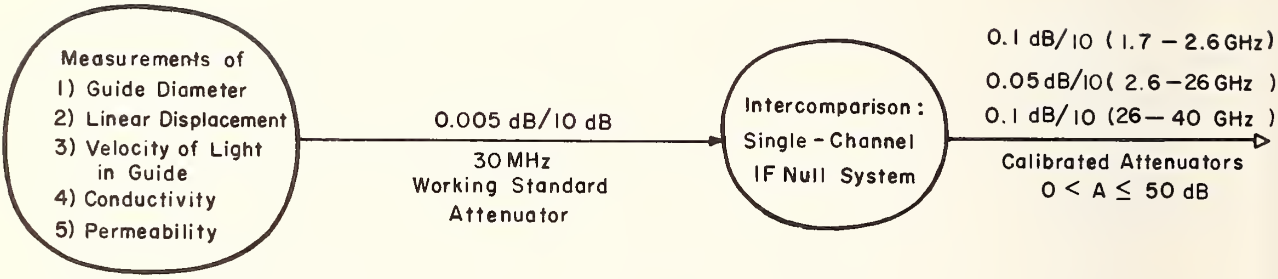
B. O. Weinschel, G. U. Sorger, and A. L. Hedrich, Relative voltmeter for VHF/UHF signal generator attenuator calibration, IRE Trans. Instr., I-8, 22 (1959).

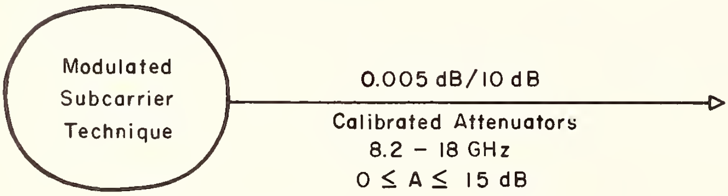
A. L. Hedrich, B. O. Weinschel, G. U. Sorger, and S. J. Raff, Calibration of signal generator output voltage in the range of 100 to 1000 megacycles, IRE Trans. Instr., I-7, 275 (1958).

Personnel: R. T. Adair

ATTENUATION : WAVEGUIDE SYSTEMS

1.7 – 40 GHz
0 – 50 dB





Attenuation: Waveguide Systems
1.7 - 40 GHz
0 - 50dB

PISTON ATTENUATOR: See page 26-1.

SINGLE-CHANNEL IF SYSTEM:

Bias Uncertainties:
Random Errors: See Error Flow Diagram, page 27-2
Total Uncertainty:

Uncertainty quoted customer:

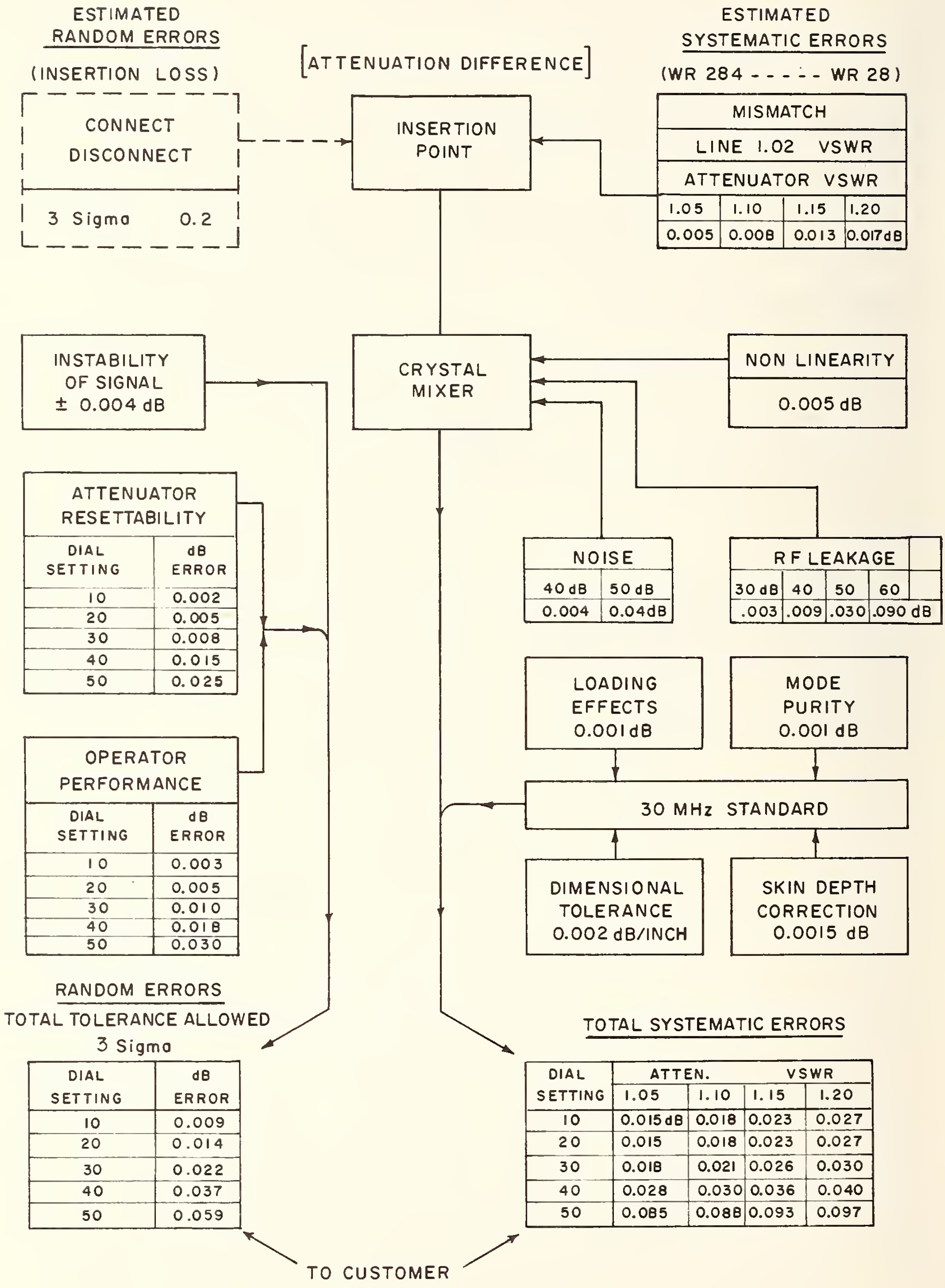
0.1dB/10dB;	1.7 - 2.6 GHz
0.05dB/10dB;	2.6 - 26 GHz
0.1dB/10dB;	26 - 40 GHz

Notes: None

Reference: R. E. Larson, Microwave measurements in the NBS Electronic Calibration Center, Proc. IEE (London), 109, part B, suppl. 23, 644 (1962).

Personnel: W. Larson

IF ATTENUATION CALIBRATION SYSTEM
ERROR FLOW DIAGRAM
FREQUENCY 1.7 – 40 GHz WR 430 --------WR 28



MISMATCH

LINE 1.02 VSWR

ATTENUATOR VSWR

1.05	1.10	1.15	1.20
0.005	0.008	0.013	0.017dB

NON LINEARITY

0.005 dB

ATTENUATOR RESETTABILITY

DIAL SETTING	dB ERROR
10	0.002
20	0.005
30	0.008
40	0.015
50	0.025

NOISE

40 dB	50 dB
0.004	0.04dB

RF LEAKAGE

30 dB	40	50	60
.003	.009	.030	.090 dB

OPERATOR PERFORMANCE

DIAL SETTING	dB ERROR
10	0.003
20	0.005
30	0.010
40	0.018
50	0.030

RANDOM ERRORS

TOTAL TOLERANCE ALLOWED

3 Sigma

DIAL SETTING	dB ERROR
10	0.009
20	0.014
30	0.022
40	0.037
50	0.059

TOTAL SYSTEMATIC ERRORS

DIAL	ATTEN.		VSWR	
SETTING	1.05	1.10	1.15	1.20
10	0.015dB	0.018	0.023	0.027
20	0.015	0.018	0.023	0.027
30	0.018	0.021	0.026	0.030
40	0.028	0.030	0.036	0.040
50	0.085	0.088	0.093	0.097

MODULATED SUBCARRIER TECHNIQUE:

Bias Uncertainties:

Random Errors: See Error Flow Diagram, page 27-4

Total Uncertainty:

