NBS

Technical Note No. 262-A

EXCERPT FROM TN 262

ACCURACY IN ELECTRICAL AND RADIO MEASUREMENTS AND CALIBRATIONS, 1965

EDITED BY R. C. POWELL

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS

Technical Note.262-A

ISSUED June 15, 1965

ACCURACY IN ELECTRICAL AND RADIO MEASUREMENTS AND CALIBRATIONS, 1965

Edited by R. C. Powell
Radio Standards Laboratory
National Bureau of Standards
Boulder, Colorado

Excerpt from TN 262, Accuracy in Measurements and Calibrations, 1965; edited by W. A. Wildhack, R. C. Powell, and H. L. Mason; NBS Institute for Basic Standards.

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Editor's Preface

As a convenience to those interested primarily in the field of electrical and radio measurements, the content of this Note has been extracted from a more comprehensive Technical Note 262.[1] In addition to the electrical and radio quantities considered here, Technical Note 262 contains charts for other basic physical quantities, for mechanical quantities and for optical and ionizing radiation.

Electrical quantities for frequencies above 30 kHz are the responsibilities of the Radio Standards Laboratory. Therefore, the sections on measurements in this area pertain only to the Boulder, Colorado, laboratories of the National Bureau of Standards. The section on electrical quantities d-c to 30 kHz refers to measurements for which services are currently available in both Washington, D. C. and Boulder, Colorado, with the following exceptions:

Low frequency current, current ratio, power, energy, and magnetic flux density measurements are not made at Boulder.

The uncertainties indicated as attainable accuracy are usually available only in Washington.

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1. W.A. Wildhack, R. C. Powell, H. L. Mason, Accuracy in Measurements and Calibrations, 1965. National Bureau of Standards Technical Note 262, June 15, 1965. U.S. Government Printing Office.

CONTENTS

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1. Time delay, the time for an electromagnetic wave to travel through a device, is given in seconds, but time delay standards should not be confused with standards of time.

2. Power and voltage are often given as the percent of AC-DC difference, percent of RF-DC difference, efficiency, etc., which are actually dimensionless properties of devices.

3. While noise is measured in units of power per unit bandwidth, it is often expressed as effective noise temperature since the power per unit bandwidth is equal to the Boltzmann constant times the effective noise temperature.

4. While impulse spectral density has the units of power per unit bandwidth, it is common practice to express it in decibels above one microvolt per megahertz, assuming a 50 ohm impedance level.

5. Field strength is often given as a coefficient or gain, both of which are actually dimensionless quantities.

ABSTRACT

NBS estimates of uncertainties associated with physical measurements, and with some NBS calibration services, are shown by 42 provisional "accuracy charts." Each chart is accompanied by a facing page giving a brief statement of the state of the art and tentative plans for NBS work in areas where improvement is needed.

