Radio-Frequency Measurements in the NBS Institute for Basic Standards
The National Bureau of Standards 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:


**THE INSTITUTE FOR MATERIALS RESEARCH** conducts materials research leading to improved methods of measurement standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; develops, produces, and distributes standard reference materials; relates the physical and chemical properties of materials to their behavior and their interaction with their environments; and provides advisory and research services to other Government agencies. The Institute consists of an Office of Standard Reference Materials and the following divisions:


**THE INSTITUTE FOR APPLIED TECHNOLOGY** provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations in the development of technological standards, and test methodologies; and provides advisory and research services for Federal, state, and local government agencies. The Institute consists of the following technical divisions and offices:


**THE CENTER FOR RADIATION RESEARCH** engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center consists of the following divisions:


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**THE OFFICE FOR INFORMATION PROGRAMS** promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System, and provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:


---

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 52-5 Port Royal Road, Springfield, Virginia 22151.
NBS TECHNICAL NOTE 373
ISSUED JUNE 1969

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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

NBS Technical Notes are designed to supplement the
Bureau's regular publications program. They provide a
means for making available scientific data that are of
transient or limited interest. Technical Notes may be
listed or referred to in the open literature.
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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.


** 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: $\text{Measurement} \quad M$

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 \times 10^{-7}", or "10 \mu\text{sec}". These outputs are usually available to NBS customers.

A measurement output available to NBS customers.
TIME AND FREQUENCY STANDARDS

Calculated Time Scales
AT (NBS), SAT (NBS), and UTC (NBS)

Nominal Standard Frequencies
100, 1000, 5000 kc/UTC (NBS) Second

Frequency and Time Synthesis System
Nominal 1 Pulse
Per UTC (NBS) Second

Clock #8

Ft. Collins TV Comparison

Computer: Optimum Time Generation from Statistical Weighting of Clocks

Intercomparison Data

1 PPS 5 MHz

Intercomparison of Frequencies and Time Ticks

Set of Six Clocks (Oscillators and Dividers)

NBS-III Cesium Beam Standard
## Time and Frequency Standards

### Bias Uncertainties:

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Fractional Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of $H(x)$ (3σ limits)</td>
<td>0.3</td>
</tr>
<tr>
<td>Overlap of neighboring transitions</td>
<td>1.0</td>
</tr>
<tr>
<td>Use of $H(x)^2$ for $H^2(x)$</td>
<td>0.1</td>
</tr>
<tr>
<td>Distortion arising from C-field nonuniformity</td>
<td>0.5</td>
</tr>
<tr>
<td>Cavity mistuning</td>
<td>0.1</td>
</tr>
<tr>
<td>Uncertainty in magnitude of cavity phase shift</td>
<td>3.0</td>
</tr>
<tr>
<td>Doppler shifts</td>
<td>1.0</td>
</tr>
<tr>
<td>Microwave power level</td>
<td>1.0</td>
</tr>
<tr>
<td>Spectral purity of excitation</td>
<td>2.0</td>
</tr>
<tr>
<td>Second harmonic distortion of servo modulation</td>
<td>0.5</td>
</tr>
<tr>
<td>Miscellaneous servo system effects</td>
<td>2.0</td>
</tr>
<tr>
<td>Multiplier chain transient phase shifts</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### 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."


**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:

Clock #8 UTC (NBS)
(Standards Section)

1 PP/(sec-UTC)

Time Interval Counter

Horizontal Synchronizing Pulses

Television Receiver

Telephone Comparison with Ft. Collins Counter

AT FT. COLLINS:

Quartz Oscillator
(Re Cesium Beam at Ft. Collins)

2.5 MHz

Oscillator Drift Corrector
(Continuous Phase Shifter)

2.5 MHz

Frequency Offsetter and Synthesizer

19.9 or 20.5 kc/(sec-UTC)

20.0 kc/(sec-UTC)

100 kc/(sec-UTC)

To WWVL Transmitter

WWVL Master Clock UTC (NBS)

1 PP/(sec-UTC)

Time Interval Counter

Horizontal Synchronizing Pulses

Television Receiver

Telephone Comparison with Boulder Counter
TIME AND FREQUENCY DISSEMINATION - WWVB

60 kHz SAT (NBS) Time Scale

AT FT. COLLINS:

Quartz Oscillator

2.5 MHz

Oscillator Drift Corrector
(Continuous Phase Shifter)

Frequency Synthesis Identification, WWVB
Level-Shift Time Code
and 200 m sec
Shift Systems

2.0 μsec

60 kHz to Transmitter

1 PPS SAT (NBS)

Time Comparison System

1 PP/(sec-UTC)

WWVL Master Clock
UTC (NBS)

To WWV
TIME AND FREQUENCY DISSEMINATION - WWV
2.5, 5, 10, 15, 20 & 25 Mc/(sec-UTC)
UTC (NBS) Time Scale

C₀ Beam Oscillator
(Manually Adjusted)

Frequency Shifter & Synthesizer

Driver
(2.5 thru 25 Mc/(sec-UTC))

Time-Code Generator & Clock
(Time Manually Adjusted)

Audichron
Automatic Announcer

Voice and Code I.D. and Forecasts

Complete Modulation Format

Error Display

Intercomparison With WWVL Time Markers

From WWVL

5 µsec Signals to Transmitters

100 kc/(sec-UTC) to WWVL for Reference

100 kc/(sec-UTC)

5.0 MHz

From WWVL

Clock

1 ppm/sec-UTC
TIME AND FREQUENCY DISSEMINATION - WWVH

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

- Quartz Oscillator (Manually Adjusted)
- Intercomparison With Three Other Oscillators
- Audichron Automatic Announcer
- Frequency Synthesizer
- Phase Shifter (Manually Adjusted)
- Clock
- Intercomparision With WWVL & WWVB Signals
- 2.5, 5, 10 & 15 Mc/sec-UTC Transmitters

2.5 Mc/sec-UTC
100 kc/sec-UTC
Corrected Phase (Time)

Voice, Time Tick & Audio Tone Modulation

10 µsec
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.

<table>
<thead>
<tr>
<th>Station</th>
<th>Maximum Phase Error [re SAT(NBS) or UTC(NBS)] (microseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWVL</td>
<td>2.0</td>
</tr>
<tr>
<td>WWVB</td>
<td>2.0</td>
</tr>
<tr>
<td>WWV</td>
<td>5.0</td>
</tr>
<tr>
<td>WWVH</td>
<td>10.0</td>
</tr>
</tbody>
</table>

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, \( c/(sec \cdot UTC) \), 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.