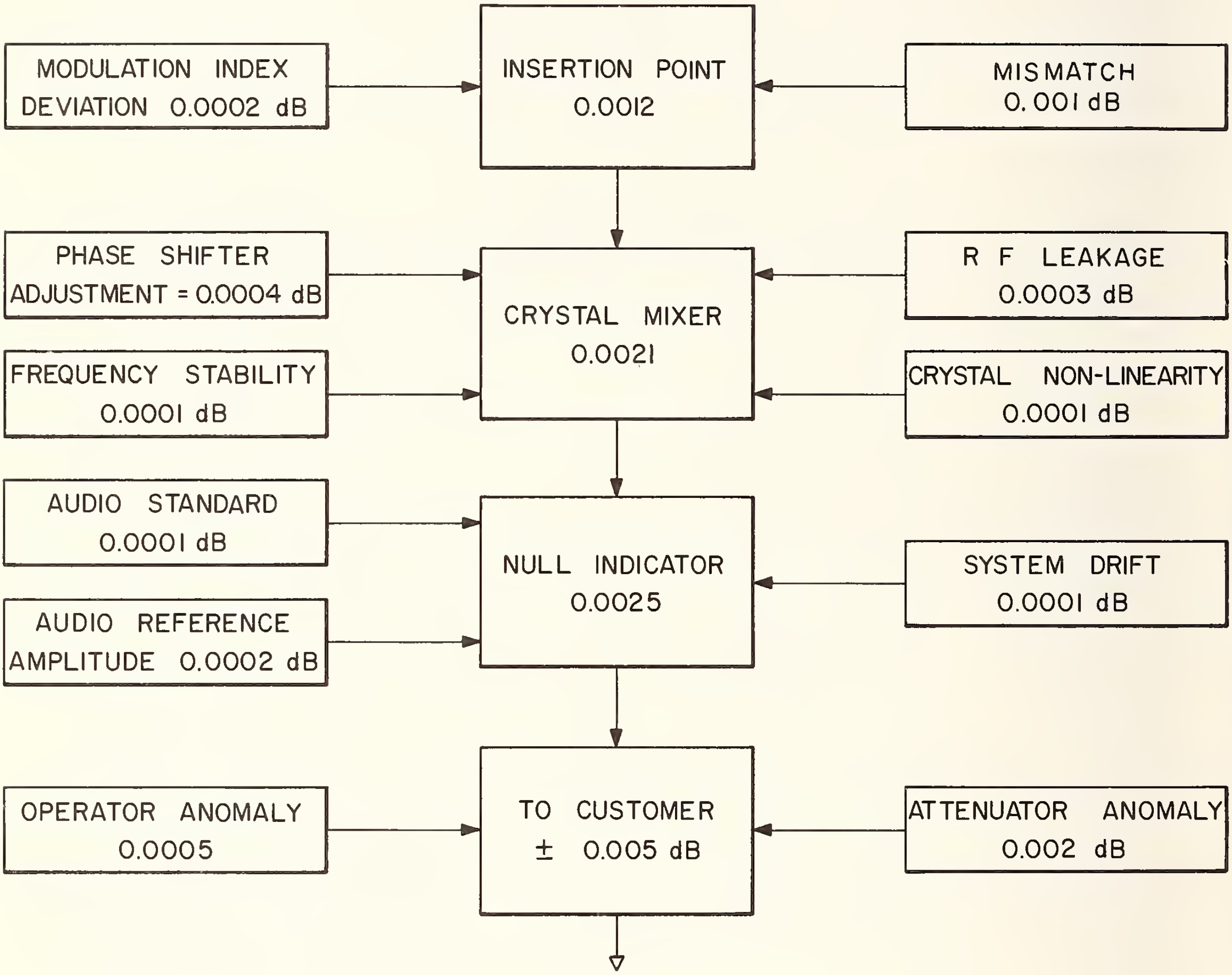
Uncertainty quoted customer: 0.005dB/10dB; 8.2 - 18.0GHz

Notes: none

Reference: G. E. Schafer and R. R. Bowman, A modulated subcarrier technique of measuring microwave attenuation, Proc. IEE (London), 109, part B, suppl. 23, 783 (1962).

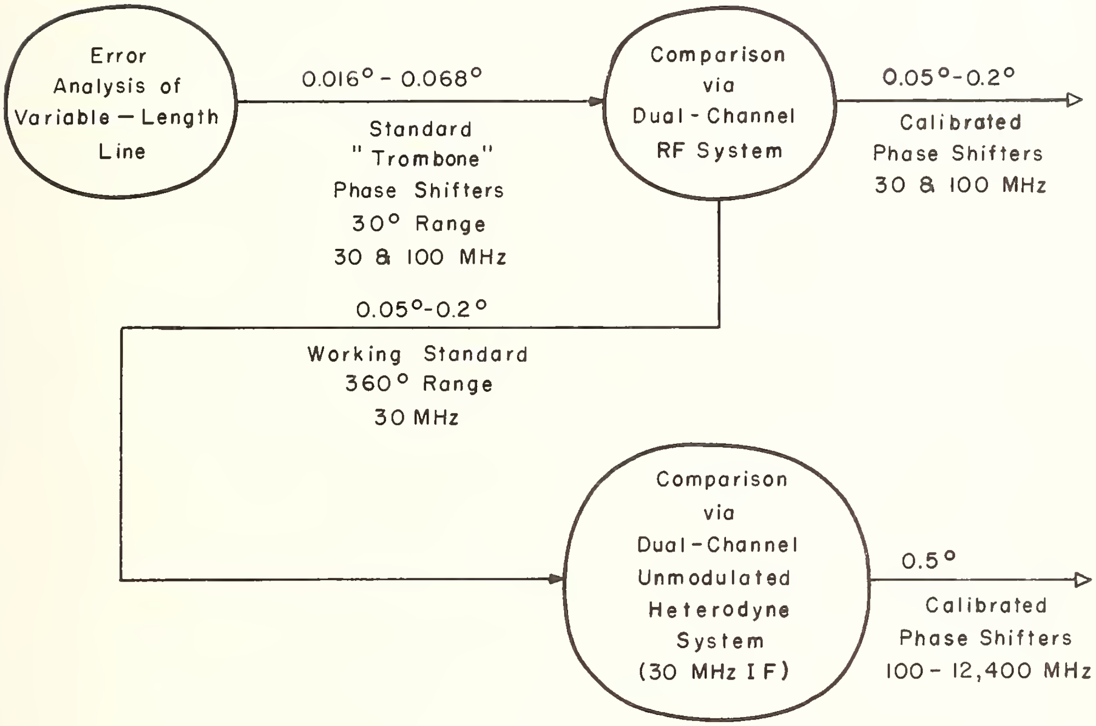
Personnel: W. Larson

ATTENUATION : WAVEGUIDE SYSTEMS
ERROR FLOW CHART FOR MODULATED SUBCARRIER



PHASE SHIFT IN COAXIAL PHASE SHIFTERS

30-12,400 MHz
0-360 Degrees



Phase Shift in Coaxial Two-Ports
30 and 100 MHz
0.05 - 360 Degrees

DUAL-CHANNEL RF COMPARISONS:

Bias Uncertainties:

Mechanical stability and length measurement in trombone phase shifter	0.004 - 0.048 degree	(30 MHz)
	0.012 - 0.144	(100 MHz)
Mismatch of trombone	0.012	
Phase shift in standard attenuator	0.01	
Resolution in auxilary phase shifter	0.02 - 0.13	

Random Errors:	negligible	
Total Uncertainty:	0.046 - 0.2 degree	(30 MHz)
	0.054 - 0.208 degree	(100 MHz)

Uncertainty quoted customer: Reported as estimated for each individual case.

Notes: Where there is a range of uncertainty in the list above, the uncertainty is a function of the phase shift in the coaxial two-port.

Reference: David H. Russell, An unmodulated twin-channel microwave measurement system, ISA Trans., 4, 162 (1965).

Personnel: R. T. Adair

Phase Shift in Coaxial Phase Shifters
30 - 12,400 MHz
0 - 360 degrees

DUAL-CHANNEL RF COMPARISONS:

Bias Uncertainties:

Mechanical stability and length measurement in trombone phase shifter	0.004 - 0.048 degree	(30 MHz)
	0.012 - 0.144	(100 MHz)
Mismatch of trombone	0.012	
Phase shift in standard attenuator	0.01	
Resolution in auxiliary phase shifter	0.02 - 0.13	
Random Errors:	negligible	
Total Uncertainty:	0.05 - 0.2 degree	(30 MHz)
	0.05 - 0.21 degree	(100 MHz)

Uncertainty quoted customer: Reported as estimated for each individual case.

Notes: Where there is a range of uncertainty in the list above, the uncertainty is a function of the phase shift in the coaxial phase shifter.

Reference: David H. Russell, An unmodulated twin-channel microwave measurement system, ISA Trans., 4, 162 (1965).

Personnel: R. T. Adair

DUAL-CHANNEL IF UNMODULATED COMPARISON SYSTEM:

100 - 18,000 MHz
0 - 360 degrees

Bias Uncertainties:

30 MHz working standard (resolver)	0.2 degree
Mismatch of unknown phase shifter	0.05
Mixer non-linearity (See Notes)	
Resolution (null sensitivity)	0.1

Random Errors: negligible

Total Uncertainty: < 0.35 degree

Uncertainty quoted customer: 0.5 degree.

Notes: The mixer non-linearity error is determined separately for each calibration.

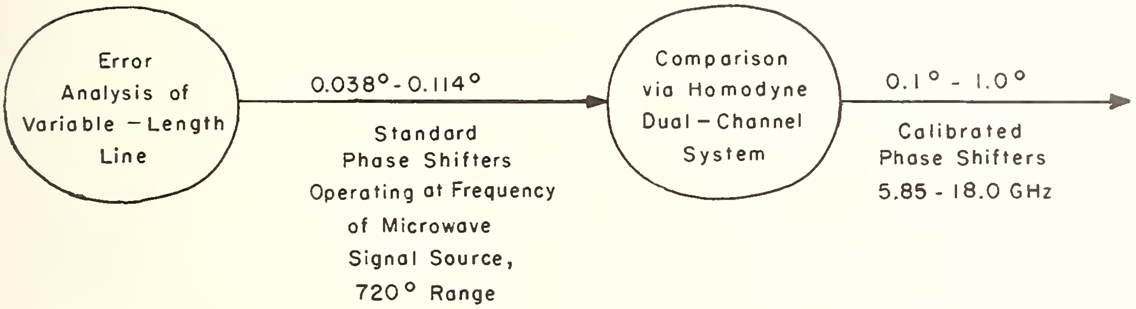
Reference: David H. Russell, An unmodulated twin-channel microwave measurement system, ISA Trans., 4, 162 (1965).

Personnel: R. T. Adair

PHASE SHIFT
IN WAVEGUIDE PHASE SHIFTERS

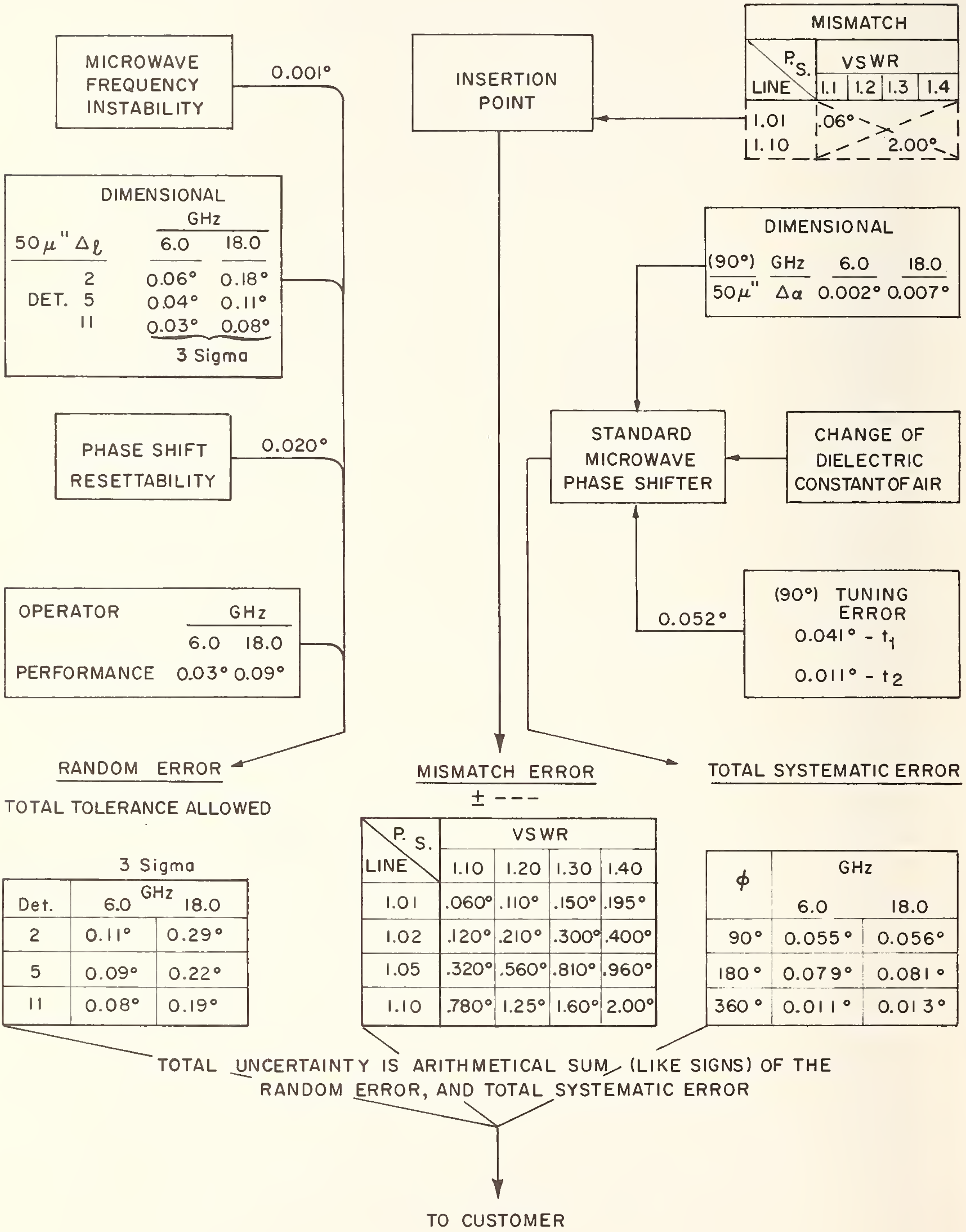
WR 62 : 12.4 -18.0 GHz
WR 90 : 8.20 -12.4 GHz
WR 137 : 5.85 - 8.20 GHz

0-720 Degrees



PHASE SHIFT IN WAVEGUIDE PHASE SHIFTERS
ERROR FLOW DIAGRAM

FREQUENCY 5.85 - 18.0 GHz   WR 62, WR 90 and WR 137



MISMATCH

P.S. / LINE	VSWR 1.1	1.2	1.3	1.4
1.01	.06°			
1.10				2.00°

DIMENSIONAL

50μ" Δℓ		GHz 6.0	18.0
DET.	2	0.06°	0.18°
	5	0.04°	0.11°
	11	0.03°	0.08°

3 Sigma

DIMENSIONAL

(90°)	GHz	6.0	18.0
50μ"	Δα	0.002°	0.007°

OPERATOR	GHz 6.0	18.0
PERFORMANCE	0.03°	0.09°

RANDOM ERROR

TOTAL TOLERANCE ALLOWED

3 Sigma

Det.	GHz 6.0	18.0
2	0.11°	0.29°
5	0.09°	0.22°
11	0.08°	0.19°

MISMATCH ERROR

± ---

P. S. / LINE	VSWR 1.10	1.20	1.30	1.40
1.01	.060°	.110°	.150°	.195°
1.02	.120°	.210°	.300°	.400°
1.05	.320°	.560°	.810°	.960°
1.10	.780°	1.25°	1.60°	2.00°

TOTAL SYSTEMATIC ERROR

ϕ	GHz 6.0	18.0
90°	0.055°	0.056°
180°	0.079°	0.081°
360°	0.011°	0.013°

TOTAL UNCERTAINTY IS ARITHMETICAL SUM (LIKE SIGNS) OF THE RANDOM ERROR, AND TOTAL SYSTEMATIC ERROR

TO CUSTOMER

Phase Shift in Waveguide Phase Shifters

5.85 - 18 GHz
0 - 720 degrees

Bias Uncertainties:
Random Errors: See Error Flow Diagram, page 28-1
Total Uncertainty:

Uncertainty quoted customer: Same as Total Uncertainty.

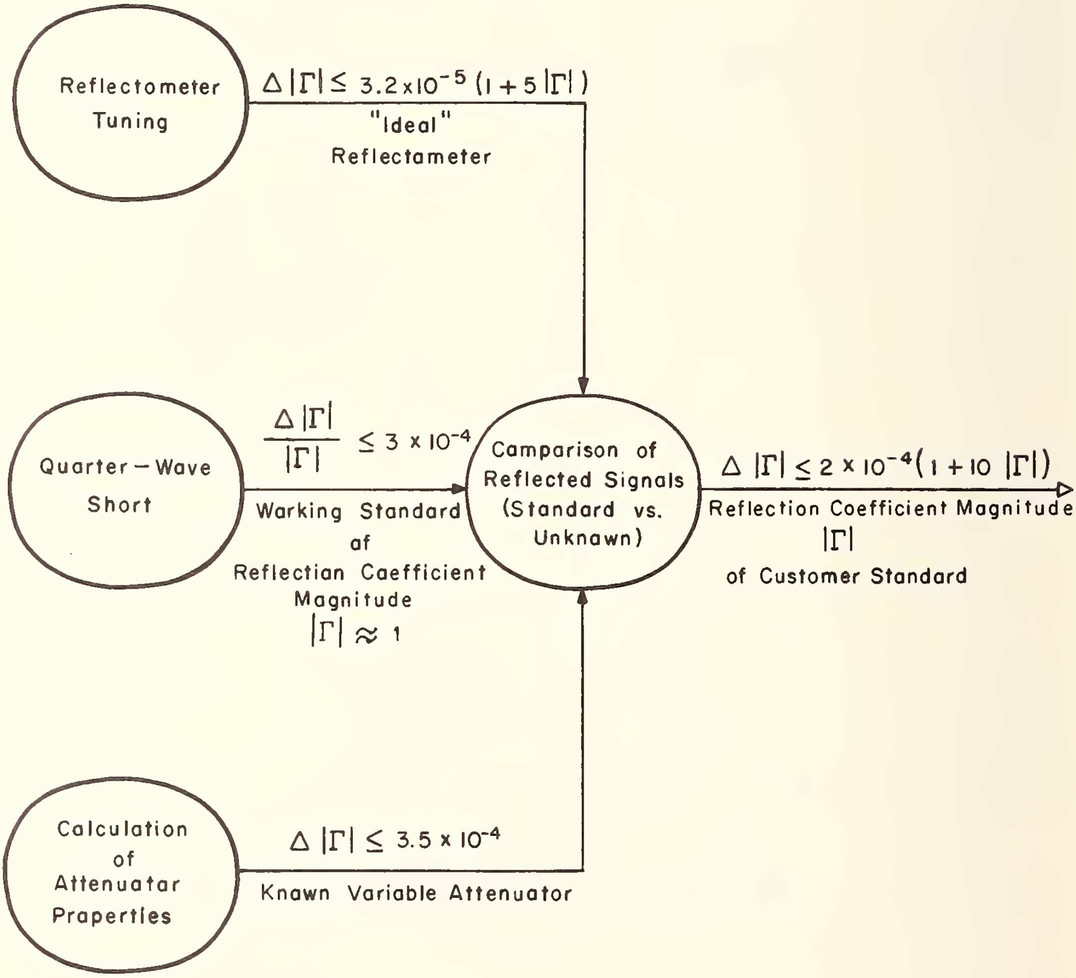
Notes: The VSWR of the phase shifter must be less than 1.5. Resolution of the phase shifter should be 0.5° or better.

Reference: D. A. Ellerbruch, Evaluation of a microwave phase measurement system, J. Res. NBS, 69C, 55 (1965).