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.


Personnel: D. W. Allan
CAVITY WAVEMETERS
100 MHz - 90 GHz

Resonance Distortion

Desired Calibration
t Signal Synthesizer
and Harmonic Generator
(Error Negligible)

±2 x 10^-11

Standard Frequency
(5 MHz)

±2 x 10^-11

Frequency Pulling
≤ 6 x 10^-7

≤ 5 x 10^-7

Cavity Asymmetry
≤ 1 x 10^-7

≤ 1 x 10^-7

Cavity Asymmetry
≤ 4 x 10^-7

≤ 4 x 10^-7

Apparent Time Shift
Between Channels
≤ 1.1 x 10^-6

Cavity Resonance
Observation on C.R.T.
(Error Negligible)

±1.5 x 10^-6

±0.4 ± 0.0 ± 0.0

±0.4 ± 0.0 ± 0.0

Calibrated Waveform
To Customer
Cavity Wavemeters
100 MHz - 90 GHz

Bias Uncertainties:
Random Errors: See Error Flow Diagram, page 11
Total Uncertainty:
Uncertainty quoted customer:

Notes: None


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 0.1dB

Total Uncertainty: Less than 5dB 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.


Personnel: J. H. Shoaf
D. Halford

12-1
RF POWER IN COAXIAL SYSTEMS

10 - 4000 MHz
1 - 10 mW Power Level

BOLOMETER CALIBRATION FROM
DRY LOAD CALORIMETRIC MEASUREMENT

Dry Load Calorimeter at 10 mW

* \[
\frac{0.26}{0.35}
\] %

Standard Transfer Bolometer

Direct Comparison at 1 & 10 mW

Working Standard Bolometer

* \[
\frac{0.40}{0.50}
\] %

Direct Comparison at 1 - 10 mW

Customer Bolometer

* \[
\left\{ \begin{array}{l}
1.0 \\
1.0
\end{array} \right. 
\] %

* \[
\left\{ \begin{array}{l}
10 \text{ to } 1000 \text{ MHz} \\
1000 \text{ to } 4000 \text{ MHz}
\end{array} \right. 
\]
RF Power in Coaxial Systems

DRY LOAD CALORIMETRIC MEASUREMENT:

10 - 4000 MHz
50 mW - 5W

Bias Uncertainties:

<table>
<thead>
<tr>
<th></th>
<th>10 - 1000 MHz</th>
<th>1000 - 4000 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter efficiency</td>
<td>0.04%</td>
<td>0.08%</td>
</tr>
<tr>
<td>VSWR mismatch</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>RF - dc substitution</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>dc power</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Feedback loop error</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Random Errors: 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.


Personnel: P. A. Hudson
RF Power in Coaxial Systems

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%


Personnel: F. X. Ries
RF POWER IN COAXIAL SYSTEMS

dc - 4000 MHz
2 - 100 W Power Level

FLOW CALORIMETER MEASUREMENT

Flow Calorimeter 2 - 100 W

0.38% Working Standard: Bolometer-Coupler Units

Direct Comparison 2 - 100 W

≥ 1 %* Calibrated Power Meter

* 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
RF Power in Coaxial Systems

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

\[ \frac{\eta_1 \eta_c}{\eta_w} \]

\[ \frac{\eta_c}{\eta_2 \eta_w} \]

\( \eta_c \): Effective Efficiency of Coaxial Unit
\( \eta_w \): Effective Efficiency of Waveguide Standard Unit
\( \eta_2 \): 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:


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.


Personnel: R. F. Desch
MICROWAVE POWER: COAXIAL BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR CALIBRATION TRANSFER SYSTEM
FOR TYPE N CONNECTORS
ADAPTOR METHOD

STANDARD RESISTOR
REFERENCE VOLTAGE ± 0.01 %
BRIDGE CURRENT MEASUREMENT ± 0.03 % ± 0.01 %
SELF BALANCING BOLOMETER BRIDGES ± 0.09 % ± 0.1 \( \mu \)W ± 0.06 %
DIGITAL VOLTMETER
FINITE GAIN ± 0.1 \( \mu \)W INSTABILITY
ADDITONAL ERROR IN CALIBRATING A TUNED WAVEGUIDE STANDARD (12.4 - 18.0 GHz)
WAVEGUIDE WORKING STANDARD
FREQ (GHz) LIMITS OF ERROR (%)
4.0 - 7.05 ± 0.75 (IMPEDANCE)
7.05-12.4 ± 0.20 (CALORIMETER)
12.4 - 18.0 ± 0.68 (CALORIMETER & REFLECTOMETER)
± 0.38 % ± 0.22 %
TEMPERATURE INSTABILITY AND RESOLUTION
\( \sqrt{\eta_1/\eta_2} = 1 \) APPROXIMATION

CONNECTOR DISSIPATION ± 0.15 %
POWER AND FREQUENCY INSTABILITY ± 0.01 %
CALIBRATION TRANSFER LONG METHOD
FREQ (GHz) LIMITS OF ERROR (%)
4.0 - 7.05 ± 1.54
7.05-10.0 ± 0.99 ± 0.22 %
TO CUSTOMER

4.0-7.05 GHz ± 1.6 %
7.05-10.0 GHz ± 1.0 %

ERROR IN \( K_1 \) AND \( K_2 \)
DUE TO BRIDGES ± 0.18 %

TEMPERATURE INSTABILITY AND RESOLUTION ± 0.02 %

CALIBRATION OF ADDITIONAL BOLOMETER UNITS USING
\[ P_2 = K_1 P_4 - K_2 P_3 \]
SHORT METHOD
FREQ (GHz) LIMITS OF ERROR (%)
4.0 - 7.05 ± 1.79
7.05-10.0 ± 1.24 ± 0.05 %
TO CUSTOMER

4.0 - 7.05 GHz ± 1.8 %
7.05 - 10.0 GHz ± 1.3 %
MICROWAVE POWER: COAXIAL BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR CALIBRATION TRANSFER SYSTEM
FOR PRECISION CONNECTORS (GPC-14 Stops AT 8.5 GHz)
ADAPTOR METHOD