Personnel: W. Larson
E. D. Hall

REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

WR 42 : 18.0 – 26.5 GHz
WR 62 : 12.4 – 18.0
WR 90 : 8.2 – 12.4
WR 112 : 7.05 – 10.0
WR 137 : 5.85 – 8.2
WR 187 : 3.95 – 5.85
WR 284 : 2.6 – 3.95
$0.024 \leq |\Gamma| \leq 0.2$
Power Level : 0.01 mW



Reflection Coefficient Magnitude of Waveguide Devices

WR 42: 18.0 - 26.5 GHz
WR 62: 12.4 - 18.0
WR 90: 8.2 - 12.4
WR 112: 7.05 - 10.0
WR 137: 5.85 - 8.2
WR 187: 3.95 - 5.85
WR 284: 2.6 - 3.95
Power Level: 0.01 - 4 mW

Bias Uncertainties:
Random Errors:
Total Uncertainty:
See Error Flow Diagrams, pages 30-2 and 30-3

Uncertainty (typical) quoted customer: $|\Gamma| \geq 0.024$,

$$\Delta |\Gamma| = 2 \times 10^{-4} (1 + 6|\Gamma|).$$

$|\Gamma| < 0.024$,

$$\Delta |\Gamma| = 2 \times 10^{-4} (1 + 10|\Gamma|).$$

Notes: The uncertainties due to the precision waveguide section (see error flow diagrams, pages 30-2 and 30-3) are as follows:

Waveguide	Uncertainty in $|\Gamma|$
WR 284	<0.0001
WR 187	<0.0001
WR 137	<0.0001
WR 112	<0.0001
WR 90	<0.00015
WR 62	<0.0001
WR 42 (square flange)	<0.0004
WR 42 (round flange)	<0.0003

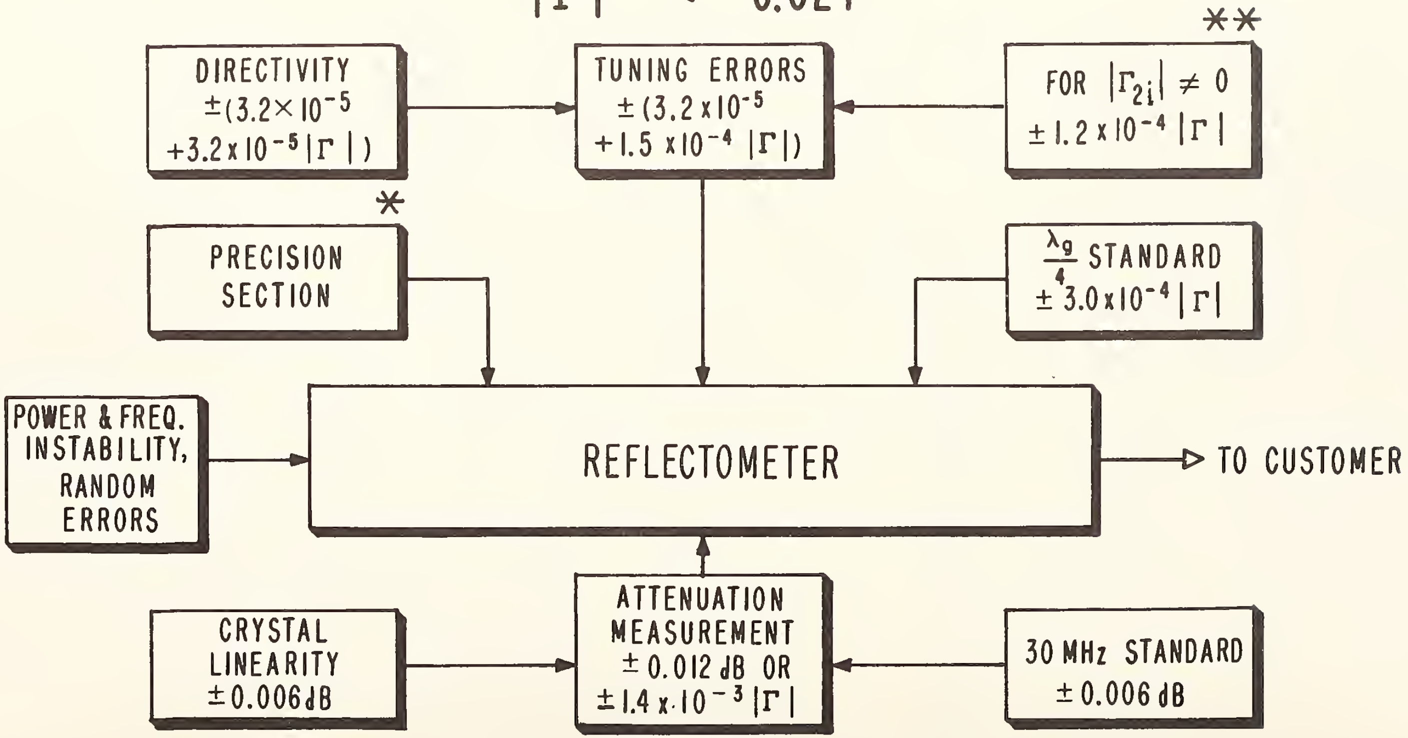
Reference: Wilbur J. Anson, A guide to the use of the modified reflectometer technique of VSWR measurement, J. Res. NBS, 65C, 217 (1961).

Personnel: B. C. Yates

ERROR FLOW DIAGRAM

FOR REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

$|\Gamma| < 0.024$



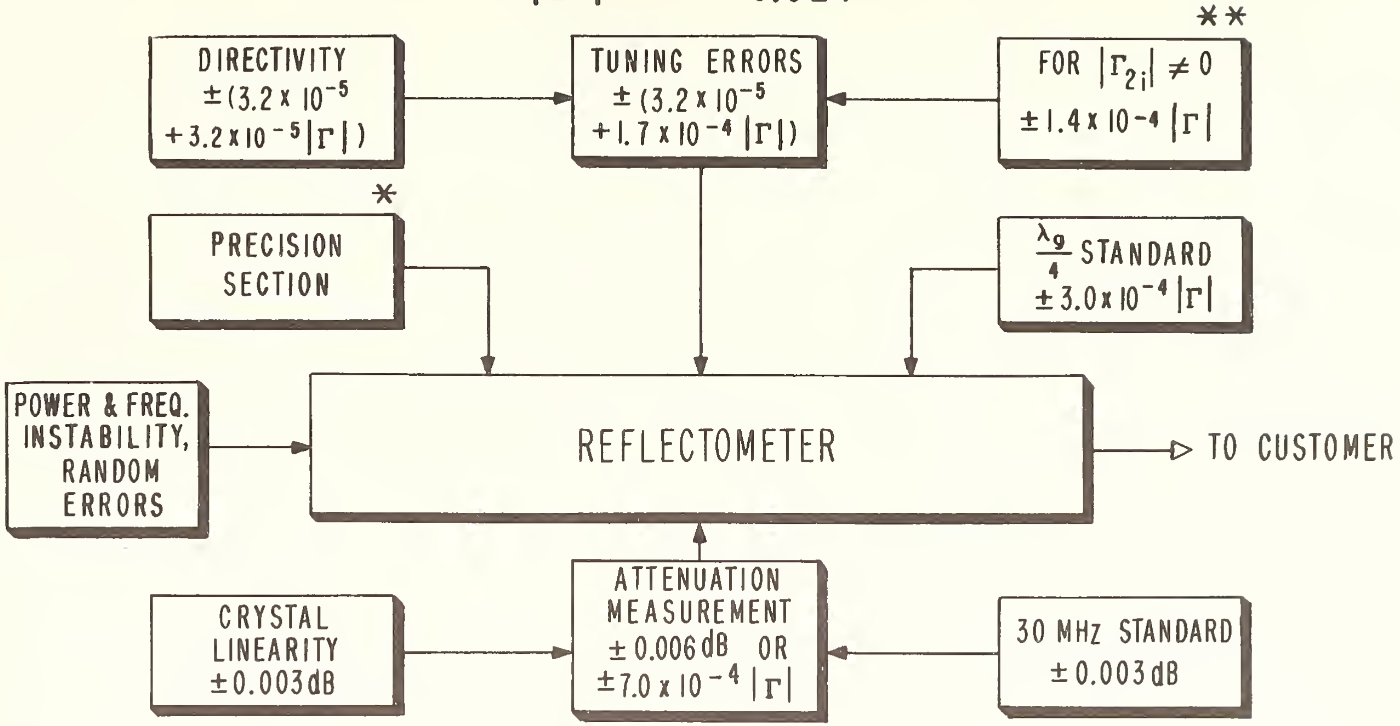
* See Notes

** See Reference

ERROR FLOW DIAGRAM

FOR REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

$|\Gamma| \geq 0.024$

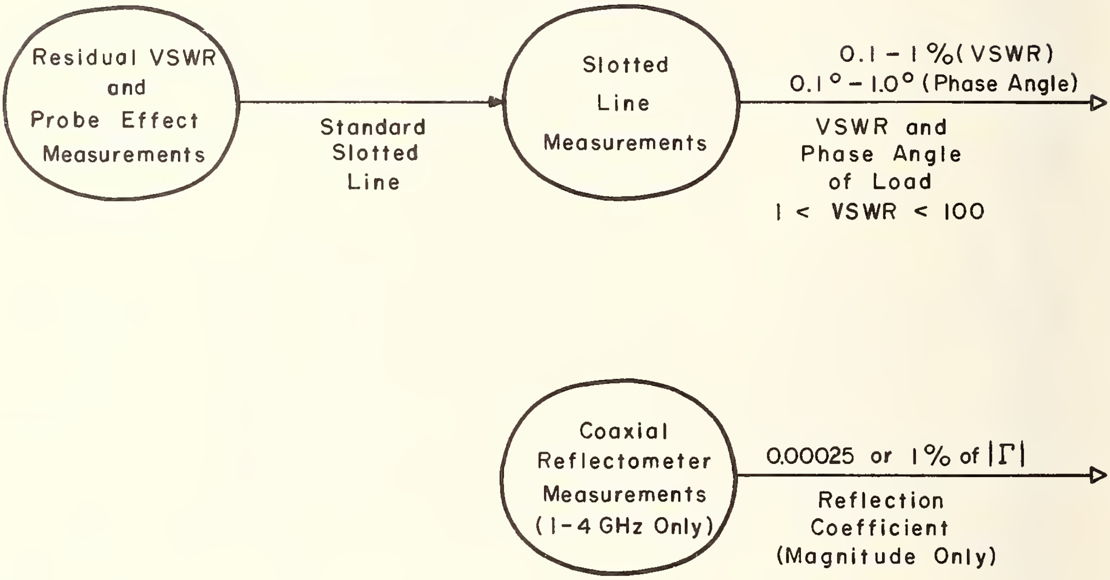


* See Notes

** See Reference

DISTRIBUTED PARAMETERS IN COAXIAL SYSTEMS

0.5 - 8 GHz



Distributed Parameters in Coaxial Systems
0.5 - 8 GHz

SLOTTED LINE MEASUREMENTS:

500 MHz - 8 GHz
$1 \leq \text{VSWR} \leq 100$

Bias Uncertainties:

Residual VSWR

- (a) Imperfect transition from connector to slotted line
- (b) Variation in characteristic impedance
- (c) Slot effects

Probe Effects

- (a) Variation of probe coupling with probe position
- (b) Probe loading of the slotted line

Line losses

Detector nonlinearity

Determination of the position of a voltage minimum

Power and frequency instability

Random Errors: Negligible

Total Uncertainty:

0.1 - 1.0% for $1 \leq (\text{VSWR}) \leq 4$
0.1 - 1 degree (phase angle)

Uncertainty quoted customer: As above.

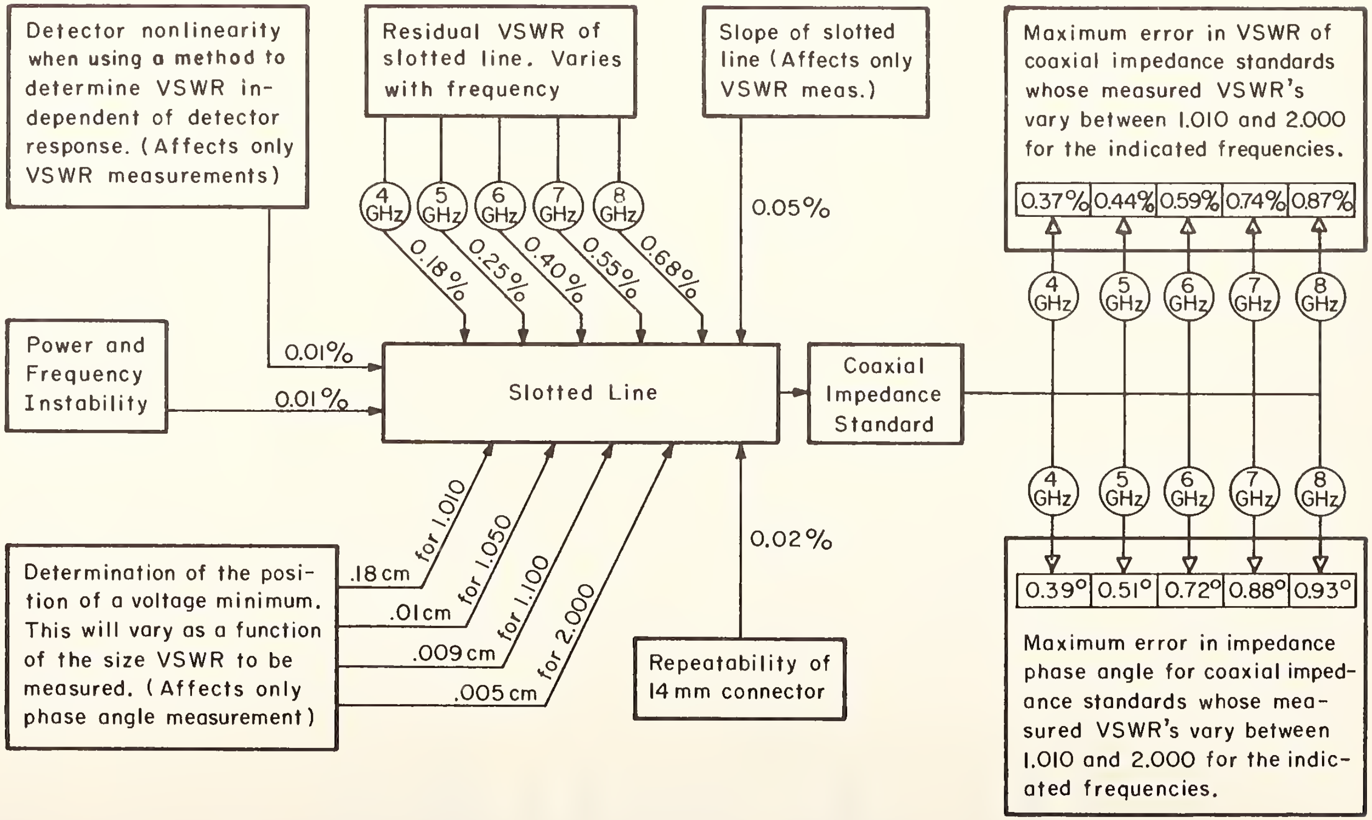
Notes: Page 31-2 gives some details of the error sources. Further details are available from R. L. Jesch (below).

Uncertainty figures assume precision 14mm coaxial connectors. Uncertainties for other connectors and larger VSWR's will, in most cases, be larger.

Reference: R. L. Jesch and R. M. Jickling, Impedance measurements in coaxial waveguide systems, Proc. IEEE, 55, 912 (June 1967).

Personnel: R. L. Jesch

ERROR FLOW DIAGRAM FOR COAXIAL IMPEDANCE STANDARDS EQUIPPED WITH PRECISION 14 mm COAXIAL CONNECTORS MEASURED WITH A 14 mm COAXIAL SLOTTED LINE EMPLOYING REGULAR MEASUREMENT TECHNIQUES UP TO 8 GHz



COAXIAL REFLECTOMETER MEASUREMENTS:

1 - 4 GHz
$0 \leq |\Gamma| \leq 1$

Bias Uncertainties:

- Tuning errors
- Detector errors
- Precision air-line section
- Power and frequency instability

Random Errors: Negligible

Total Uncertainty:

for $0 \leq |\Gamma| \leq 0.025$: $\Delta |\Gamma| \leq 0.00025$
for $0.025 \leq |\Gamma| \leq 1$: $\Delta |\Gamma| \leq 1\% |\Gamma|$

Uncertainty quoted customer: As above

Notes: In other than exacting standards work, or unless specially requested, this measurement is rarely done for customers. Satisfactory results may be obtained at a much lower cost by the slotted-line technique.

Reference: W. E. Little and J. P. Wakefield, Measurement of Precision coaxial connectors using reflectometer techniques, IEEE International Conv. Rec., pt. 11, 89-97, March 1965.