STANDARD RESISTOR

REFERENCE VOLTAGE ± 0.01%

BRIDGE CURRENT MEASUREMENT ± 0.03%

DIGITAL VOLTMETER ± 0.01%

BRIDGE ARM RESISTANCE ± 0.01%

SELF BALANCING BOLOMETER BRIDGES ± 0.09% ± 0.1 µW

FINITE GAIN ± 0.1 µW INSTABILITY ± 0.02% ± 0.1 µW

ADDITIONAL ERROR IN CALIBRATING A TUNED WAVEGUIDE STANDARD (12.4 - 18.0 GHz) ± 0.38%

WAVEGUIDE FREQUENCY (GHz) WORKING STANDARD LIMITS OF ERROR (%) 4.0 - 7.05 ± 0.75 (IMPEDANCE) 7.05 - 12.4 ± 0.20 (CALORIMETER) 12.4 - 18.0 ± 0.68 (CALORIMETER & REFLECTOMETER)

TEMPERATURE INSTABILITY AND RESOLUTION ± 0.05% 

CONNECTOR DISSIPATION ± 0.01%

NEGLIGIBLE検測。± 0.13%

CONNECTOR DISSIPATION ± 0.5%

ADORATION DISSIPATION ± 0.15%

ERROR IN K1 AND K2 DUE TO BRIDGES ± 0.13%

POWER AND FREQUENCY INSTABILITY ± 0.01%

ADDITIONAL ERROR IN CALIBRATING A TUNED WAVEGUIDE STANDARD (12.4 - 18.0 GHz) ± 0.38%

ERROR IN √m1 m2 DUE TO BRIDGES ± 0.20%

CONNECTOR DISSIPATION ± 0.05%

TO CUSTOMER 4.0 - 7.05 GHz ± 1.3% 7.05 - 12.4 GHz ± 0.8% 12.4 - 18.0 GHz ± 1.2%

CALIBRATION OF ADDITIONAL BOLOMETER UNITS USING P2 = K1 P4 - K2 P3
SHORT METHOD

FREQ. (GHz) LIMITS OF ERROR (%) 4.0 - 7.05 ± 1.47 7.05 - 12.4 ± 0.92 12.4 - 18.0 ± 1.40

NEGLIGIBLE POWER AND FREQUENCY INSTABILITY ± 0.05%

TO CUSTOMER 4.0 - 7.05 GHz ± 1.5% 7.05 - 12.04 GHz ± 1.0% 12.4 - 18.0 GHz ± 1.5%

TUNING OF Tx ± 0.01%

TUNING OF Ty ± 0.01%

CONNECTOR DISSIPATION ± 0.01%

CONNECTOR DISSIPATION ± 0.01%

TEMPERATURE INSTABILITY AND RESOLUTION ± 0.02%

IMPEDANCE ± 1.3%

CALIBRATION TRANSFER LONG METHOD

FREQ. (GHz) LIMITS OF ERROR (%) 4.0 - 7.05 ± 1.27 7.05 - 12.04 ± 0.72 12.4 - 18.0 ± 1.20

TO CUSTOMER 4.0 - 7.05 GHz ± 1.3% 7.05 - 12.4 GHz ± 0.8% 12.4 - 18.0 GHz ± 1.2%
MICROWAVE POWER : WAVEGUIDE BOLOMETER UNITS

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

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.

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

REFERENCE VOLTAGE ±0.01%

BRIDGE CURRENT MEASUREMENT ±0.03%

DIGITAL VOLTMETER ±0.01%

SELF-BALANCING BOLOMETER BRIDGE ±0.09% ±0.1 μW

BRIDGE ARM RESISTANCE ±0.01%

FINITE AMP. GAIN ±0.1 μW INSTABILITY ±0.02% ±0.1 μW

INSTRUMENTATION ±0.01%

MICRO-POTENTIOMETER

MICROCALORIMETER CALIBRATED BOLOMETER UNIT EFFECTIVE EFFICIENCY ±0.20% (WR 90) ±0.30% (WR 62)

MICROCALORIMETRIC SUBSTITUTION ERROR ±0.03% (WR 90) ±0.05% (WR 62)

WAVEGUIDE WORKING STANDARD

FLANGE LOSS ±0.07% (WR 90) ±0.12% (WR 62)

TEMPERATURE INSTABILITY

THERMOPILE NONLINEARITY ±0.12% (WR 62)

(0.12%) ±0.13% (WR 62)

±0.03% (WR 90)

±0.01% (WR 90) ±0.01% (WR 62)

16-2
Microwave Power

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 < |\Gamma| < 0.20): 0.03 to 1.23

Random Errors: Typical value: 0.04

Total Uncertainty: (for 0.01 < |\Gamma| < 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 ($\eta$), effective efficiency ($\eta_e$), and calibration factor ($K_b$) of bolometer units are as follows:

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

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

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

16-3
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.


**Personnel:** R. F. Desch
MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM
MICROCALORIMETRIC MEASUREMENT,
DIRECT COMPARISON METHOD
WR 90 WAVEGUIDE

BOLOMETER BRIDGE
± .10%
± .04%
± .01%
± .10%
± .05%
± .42%

TEMPERATURE INSTABILITY AND RESOLUTION
± .02%

POWER & FREQUENCY INSTABILITY
± .01%

FLANGE LOSS
± .05%

MISMATCH ERROR
|Γg| ≤ .01, |Γs| ≤ .01
.01 ≤ |Γu| ≤ .20

UNCERTAINTY IN MISMATCH ERROR CORRECTION
± .01% TO ± .43%

BOLOMETER UNIT EFFECTIVE EFFICIENCY
WR 90 LIMITS OF ERROR ± .20%

CALIBRATED BOLOMETER COUPLER UNIT
CALIBRATION FACTOR LIMITS OF ERROR
± .41%

CALIBRATED BOLOMETER UNIT
CALIBRATION FACTOR LIMITS OF ERROR
± .81% TO ± 1.18%

CALIBRATED BOLOMETER UNIT EFFECTIVE EFFICIENCY
LIMITS OF ERROR
± .829 TO ± 1.61%

TO CUSTOMER

TO CUSTOMER

TO CUSTOMER
Microwave Power

MICROCALORIMETER MEASUREMENT, REFLECTOMETER METHOD:

Bias Uncertainties:

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

Total Uncertainty:

Uncertainty quoted customer:

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

This measurement method is used for $\eta_e$ 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 $\eta_e$, 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.


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

BOLOMETER UNIT EFFECTIVE EFFICIENCY

<table>
<thead>
<tr>
<th>IMPEDANCE SYSTEM</th>
<th>REFERENCE STANDARD</th>
<th>CALORIMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR 284</td>
<td>WR 187</td>
<td>WR 137</td>
</tr>
<tr>
<td>±0.75%</td>
<td>±0.20%</td>
<td>±0.30%</td>
</tr>
</tbody>
</table>

SELF-BALANCING BOLOMETER BRIDGE
±0.10%

TUNING $T_y$
±0.01%

TEMPERATURE INSTABILITY AND RESOLUTION
±0.05%

POWER AND FREQUENCY INSTABILITY
±0.01%

FLANGE LOSS
±0.10% TO ±0.20%

CALIBRATED BOLOMETER UNIT EFFECTIVE EFFICIENCY
LIMITS OF ERROR
±0.57% TO ±1.23% TO CUSTOMER

UNCERTAINTY IN MISMATCH ERROR CORRECTION
±0.01% TO ±0.43% TO CUSTOMER

CALIBRATED BOLOMETER UNIT CALIBRATION FACTOR
LIMITS OF ERROR
±0.58% TO ±1.66% TO CUSTOMER
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 $\eta$, the efficiency of a bolometer unit. The limits on the effective efficiency of the working standard are obtained from the measured efficiency, $\eta$, 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 $\eta_e$, $K_b$, or $K_c$ is desired.

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


**Personnel:** R. F. Desch
MICROWAVE POWER: WAVEGUIDE BOLOMETER UNITS
ERROR FLOW DIAGRAM FOR WORKING STANDARD
IMPEDANCE METHOD
WR284, WR187, WR137

STANDARD RESISTOR

REFERENCE VOLTAGE

BRIDGE CURRENT MEASUREMENT

DIGITAL VOLTOMETER

BRIDGE ARM RESISTANCE

SELF-BALANCING BOLOMETER BRIDGES

FINITE AMPLIFIER GAIN

BRIDGE CURRENT MEASUREMENT

±0.01%

±0.01%

±0.01%

±0.10%

±0.015%

±0.05%

±0.005%

±0.05%

±0.05%

±0.015%

±0.015%

±0.01%

±0.02%

±0.02%

±0.20%

±0.20%

±0.50%

±0.50%

±0.50%

±0.25%

±0.25%

±0.06%

±0.06%

±0.09% ±0.1 µW

±0.09% ±0.1 µW

±0.10% ±0.10% ±0.10% ±0.10% ±0.10%

NEGLIGIBLE

NEGLIGIBLE

MEASUREMENT OF SIGNAL AMPLITUDES

USE OF APPROXIMATE METHOD

REFERENCE SHORT

IMPERFECT NULL IN AUXILIARY CHANNEL

CALIBRATED BARRETTER UNIT EFFICIENCY

±0.50%

±0.75%

WAVEGUIDE WORKING STANDARD
IMPEDANCE METHOD OF MEASUREMENT, DIRECT COMPARISON METHOD:

Bias Uncertainties: 

Random Errors: 
See Error Flow Diagram, page 16-5

Total Uncertainty: 

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
Microwave Power

**IMPEDANCE METHOD OF MEASUREMENT, REFLECTOMETER METHOD:**

**Bias Uncertainties:**

**Random Errors:**

See Error Flow Diagram, page 16-7

**Total Uncertainty:**

Uncertainty quoted customer: \( \eta_e \) for \(|\Gamma| < 0.01\) : 1%

\( K_b \) for \(|\Gamma| < 0.2\) : 1%

**Notes:** This measurement is used to obtain \( \eta_e \) 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: 3.3 x 10^-4
Peak-Pulse Power: 1.0 mW - 3.0 kW

Bolometric CW Power Standard

RF Pulse (Unknown Power Level)

1%

Sampling—Comparison System

Range Extending Directional Couplers

3%
Calibrated Pulse Power Meter
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 $33 \times 10^{-4}$.
   4. The peak-pulse power range must be between 1.0 mW and 3.0 kW.


Personnel: P. A. Hudson
          P. A. Simpson
NOISE TEMPERATURE
Coaxial Noise Generator at 3 MHz
75 K to 30,000 K

Measurements of:
1) Thermodynamic Temperature
2) Impedance

0.2% Cold Reference Standard

Measurements of:
1) Thermodynamic Temperature
2) Impedance

0.2% Hot Reference Standard

1% Calibrated Noise Generator

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

THERMOMETER CALIBRATION
± 0.04 K

THERMOMETER BRIDGE CALIBRATION
± 0.01 K

TEMPERATURE GRADIENTS
± 0.01 K

TRANSMISSION LINE LOSS
± 0.04 K

TEMPERATURE STABILITY
± 0.01 K

NBS REFERENCE NOISE GENERATOR, COLD (77 K)
± 0.11 K, ± 0.2% OF T_x

THERMOMETER CALIBRATION
± 0.08 K

THERMOMETER BRIDGE CALIBRATION
± 0.08 K

TEMPERATURE GRADIENTS
± 0.5 K

TRANSMISSION LINE LOSS
± 0.02 K

TEMPERATURE STABILITY
± 0.02 K

NBS REFERENCE NOISE GENERATOR, HOT (373 K)
± 0.70 K, ± 0.2% OF T_x

COMPARISON RADIOMETER
(3σ)
± 0.2% OF T_x

ATTENUATOR CALIBRATION
± 0.08% OF T_x

SOURCE IMPEDANCE ERROR
± 0.08% OF T_x

TOTAL BIAS UNCERTAINTY: APPROX. ± 0.6% OF T_x

RANDOM UNCERTAINTY (3σ): APPROX. ± 0.4% OF T_x

CUSTOMER'S MAX. UNCERTAINTY: APPROX. ± 1% OF T_x

19-1
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, $T_x$.


Personnel: M. G. Arthur
EFFECTIVE NOISE TEMPERATURE
WAVEGUIDE NOISE SOURCE AT 9 GHz
11,000 K

Thermocouple Calibration

Radiometer Comparator

Radiometer Comparator

Attenuation Calibration
Ambient Temperature Reflectometer Measurement Mismatch

Attenuator Calibration Reflection Coefficient Magnitude

NBS Reference Noise Standard

NBS Working Noise Standard

Calibrated Noise Source

±4.0 K

±109.4 K

±136.4 K

±109.4 K
EFFECTIVE NOISE TEMPERATURE FOR ARGON NOISE SOURCE, OR WAVEGUIDE NOISE SOURCE AT 9 GHz OPERATING AT 11,000 K

- THERMOCOUPLE CALIBRATION ± 0.3 K
- AVERAGE OF THERMOCOUPLES AND TEMPERATURE MEASUREMENTS OF NOISE GENERATOR ± 0.7 K
- DETERMINING GRADIENT CORRECTION VALUES ± 3.0 K