Personnel: R. J. Jesch

HIGH FREQUENCY IMMITTANCE

30 KHz – 300 MHz

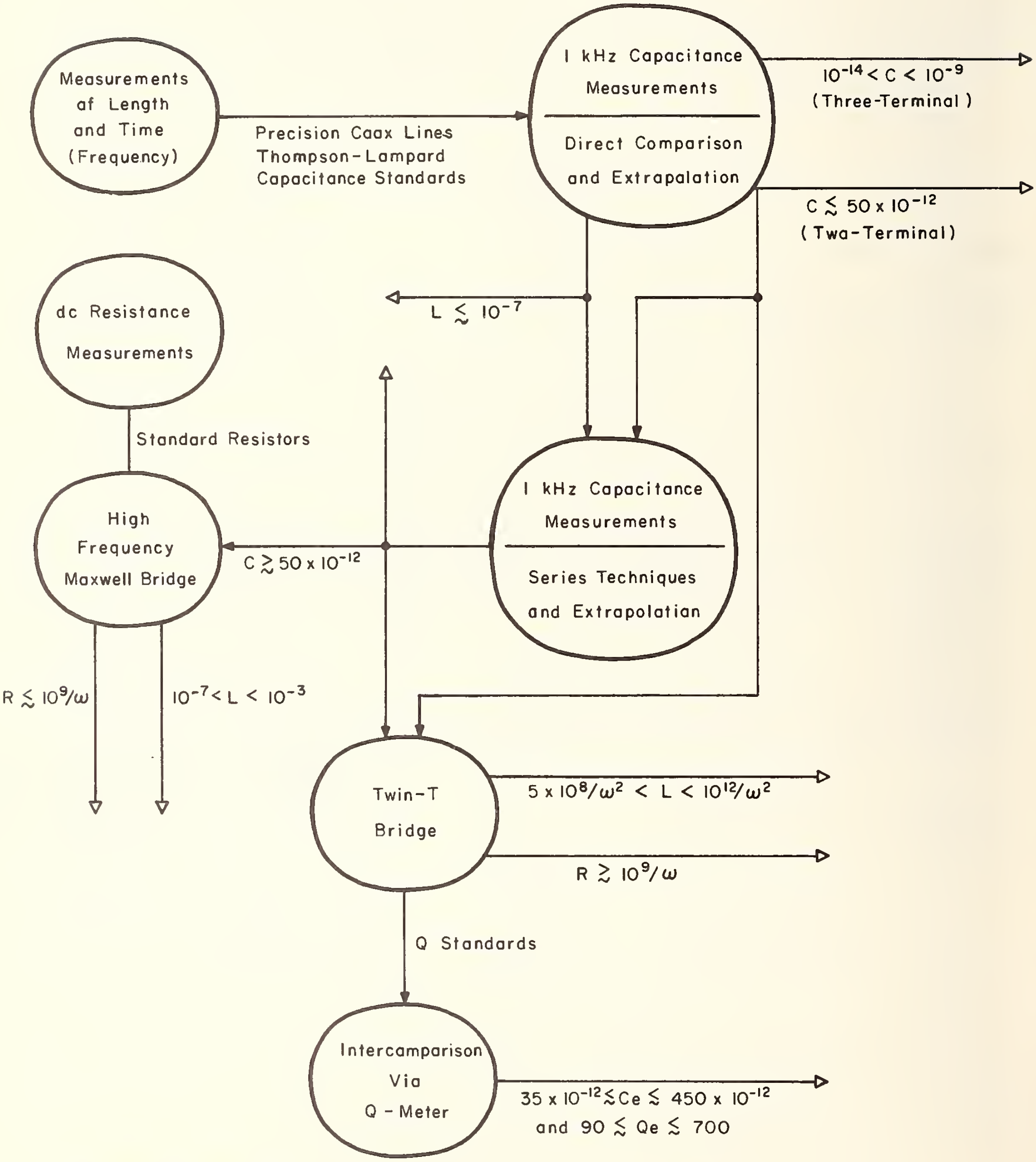
C : $10^{-12} - 10^{-7}$ F

L : 10^{-8} – 1 H

R : 0.1 – 10^{6} Ω

Effective Resonating Capacitance (Ce) : $35 \times 10^{-17} - 450 \times 10^{-2}$ F

Effective Quality Factor (Qe) : 90 – 700



ω : Angular Frequency

High Frequency Immittance
30 kHz - 300 MHz

Capacitance: 10^{-12} - 10^{-7} F
Inductance: 10^{-8} - 1 H
Resistance: 0.1 - 10^{6} Ω

Bias Uncertainties:

- Null detection
- Generator frequency stability
- Mechanical errors (e.g., gears)
- Connectors

Random Errors: 0.01 to 0.05% (see Notes).

Total Uncertainty:

Capacitance (2 terminal)	0.1 - 0.5%
Capacitance (3 terminal, see Notes)	0.01 - 2%
Inductance	0.1 - 20%
Resistance	0.1 - 10%

Uncertainty quoted customer: Quoted as estimated for each individual case.

Notes: The 3-terminal capacitance measurements are made only in the frequency range 100 kHz - 1 MHz, and in the capacitance range 0.01 - 1000 pF.

A more detailed listing of the uncertainties as a function of frequency and value of the immittance is available from R. N. Jones or R. E. Nelson (below).

The distribution of random errors depends strongly on the nature of the device being calibrated. In the field of immittance there is little uniformity in the transfer standards used throughout the industry. Thus, it is not generally possible for NBS to give information on random errors based on a large amount of experience with a particular type of transfer standard.

The uncertainties are stated on the basis of the use of precision connectors, which are not always used on devices NBS is asked to calibrate. Where precision connectors are not used the errors can be considerably larger than those quoted.

The uncertainties listed under bias uncertainties above apply to all bridge measurements shown on page 32.

The chart on page 32 shows the most commonly used sequence of measurements. The procedure varies somewhat for specific frequencies and magnitudes.

Reference: L. F. Huntley and R. N. Jones, Lumped parameter impedance measurements, Proc. IEEE 55, 900 (1967).

Personnel: R. N. Jones
R. E. Nelson

Quality Factor and Effective Resonating Capacitance

50 kHz - 45 MHz

Ranges: Effective Quality Factor (Q_e): 100 - 700
Effective Resonating Capacitance (C_e): 30 - 500 pF

Bias Uncertainties:

Inductance and resistance measurements using NBS standards
Connector errors

Random Errors: See Notes

Effective resonating capacitance (C_e)	0.15 - 0.5%
Effective quality factor (Q_e)	0.8 - 2.3%

Total Uncertainty: See Notes

Uncertainty quoted customer: Same as Random Errors. See Notes.

Notes: The Q standards calibrated by NBS are used largely to establish measurement agreement, with less concern with the absolute accuracy of the measurement of quality factor or effective resonating capacitance. The bias uncertainties are believed to be about the same as the random errors stated above, except for Q_e above 5 MHz, where difficulties due to connectors and measurement of small resistances become more severe.

As in the immittance standards calibrated by NBS, the uncertainties associated with connectors other than precision connectors are serious.

A more detailed display of the uncertainties as a function of frequency and magnitude of the parameter being measured is available from R. N. Jones or R. E. Nelson (below).

Reference: R. N. Jones, Standards for the calibration of Q-meters, 50 kHz to 45 MHz, J. Res. NBS, 68C, 243 (1964).

Personnel: R. N. Jones
R. E. Nelson

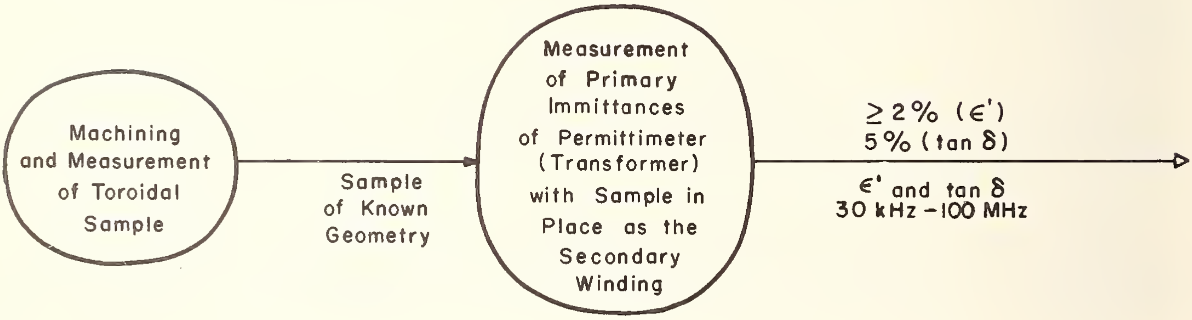
LARGE
COMPLEX RELATIVE DIELECTRIC PERMITTIVITY

30 kHz – 100 MHz

Ranges : ϵ' (Real Part) >1

$10^{-2} <$ tan δ (Loss Tangent) $< 10^{2}$

Frequencies : 30 kHz – 100 MHz



Large
Complex Relative Dielectric Permittivity

PERMITTIMETER MEASUREMENT:

30 kHz - 100 MHz

Range: $\epsilon' > 10^{14}/[f\ (Hz)]^{1.5}$

$\sigma > 10^{4}/[f\ (Hz)]^{0.5}$

$10^{-2} < \tan\ \delta < 10^{2}$ (see Notes)

Bias Uncertainties:
- Toroidal sample geometry
- Reproducibility of making and breaking magnetic circuit
- Immittance measurements on primary winding of permittimeter

Random Errors: Not reported.

Total Uncertainty: ϵ' : $\geq 2\%$

$\tan\delta$: $\geq 5\%$

Uncertainty quoted customer: Same as Total Uncertainty.

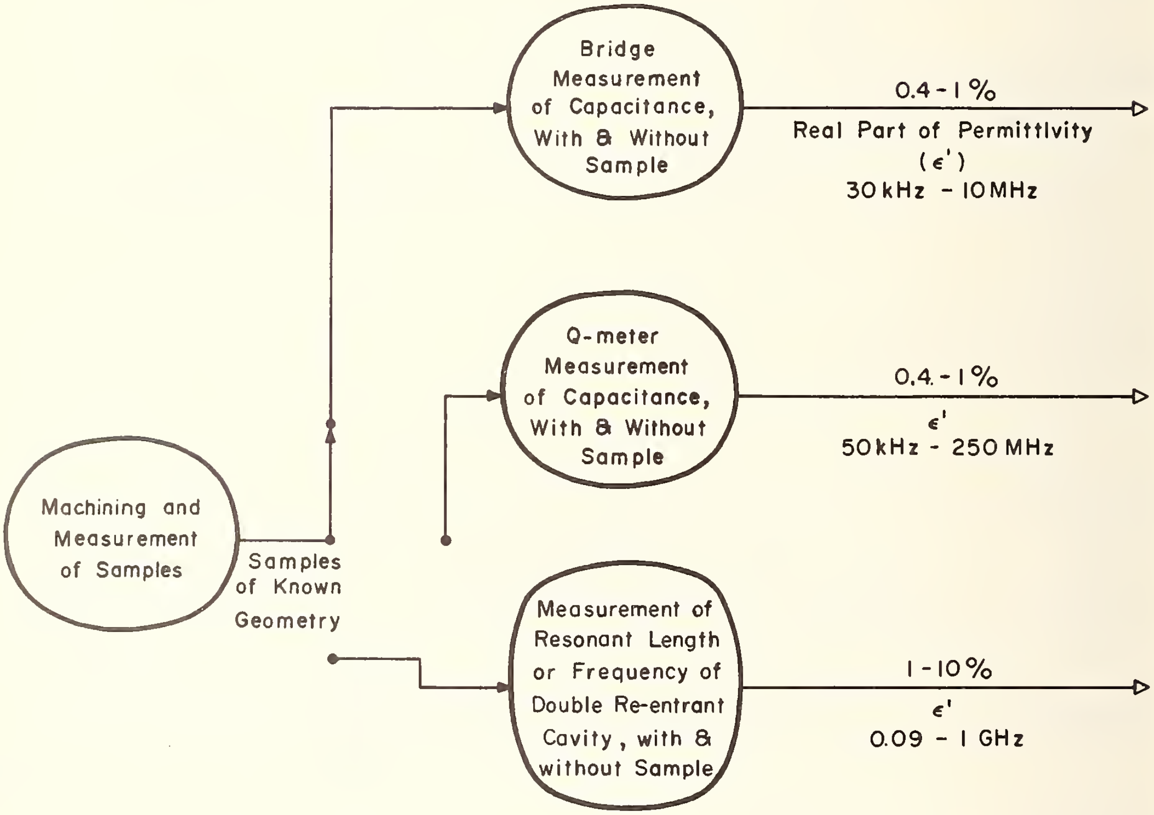
Notes: The range of $\tan\delta$ is approximate. The specified rather large values of either ϵ' or δ, to give either displacement or real currents, is a fundamental requirement.