NBS REFERENCE NOISE STANDARD ± 4.0 K

8Δ (CALIBRATION OF ATTENUATOR, BALANCE AND OPERATOR) ± 0.01 dB

8TΔ (ATTENUATOR AMBIENT TEMPERATURE) ± 2.0 K

COMPARISON RADIOMETER

- THESE ARE PERCENTAGES OF THE LIMITS OF ERROR IN AN NBS WORKING STANDARD
- ± 24.6 K (22.5%)
- ± 43.9 K (40.1%)
- ± 20.0 K (18.3%)
- ± 1.6 K (1.5%)

NBS WORKING STANDARD ± 109.4 K

8Δ (CALIBRATION OF ATTENUATOR, BALANCE AND OPERATOR) ± 0.007 dB

MISMATCH (REFLECTION COEFFICIENT MAGNITUDE OF CUSTOMERS ITEM LESS THAN 0.02) ± 8.6 K

COMPARISON RADIOMETER

- THESE ARE THE PERCENTAGES OF THE LIMITS OF ERROR IN THE FINAL CALIBRATION
- ± 17.4 K (12.8%)
- ± 110.4 K (80.9%)
- ± 8.6 K (6.3%)

CUSTOMER'S INTERLABORATORY STANDARD ± 136.4 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.


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:

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Total Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>300, 500</td>
<td>1</td>
</tr>
<tr>
<td>700, 1000</td>
<td>5</td>
</tr>
</tbody>
</table>

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.


Personnel: M. C. Selby
RF Voltage (cw) in Coaxial Systems

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:

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>3, 10</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>3, 10</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>300, 400</td>
<td>3</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>700, 1000</td>
<td>7</td>
</tr>
</tbody>
</table>

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

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

21-3
RF MICROVOLTAGE

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

Set of 10 Working Standard Micropotentiometers

Auxiliary † Intercomparison Using Calibrated Attenuators (RF - dc)

Working Standard Micropotentiometer (0.1 V)

RF - dc Substitution Bridge Measurements at 0.1 Volt

1% (50 kHz - 500 MHz)
5% (700 - 1000 MHz)

Working Standard Micropotentiometer (0.1 V)

Set of 10 Working Standard Micropotentiometers

2% - 10%

Set of 10 "Microvolt Calibrator" (RF - dc)

2% - 10%

Calibrated Customer Micropotentiometer

Direct Intercomparison of Working Standards (RF - dc Substitution)

Direct Comparison Using “Microvolt Calibrator” (RF - dc)

† Each Set of 10 Working Standards is Intercompared by Two Different Techniques as an Internal Check.
RF Microvolts
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:

<table>
<thead>
<tr>
<th>Frequency MHz</th>
<th>Voltage Range microvolts</th>
<th>Uncertainty %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05 - 300</td>
<td>1 - 100</td>
<td>5</td>
</tr>
<tr>
<td>300 - 500</td>
<td>1 - 100</td>
<td>10</td>
</tr>
<tr>
<td>0.05 - 10</td>
<td>100 - 100,000</td>
<td>2</td>
</tr>
<tr>
<td>10 - 300</td>
<td>100 - 100,000</td>
<td>3</td>
</tr>
<tr>
<td>300 - 900</td>
<td>100 - 100,000</td>
<td>5</td>
</tr>
</tbody>
</table>

Uncertainty quoted customer: Same as Total Uncertainty, above.

Notes: None


Personnel: M. C. Selby
F. X. Ries
PULSE VOLTAGE
5 - 1000 Volts
Pulse Length: ≥ 10 Nanoseconds

- Pulse Generation
  - Unknown Pulse

- Measurement with Slideback Voltmeter
  - 1%
    - Known Pulse Voltage and Calibrated Generator
    - 1%
      - Calibrated Voltmeter

- Intercomparison of Independent Methods
  - ± 0.3 % Agreement

- Limit Pulse Using Zener Diode Calibrated at dc
  - 10 % Voltage Pulse

- Measurement of Known Pulse with Voltmeter to be Calibrated
  - 0.25 % Known Pulse

- 1%
  - Calibrated Voltmeter
Pulse Voltage
5 - 1000 Volts
Pulse Duration: \( \leq 10 \) Nanoseconds

SLIDEBACK VOLTOMETER 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.


Personnel: P. A. Hudson
P. A. Simpson
Pulse Voltage

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.


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

23-2
FIELD STRENGTH

30Hz - 1 GHz
20 - 400 mV/m

MAGNETIC FIELDS - LOOP ANTENNAS

Measurement of Geometry and Input Current to Standard Transmitting Antenna

Field Calculations

3-5% Known Field at Receiver
20 - 200 mV/m
30 Hz - 30 MHz

Standard Field Method
Normally Used 30 Hz - 30 MHz

ELECTRIC FIELDS - DIPole ANTENNAS

Measurement of Geometry and Voltage Output of Standard Receiving Antenna

Antenna Calculations

12% Known Field at Receiver
20 - 400 mV/m
0.03 - 1 GHz

Standard Antenna Method
Normally Used 30 MHz - 1 GHz
Field Strength

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).


Personnel: F. M. Greene  
H. E. Taggart
**Field Strength**

**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).


**Personnel:** F. M. Greene
H. E. Taggart
FIELD STRENGTH METER
30 Hz - 1 GHz
(20 - 400 mV/m)
Field Strength Meter
30 Hz - 1 GHz
20 - 400 mV/m

RECEIVER CALIBRATION: (See Notes)

Bias Uncertainties:

<table>
<thead>
<tr>
<th>Voltage measurement</th>
<th>30 Hz - 100 MHz</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 - 500 MHz</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>500 - 900 MHz</td>
<td>7%</td>
</tr>
</tbody>
</table>

| Calibration of attenuators and | 30 Hz - 400 MHz | 0.1dB+0.03dB/10dB |
| overall linearity of receiver  | 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
Antennas

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).


Personnel: F. M. Greene
            H. E. Taggart
ATTENUATION: COAXIAL SYSTEMS

10 - 18,000 MHz
0 - 140 dB

Measurements of
1) Guide Diameter
2) Linear Displacement
3) Velocity of Light in Guide
4) Conductivity
5) Permeability

Intercomparison: Dual - Channel rf Null System

0.002 dB/10 db to 0.01 dB/10 db
Reference Standard Piston Attenuators 10, 30, 60, 100 MHz

0.005 to 0.23 dB
Calibrated Attenuators 10, 30, 60, 100 MHz

Intercomparison: Single - Channel IF Null System

0.005 dB/10 db
30 MHz Working Standard Attenuator

0.03 to 0.15 dB
Calibrated Attenuators 0 db ≤ A ≤ 50 db
100 - 18,000 MHz

Intercomparison: Dual - Channel IF Null System

0.15 to 0.36 dB
Calibrated Attenuators 50 db < A ≤ 80 db
100 - 18,000 MHz
Attenuation: Coaxial Systems

PISTON ATTENUATION:

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

Bias Uncertainties:

- Coaxial waveguide diameter
- Linear displacement of receiving coil
- Velocity of electromagnetic waves in medium inside guide
- RF conductivity of guide
- RF permeability of guide

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coaxial waveguide diameter</td>
<td>0.0003dB/10dB</td>
</tr>
<tr>
<td>Linear displacement of receiving coil</td>
<td>0.001dB/10dB-0.01dB/10dB</td>
</tr>
<tr>
<td>Velocity of electromagnetic waves in medium inside guide</td>
<td>negligible</td>
</tr>
<tr>
<td>RF conductivity of guide</td>
<td>0.00026dB/10dB</td>
</tr>
<tr>
<td>RF permeability of guide</td>
<td>negligible</td>
</tr>
</tbody>
</table>

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.


Personnel: R. T. Adair
Attenuation: Coaxial Systems

DUAL-CHANNEL RF NULL SYSTEM:

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

Bias Uncertainties:

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference standard piston attenuator</td>
<td>0.002dB/10dB-0.01dB/10dB</td>
</tr>
<tr>
<td>Mismatch errors</td>
<td>0.001dB/10dB</td>
</tr>
<tr>
<td>Leakage</td>
<td>0.001dB/10dB</td>
</tr>
</tbody>
</table>

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.


Personnel: R. T. Adair
Attenuation: Coaxial Systems

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.


Personnel: R. T. Adair
Attenuation: Coaxial Systems

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:

Personnel: R. T. Adair
ATTENUATION: WAVEGUIDE SYSTEMS

1.7 - 40 GHz
0 - 50 dB

Measurements of
1) Guide Diameter
2) Linear Displacement
3) Velocity of Light in Guide
4) Conductivity
5) Permeability

0.005 dB/10 dB
30 MHz Working Standard Attenuator

Intercomparison:
Single-Channel IF Null System

0.1 dB/10 (1.7 - 2.6 GHz)
0.05 dB/10 (2.6 - 26 GHz)
0.1 dB/10 (26 - 40 GHz)

Calibrated Attenuators
0 < A < 50 dB

Modulated Subcarrier Technique

0.005 dB/10 dB
Calibrated Attenuators
8.2 - 18 GHz
0 ≤ A ≤ 15 dB

27
Attenuation: Waveguide Systems
1.7 - 40 GHz
0 - 50 dB

PISTON ATTENUATOR: See page 26-1.

SINGLE-CHANNEL IF SYSTEM:

Bias Uncertainties:


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


Personnel: W. Larson
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


Personnel: W. Larson
ATTENUATION: WAVEGUIDE SYSTEMS
ERROR FLOW CHART FOR MODULATED SUBCARRIER

MODULATION INDEX DEVIATION 0.0002 dB

PHASE SHIFTER ADJUSTMENT = 0.0004 dB

FREQUENCY STABILITY 0.0001 dB

AUDIO STANDARD 0.0001 dB

AUDIO REFERENCE AMPLITUDE 0.0002 dB

OPERATOR ANOMALY 0.0005

INSERTION POINT 0.0012

CRystal MIXER 0.0021

NULL INDICATOR 0.0025

TO CUSTOMER ± 0.005 dB

MISMATCH 0.001 dB

RF LEAKAGE 0.0003 dB

CRYSTAL NON-LINEARITY 0.0001 dB

SYSTEM DRIFT 0.0001 dB

ATTENUATOR ANOMALY 0.002 dB

27-4
PHASE SHIFT
IN COAXIAL PHASE SHIFTERS
30 - 12,400 MHz
0 - 360 Degrees

Error Analysis of Variable-Length Line

0.016° - 0.068° Standard "Trombone" Phase Shifters 30° Range 30 & 100 MHz

0.05° - 0.2° Working Standard 360° Range 30 MHz

Comparison via Dual-Channel RF System

0.05° - 0.2° Calibrated Phase Shifters 30 & 100 MHz

Comparison via Dual-Channel Unmodulated Heterodyne System (30 MHz IF)

0.5° Calibrated Phase Shifters 100 - 12,400 MHz
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:

- 0.046 - 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.


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.


Personnel: R. T. Adair
Phase Shift in Coaxial Phase Shifters

**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) 0.05
- 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  WR62, WR90 and WR137

DIMENSIONAL

50 μ" Δξ GHz

<table>
<thead>
<tr>
<th>DET.</th>
<th>6.0</th>
<th>18.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.06°</td>
<td>0.18°</td>
</tr>
<tr>
<td>5</td>
<td>0.04°</td>
<td>0.11°</td>
</tr>
<tr>
<td>11</td>
<td>0.03°</td>
<td>0.08°</td>
</tr>
</tbody>
</table>

3 Sigma

OPERATOR GHz

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DET.</td>
<td>6.0</td>
<td>18.0</td>
</tr>
<tr>
<td>2</td>
<td>0.11°</td>
<td>0.29°</td>
</tr>
<tr>
<td>5</td>
<td>0.09°</td>
<td>0.22°</td>
</tr>
<tr>
<td>11</td>
<td>0.08°</td>
<td>0.19°</td>
</tr>
</tbody>
</table>

RANDOM ERROR

TOTAL TOLERANCE ALLOWED

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

TO CUSTOMER

29-1
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.