Reference: R. C. Powell and A. L. Rasmussen, A radio frequency permittimeter, IRE Trans. Instr., I-9, 179 (1960).

Personnel: H. E. Bussey

HIGH FREQUENCY
RELATIVE DIELECTRIC PERMITTIVITY, REAL PART

30 kHz – 1GHz
Range: $1 - 10^4$



High Frequency Relative Dielectric Permittivity, Real Part, ϵ'

BRIDGE MEASUREMENT:

Capacitor-type sample holder
30 kHz - 10 MHz, $1 < \epsilon' < 10^4$

Bias Uncertainties:

Capacitance (see Notes)	0.05%
Lead inductance	negligible
Fringing capacitance	negligible
Sample geometry (see Notes)	$0.5\,(10^{-2}/t)\%$
Sample stability including humidity effects	negligible
Interaction of real and imaginary parts	negligible

Random Errors: not reported

Total Uncertainty: $[0.05 + 0.5(10^{-2}/t)]\%$

Uncertainty quoted customer: 0.4 - 1%

Notes: The capacitance measurement is a change in capacitance, with and without the sample. The error depends upon the thickness of the sample and upon ϵ'.

The sample geometry uncertainty depends upon the thickness of the sample, t, which is approximately 0.1 inch.

Reference: H. E. Bussey, Measurements of RF properties of materials, a survey, Proc. IEEE, 55, 1046 (June 1967).

Personnel: H. E. Bussey

Q-METER MEASUREMENT:

Capacitor-type sample holder
50 kHz - 250 MHz, $1 < \epsilon' < 10^4$

Bias Uncertainties:

Capacitance (see Notes)	0.05%
Lead inductance	negligible
Fringing capacitance	negligible
Sample geometry	$0.5\,(10^{-2}/t)\%$
Sample stability	negligible
Indirection of real and imaginary parts	negligible
Random Errors:	not reported
Total Uncertainty:	$[0.05 + 0.5(10^{-2}/t)]\%$

Uncertainty quoted customer: 0.4 - 1%

Notes: The capacitance measurement is a change in capacitance, with and without the sample. The error depends upon the thickness of the sample and upon ϵ'.

The sample geometry uncertainty depends upon the thickness of the sample, t, which is approximately 0.1 inch.

Reference: See page 34-1

Personnel: H. E. Bussey

High Frequency Relative Dielectric Permittivity, Real Part, ϵ'

RE-ENTRANT CAVITY MEASUREMENT:

Capacitive gap in coaxial transmission line
0.09 - 1 GHz, $1 < \epsilon' < 10^4$

Bias Uncertainties:

Capacitance	0.2 to 0.5%
Sample geometry, including foil contact	$2(10^{-2}/t)\%$
Fringing fields	0.2%

Random Errors: not quoted

Total Uncertainty: $[0.4 \text{ to } 0.7 + 2(10^{-2}/t)]\%$

Uncertainty quoted customer: 1 - 10%

Notes: The sample thickness, t, is approximately 0.05 inch.

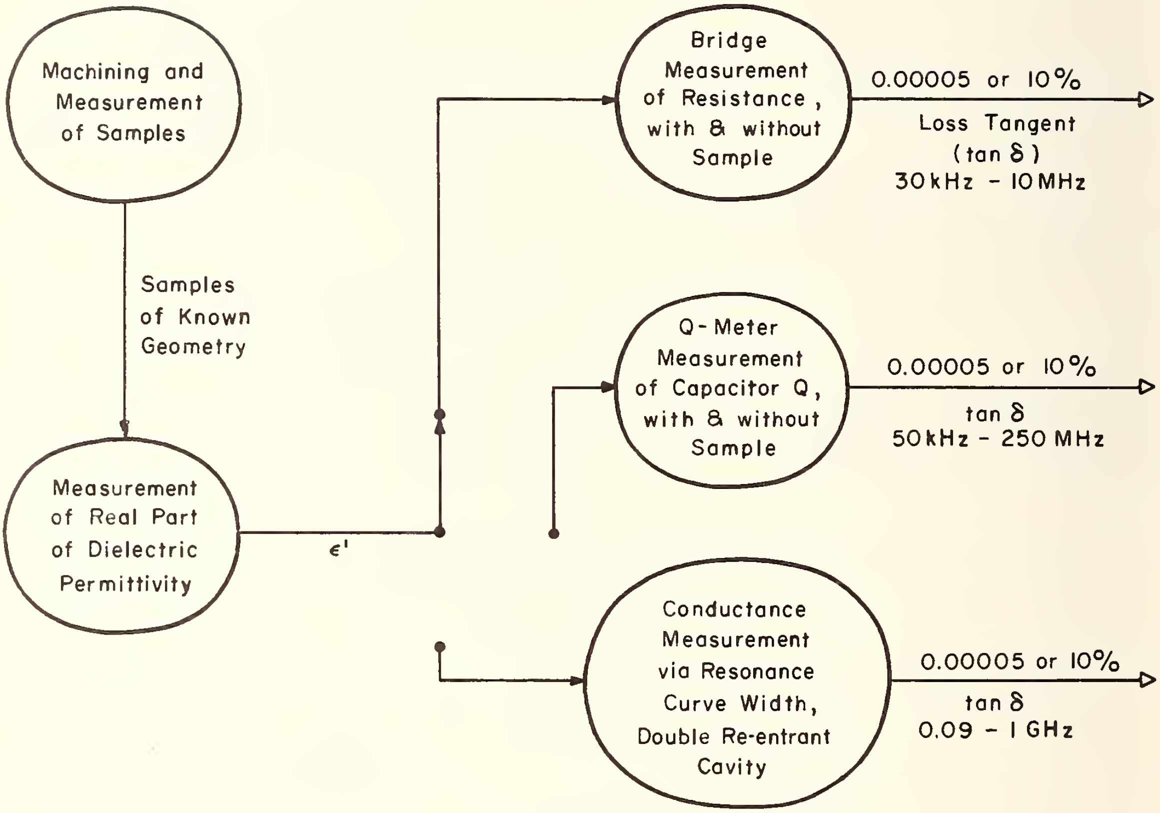
Reference: See page 34-1

Personnel: H. E. Bussey

HIGH FREQUENCY DIELECTRIC LOSS

30 kHz - 1 GHz

Range : $10^{-4} - 10^{3}$ (tan δ)



High Frequency Dielectric Loss

BRIDGE MEASUREMENTS:

Capacitor-type sample holder
30 kHz - 10 MHz, $10^{-4} < \tan \delta < 10$

Bias Uncertainties:

Sample geometry	0.5 to 1%
Bridge measurement of conductance	2%

Random Errors: $5 \times 10^{-3} / \tan \delta$ %

Total Uncertainty: $[2.5 \text{ to } 3 + 5 \times 10^{-3} / \tan \delta]$%

Uncertainty quoted customer: 0.00005 or 10%, whichever is larger.

Notes: None

Reference: See page 34-1

Personnel: H. E. Bussey

High Frequency Dielectric Loss

Q-METER MEASUREMENT:

Capacitor-type sample holder
50 kHz - 250 MHz, $10^{-4} < \tan \delta < 10$

Bias Uncertainties:

Geometry of sample	0.5 to 1%
Q-meter measurement	5%

Random Errors: $5 \times 10^{-3}/\tan \delta$ %

Total Uncertainty: $[5.5 \text{ to } 6 + 5 \times 10^{-3}/\tan \delta]$%

Uncertainty quoted customer: 0.00005 or 10%, whichever is larger.

Notes: By special request, loss tangents as low as 0.00001 are measured.

Reference: See page 34-1.

Personnel: H. E. Bussey

RE-ENTRANT CAVITY MEASUREMENT:

Capacitive gap in coaxial transmission line
0.09 - 1 GHz, $10^{-4} < \tan \delta < 1$

Bias Uncertainties:

Attenuation measurement	0.3%
Sample geometry	1 to 2%
Q measurement, including attenuation errors	2 to 3%
Bias from unknown sources (see Notes)	$4 \times 10^{-2}/\tan \delta$ %
Random Errors:	not quoted
Total Uncertainty:	$[3 \text{ to } 5 + 4 \times 10^{-2}/\tan \delta]\%$

Uncertainty quoted customer: 0.00005 or 10%, whichever is larger.