Personnel: W. Larson
E. D. Hall
### REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

<table>
<thead>
<tr>
<th>Waveguide</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR 42</td>
<td>18.0 - 26.5 GHz</td>
</tr>
<tr>
<td>WR 62</td>
<td>12.4 - 18.0</td>
</tr>
<tr>
<td>WR 90</td>
<td>8.2 - 12.4</td>
</tr>
<tr>
<td>WR 112</td>
<td>7.05 - 10.0</td>
</tr>
<tr>
<td>WR 137</td>
<td>5.85 - 8.2</td>
</tr>
<tr>
<td>WR 187</td>
<td>3.95 - 5.85</td>
</tr>
<tr>
<td>WR 284</td>
<td>2.6 - 3.95</td>
</tr>
</tbody>
</table>

\[ 0.024 \leq |\Gamma| \leq 0.2 \]

*Power Level*: 0.01 mW

#### Diagram

1. **Reflectometer Tuning**
   \[ \Delta |\Gamma| \leq 3.2 \times 10^{-5} (1 + 5 |\Gamma|) \]
   "Ideal" Reflectometer

2. **Quarter-Wave Short**
   \[ \frac{\Delta |\Gamma|}{|\Gamma|} \leq 3 \times 10^{-4} \]
   Working Standard of Reflection Coefficient Magnitude
   \[ |\Gamma| \approx 1 \]

3. **Comparison of Reflected Signals**
   (Standard vs. Unknown)
   \[ \Delta |\Gamma| \leq 2 \times 10^{-4} (1 + 10 |\Gamma|) \]
   Reflection Coefficient Magnitude
   of Customer Standard

4. **Calculation of Attenuator Properties**
   \[ \Delta |\Gamma| \leq 3.5 \times 10^{-4} \]
   Known Variable Attenuator
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:

Uncertainty (typical) quoted customer:

\[ |r| \geq 0.024, \]
\[ \Delta |r| = 2 \times 10^{-4} (1 + 6|r|). \]
\[ |r| < 0.024, \]
\[ \Delta |r| = 2 \times 10^{-4} (1 + 10|r|). \]

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

<table>
<thead>
<tr>
<th>Waveguide</th>
<th>Uncertainty in [Γ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR 284</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>WR 187</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>WR 137</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>WR 112</td>
<td>&lt; 0.000115</td>
</tr>
<tr>
<td>WR 90</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>WR 62</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>WR 42 (square flange)</td>
<td>&lt; 0.0004</td>
</tr>
<tr>
<td>WR 42 (round flange)</td>
<td>&lt; 0.0003</td>
</tr>
</tbody>
</table>


Personnel: B. C. Yates
ERROR FLOW DIAGRAM

FOR REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

\[ |\Gamma| < 0.024 \]

DIRECTIVITY
\[ \pm (3.2 \times 10^{-5} + 3.2 \times 10^{-5} |\Gamma|) \]

TUNING ERRORS
\[ \pm (3.2 \times 10^{-5} + 1.5 \times 10^{-4} |\Gamma|) \]

FOR \[ |\Gamma_2| \neq 0 \]
\[ \pm 1.2 \times 10^{-4} |\Gamma| \]

\[ \frac{\lambda_g}{4} \text{ STANDARD} \pm 3.0 \times 10^{-4} |\Gamma| \]

POWER & FREQ.
INSTABILITY,
RANDOM ERRORS

PRECISION
SECTION

REFLECTOMETER

POWER & FREQ. INSTABILITY, RANDOM ERRORS

CRYSTAL LINEARITY
\[ \pm 0.006 \text{ dB} \]

ATTENUATION MEASUREMENT
\[ \pm 0.012 \text{ dB OR } \pm 1.4 \times 10^{-3} |\Gamma| \]

30 MHz STANDARD
\[ \pm 0.006 \text{ dB} \]

TO CUSTOMER

* See Notes
** See Reference
ERROR FLOW DIAGRAM

FOR REFLECTION COEFFICIENT MAGNITUDE OF WAVEGUIDE DEVICES

$|\Gamma| \geq 0.024$

** See Reference

* See Notes

- ** DIRECTIVITY $\pm (3.2 \times 10^{-5} + 3.2 \times 10^{-5}|\Gamma|)$
- ** TUNING ERRORS $\pm (3.2 \times 10^{-5} + 1.7 \times 10^{-4}|\Gamma|)$
- ** FOR $|\Gamma_2| \neq 0$ $\pm 1.4 \times 10^{-4}|\Gamma|$

- PRECISION SECTION
- $\frac{\lambda_0}{4}$ STANDARD $\pm 3.0 \times 10^{-4}|\Gamma|$

- REFLECTOMETER

- POWER & FREQ. INSTABILITY, RANDOM ERRORS

- CRYSTAL LINEARITY $\pm 0.003$dB

- ATTENUATION MEASUREMENT $\pm 0.006$dB OR $\pm 7.0 \times 10^{-4}|\Gamma|$

- 30 MHz STANDARD $\pm 0.003$dB

TO CUSTOMER
DISTRIBUTED PARAMETERS IN COAXIAL SYSTEMS

0.5 - 8 GHz

Residual VSWR and Probe Effect Measurements

Standard Slotted Line Measurements

0.1 - 1% (VSWR)
0.1° - 10° (Phase Angle)

VSWR and Phase Angle of Load
1 < VSWR < 100

Coaxial Reflectometer Measurements (1-4 GHz Only)

0.00025 or 1% of |Γ|
Reflection Coefficient (Magnitude Only)
Distributed Parameters in Coaxial Systems
0.5 - 8 GHz

SLOTTED LINE MEASUREMENTS:

500 MHz - 8 GHz
1 ≤ VSWR ≤ 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 ≤ (VSWR) ≤ 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. Un-
certainty figures for other connectors and larger VSWR's will, in most cases,
be larger.

Reference: R. L. Jesch and R. M. Jickling, Impedance measurements in

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

Detector nonlinearity when using a method to determine VSWR independent of detector response. (Affects only VSWR measurements)

Power and Frequency Instability

Residual VSWR of slotted line. Varies with frequency

Slope of slotted line (Affects only VSWR meas.)

Maximum error in VSWR of coaxial impedance standards whose measured VSWR's vary between 1.010 and 2.000 for the indicated frequencies.

0.37% 0.44% 0.59% 0.74% 0.87%

Repeatability of 14 mm connector

Maximum error in impedance phase angle for coaxial impedance standards whose measured VSWR's vary between 1.010 and 2.000 for the indicated frequencies.

Maximum error in VSWR of coaxial impedance standards whose measured VSWR's vary between 1.010 and 2.000 for the indicated frequencies.

0.39° 0.51° 0.72° 0.88° 0.93°

0.01% 0.01% 0.05% 0.02%
COAXIAL REFLECTOMETER MEASUREMENTS:

1 - 4 GHz

0 ≤ |r| ≤ 1

Bias Uncertainties:

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

Random Errors: Negligible

Total Uncertainty:

for 0 ≤ |r| ≤ 0.025: Δ |r| ≤ 0.00025
for 0.025 ≤ |r| ≤ 1: Δ |r| ≤ 1% |r|

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.


Personnel: R. J. Jesch
HIGH FREQUENCY IMMITTANCE

30 KHz - 300 MHz
C : $10^{-12} - 10^{-7}$ F
L : $10^{-6} - 1$ 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.


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).


Personnel: R. N. Jones
R. E. Nelson
LARGE
COMPLEX RELATIVE DIELECTRIC PERMITTIVITY
30 kHz - 100 MHz
Ranges: $\epsilon' \ (\text{Real Part}) > 1$
$10^{-2} < \tan \delta \ (\text{Loss Tangent}) < 10^2$
Frequencies: 30 kHz - 100 MHz

Machining and Measurement of Toroidal Sample
Sample of Known Geometry

Measurement of Primary Immittances of Permittimeter (Transformer) with Sample in Place as the Secondary Winding

$\geq 2\% \ (\epsilon')$
$5\% \ (\tan \delta)$
$\epsilon' \ and \ \tan \delta$
30 kHz - 100 MHz
Large Complex Relative Dielectric Permittivity

PERMITTOMETER MEASUREMENT:

30 kHz - 100 MHz
Range: $\varepsilon' > 10^{14} / [f \text{ (Hz)}]^{1.5}$
$\sigma > 10^{4} / [f \text{ (Hz)}]^{0.5}$
$10^{-2} < \tan \delta < 10^{2}$ (see Notes)

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

Random Errors: Not reported.

Total Uncertainty: $\varepsilon' : \geq 2\%$
$\tan \delta : \geq 5\%$

Uncertainty quoted customer: Same as Total Uncertainty.

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


Personnel: H. E. Bussey
HIGH FREQUENCY
RELATIVE DIELECTRIC PERMITTIVITY, REAL PART

$30\text{kHz} - 1\text{GHz}$
Range: $1 - 10^4$

- Bridge Measurement of Capacitance, With & Without Sample
  - Real Part of Permittivity ($\varepsilon'$)
  - $30\text{kHz} - 10\text{MHz}$
  - $0.4 - 1\%$

- Q-meter Measurement of Capacitance, With & Without Sample
  - $50\text{kHz} - 250\text{MHz}$
  - $0.4 - 1\%$

- Measurement of Resonant Length or Frequency of Double Re-entrant Cavity, with & without Sample
  - $0.09 - 1\text{GHz}$
  - $1 - 10\%$

Machining and Measurement of Samples
Samples of Known Geometry
High Frequency Relative Dielectric Permittivity, Real Part, $\epsilon'$

**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) $0.5 \times 10^{-2}/t\%$
- 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 $\epsilon'$.

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


**Personnel:** H. E. Bussey
High Frequency Relative Dielectric Permittivity, Real Part, $\epsilon'$

**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 $0.5 (10^{-2}/t)\%$ negligible  
- 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 $\epsilon'$.

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, $\varepsilon'$

**RE-ENTRANT CAVITY MEASUREMENT:**

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

**Bias Uncertainties:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>0.2 to 0.5%</td>
</tr>
<tr>
<td>Sample geometry, including foil contact</td>
<td>$2(10^{-2}/t)%$</td>
</tr>
<tr>
<td>Fringing fields</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

**Random Errors:**

- Bias Correction
- Fringing Fields
- Sample geometry

**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

\[ 30 \text{kHz} - 1 \text{GHz} \]
Range: \( 10^{-4} - 10^3 \) \( (\tan \delta) \)

Machining and Measurement of Samples

- Samples of Known Geometry

\[ \varepsilon' \]
Measurement of Real Part of Dielectric Permittivity

Bridge Measurement of Resistance, with & without Sample

- Loss Tangent \( (\tan \delta) \)
  \[ 30 \text{kHz} - 10 \text{MHz} \]
  0.00005 or 10%

Q-Meter Measurement of Capacitor Q, with & without Sample

- \( \tan \delta \)
  \[ 50 \text{kHz} - 250 \text{MHz} \]
  0.00005 or 10%

Conductance Measurement via Resonance Curve Width, Double Re-entrant Cavity

- \( \tan \delta \)
  \[ 0.09 - 1 \text{GHz} \]
  0.00005 or 10%
High Frequency Dielectric Loss

BRIDGE MEASUREMENTS:

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

Bias Uncertainties:

Sample geometry
Bridge measurement of conductance

0.5 to 1%
2%

Random Errors:

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

Total Uncertainty:

$[2.5 + 5 \times 10^{-3}/\tan \delta] \%$

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
High Frequency Dielectric Loss

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:

$$[3 + 4 \times 10^{-2}/\tan \delta]\%$$

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)

- Machining of Sample to Fill End of Waveguide, and Measurement of Sample Length
- Load of Known Geometry
- Measurement of Impedance at Interface, Using Slotted Line
- Complex Propagation Constant, in Sample
- Complex Dielectric Permittivity ($\epsilon' - j\epsilon'\tan\delta$)

$\mu$
Microwave Complex Relative Dielectric Permittivity, Real Part, $\varepsilon'$

DIELECTRIC LOADED TRANSMISSION LINES:

Slotted line impedance measurements
0.3 - 8.6 GHz

Bias Uncertainties

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample dimensions</td>
<td>0.5%</td>
</tr>
<tr>
<td>Gap errors around sample</td>
<td>0.2 to 2%</td>
</tr>
<tr>
<td>Attenuation measurement</td>
<td>negligible</td>
</tr>
<tr>
<td>Probe position and wavelength measurements</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

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
Microwave Complex Relative Dielectric Permittivity, Loss Tangent

DIELECTRIC LOADED TRANSMISSION LINES

Slotted line impedance measurement
0.3 - 8.6 GHz

Bias Uncertainties:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contribution of magnetic permeability</td>
<td>0 to 1%</td>
</tr>
<tr>
<td>Gap errors</td>
<td>0.2 to 2%</td>
</tr>
<tr>
<td>&quot;Law&quot; of crystal</td>
<td>2%</td>
</tr>
<tr>
<td>Environment (see Notes)</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

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)

Load of Known Geometry

Measurement of Cavity Transmission, and/or Q with & without Sample

Measurement of (1) Resonant Length or Frequency of Transmission Cavity, with & without Sample (2) Sample & Cavity Volumes

5-10% Dielectric Loss Tangent ($\delta$)

1% Real Part of Permittivity ($\varepsilon'$)
TRANSMISSION CAVITIES:

1 < $\varepsilon'$ < 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:

\[ 10^{-4} \text{ to } 10^{-1} \]

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.


Personnel: H. E. Bussey
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