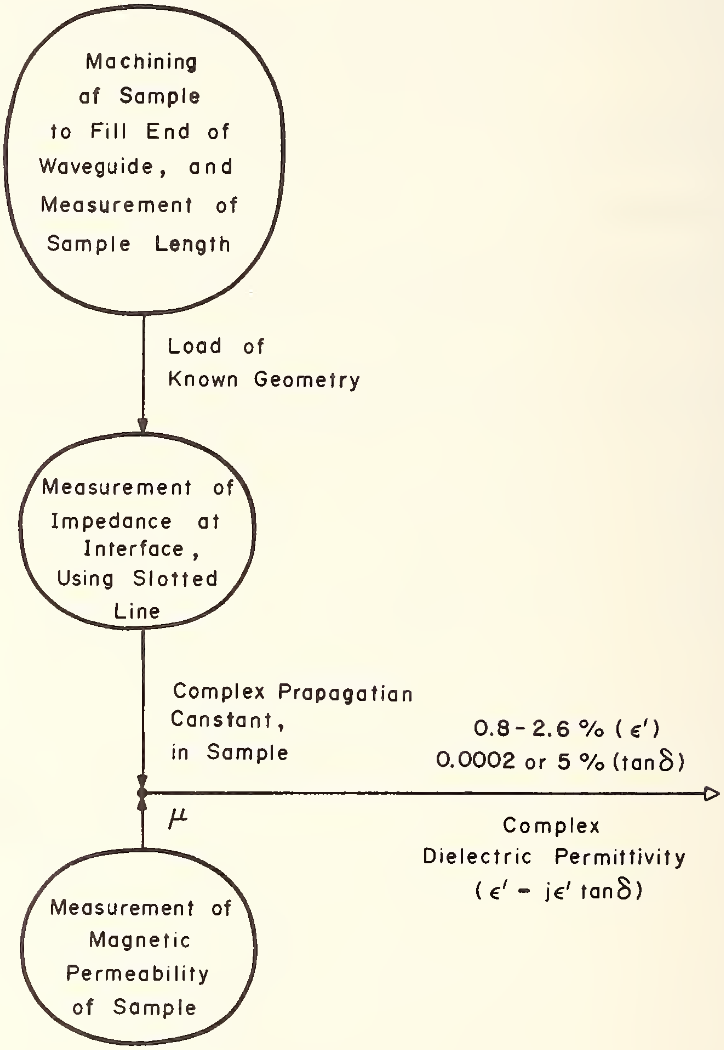
Notes: There are some bias errors from sources which have not yet been identified. Their total magnitude is determined by calibration against samples having known loss tangents.

Reference: See page 34-1.

Personnel: H. E. Bussey

MICROWAVE
COMPLEX RELATIVE DIELECTRIC PERMITTIVITY
Dielectric Loaded Transmission Lines

0.3 - 8.6 GHz
Range: 1 - 20 (Real Part)
10^{-4} - 10^{-1} (Loss Tangent)



Microwave Complex Relative Dielectric Permittivity, Real Part, ϵ'

DIELECTRIC LOADED TRANSMISSION LINES:

Slotted line impedance measurements
0.3 - 8.6 GHz

Bias Uncertainties

Sample dimensions	0.5%
Gap errors around sample	0.2 to 2%
Attenuation measurement	negligible
Probe position and wavelength measurements	0.1%
Random Errors:	not reported
Total Uncertainty:	0.8 to 2.6%

Uncertainty quoted customer: 0.8 - 2.6%

Notes: The real and imaginary parts of the permittivity are determined together in this method, as shown by the diagram on page 36. However, the errors in the real and imaginary parts are not the same, and are therefore discussed separately on pages 36-1 and 36-2.

Reference: See page 34-1.

Personnel: H. E. Bussey

DIELECTRIC LOADED TRANSMISSION LINES

Slotted line impedance measurement
0.3 - 8.6 GHz

Bias Uncertainties:

Contribution of magnetic permeability	0 to 1%
Gap errors	0.2 to 2%
"Law" of crystal	2%
Environment (see Notes)	0.5%
Random Errors:	not reported
Total Uncertainty:	3.5 to 5.5%

Uncertainty of tan δ quoted customer: 0.0002 or 5%, whichever is larger.

Notes: Errors due to environment include foreign surface conductivity, temperature effects, etc.

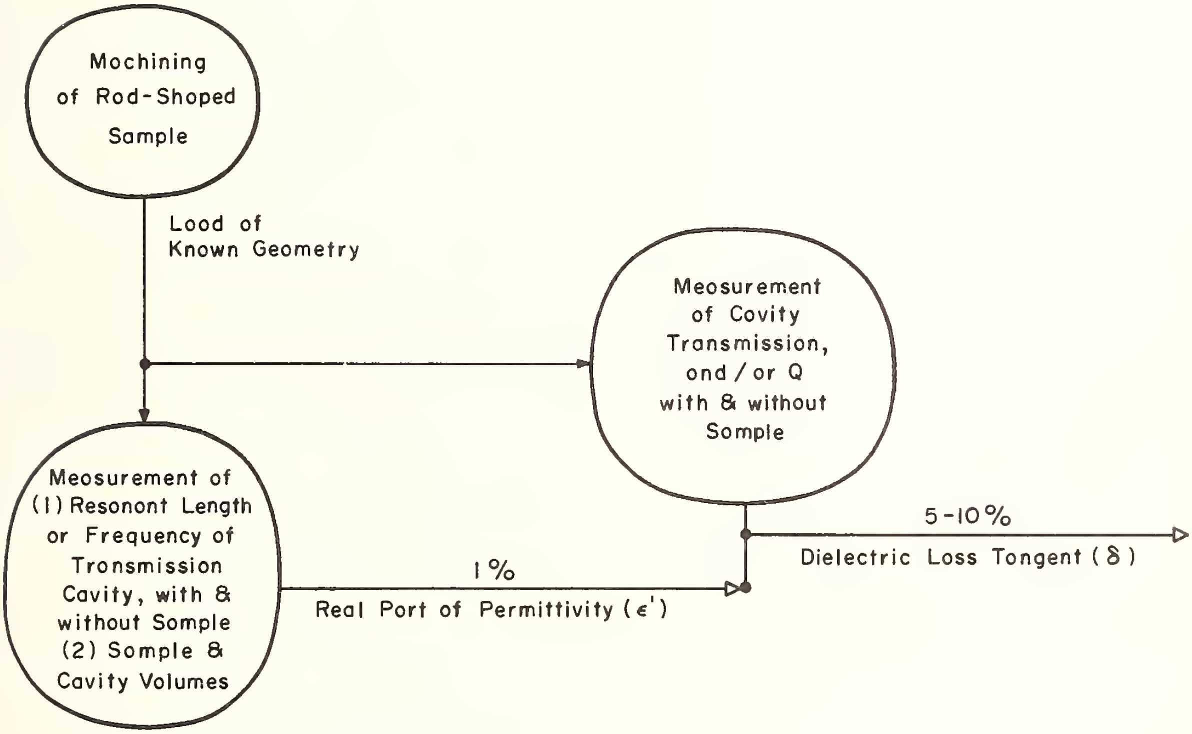
Reference: See page 34-1

Personnel: H. E. Bussey

MICROWAVE COMPLEX RELATIVE DIELECTRIC PERMITTIVITY

Transmission Cavities

0.5, 1, 3, 6, 9 and 30 GHz
Range : 1-100 (Real Part)
10^{-4}-10^{-1} (Loss Tangent)



Microwave Complex Relative Dielectric Permittivity, Real Part, ϵ'

TRANSMISSION CAVITIES:

$1 < \epsilon' < 100$
0.5, 1, 3, 6, 9, and 30 GHz

Bias Uncertainties:

Volume measurements (sample volume and cavity volume)	0.1 to 0.2%
Change in length or change in frequency	negligible
Misfit of sample in cavity	0.2 to 0.8%

Random Errors: not quoted

Total Uncertainty: 0.3 to 1%

Uncertainty quoted customer: 0.3 - 1%

Notes: A TE_{011} mode circular cavity resonator is used at 3, 9, and 30 GHz. Sample may be either a rod or a disk. At 0.5, 1, and 6 GHz other modes are used, and the accuracy is lower than for the TE_{011} modes. Results are based on exact solutions for a rod and disk. Either a complex propagation constant may be used when the loss is high, or the real and imaginary parts may be calculated separately.

Reference: See page 34-1

Personnel: H. E. Bussey

Microwave Complex Relative Dielectric Permittivity, Loss Tangent

TRANSMISSION CAVITIES:

10^{-4} - 10^{-1}
0.5, 1, 3, 6, 9 and 30 GHz

Bias Uncertainties:

Attenuation	0.3%
Q measurement, including attenuation errors	1 to 2%
Gap errors	1%
Environment	see Notes
Bias from unknown sources	$[4 \times 10^{-3}/\tan\delta]$ %

Random Errors: not reported

Total Uncertainty: $[2.5 \text{ to } 3.5 + 4 \times 10^{-3}/\tan\delta]$%

Uncertainty quoted customer: 5 - 10%

Notes: Environmental errors include foreign surface conductivity, temperature effects, etc. Their magnitudes are not well known.

There are some bias errors from sources which have not yet been identified. Their total magnitude is determined by calibration against samples having known loss tangents.

The transmission coefficient of the cavity is often used to obtain the loss; see reference below.

Also, see Notes on page 37-1.

Reference: H. E. Bussey, Cavity resonator dielectric measurements on rod samples, 1959 Annual Report, Conference on Electrical Insulation, National Academy of Sciences, Publication 756 of the National Research Council.

Personnel: H. E. Bussey

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