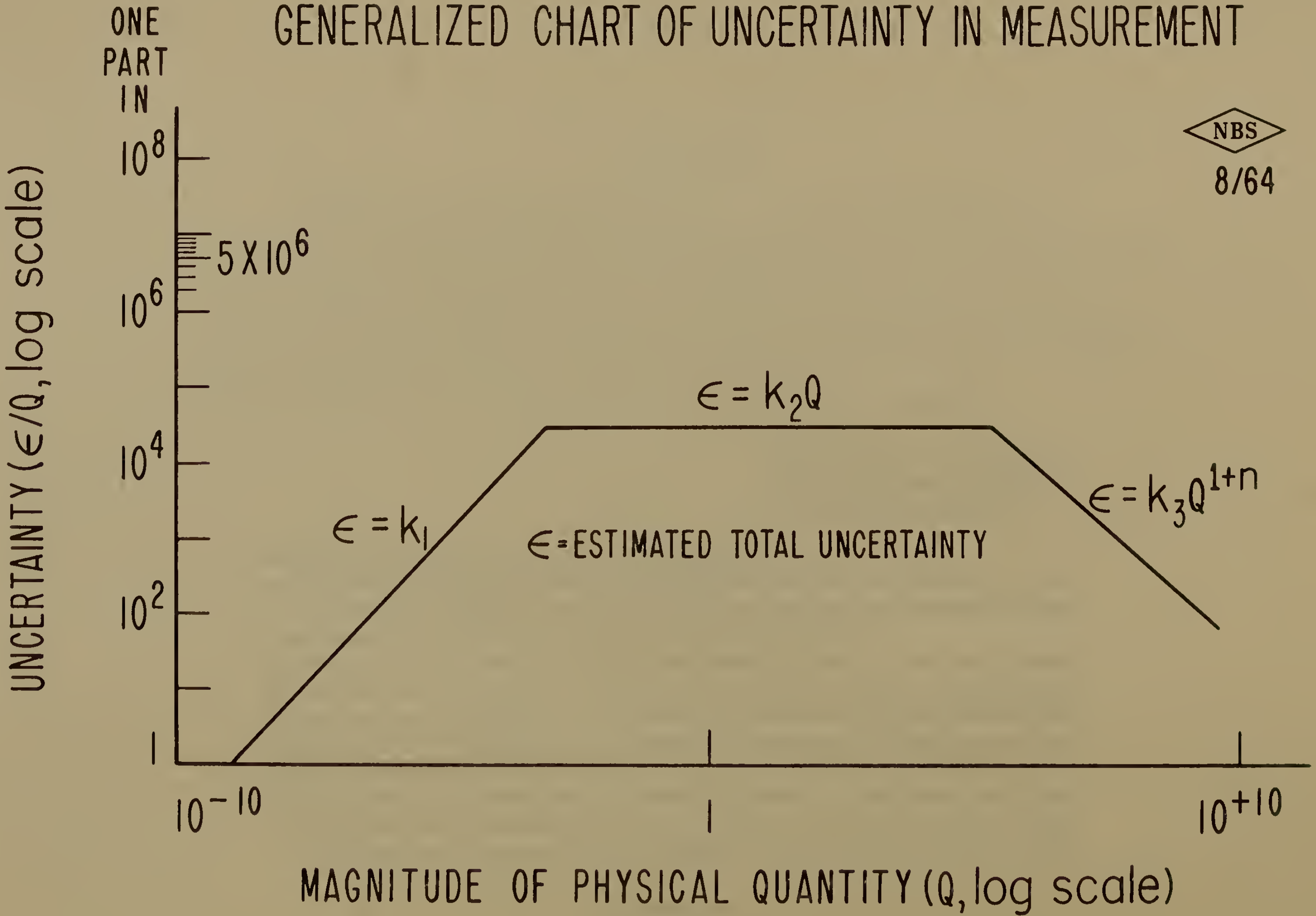
Foreword

This collection of accuracy charts provides a graphic perspective on the ranges and NBS estimates of uncertainty for measurements or calibrations of many of the physical quantities of importance in science and industry. Such charts have been found to be of value not only in portraying the present state of the art but also in planning the Bureau's programs for improving measurement capabilities to meet present and developing needs. As a summary collection, without description of the various devices, methods, and causes of uncertainty involved, the charts must be considered as provisional. Detailed discussions of some of them have already appeared in the literature and this may be expected for others.

Comments, suggestions, and additional information will be welcomed as aids both for improving the charts and for identifying important and urgent needs for measurements of greater accuracy or extended range.

R. D. HUNTOON, *Director*
Institute for Basic Standards
National Bureau of Standards

GENERALIZED CHART OF UNCERTAINTY IN MEASUREMENT



I. Introduction

The "accuracy charts" shown herein are plots of the uncertainty associated with measurement of a physical quantity, or the calibration of physical standards or measuring instruments, over the range in which direct comparison with NBS standards is feasible. Some show present estimates of precisions or accuracies for NBS standards already available as calibration services to science and industry; others indicate values sought as near-term goals. The charts and their explanatory facing sheets have been prepared by many different project leaders at NBS, with coordination by H. W. Lance and R. C. Powell for radio-frequency standards.

Because of the extended ranges over which many physical quantities are required to be measured, the charts are plotted on logarithmic scales, to provide a better perspective of the enormous ranges involved. Increasing accuracy or precision (in more general terms, decreasing relative uncertainty) is shown as an increasing ordinate. We have chosen to express the left-hand scales in terms of one part in the indicated ordinate value, e.g., 1 in 5×10^4, which is equivalent to 2 parts in 10^5, 20 ppm, or 0.002 percent. The generalized form on page vi shows how the relative uncertainty is likely to vary with the magnitude of the physical quantity in typical cases. Such a chart provides a ready base on which one may indicate various techniques or instruments or plans, or plot the comparative accuracies associated with various echelons of calibration, from the international standards to the instruments on the factory bench.

A few charts similar to these were presented in several papers [1] at the 1962 National Conference of Standards Laboratories at the Boulder (Colo.) Laboratories of NBS. The present collection extends the number to 42. On the charts for some quantities, auxiliary parameters have been indicated, e.g., frequency for microwave power measurements. On others, e.g., neutron flux density, an auxiliary parameter considered to be of primary importance (here neutron energy) appears as the abscissa, but in such cases the accuracy stated refers to measurement of the subject quantity. However, the basis for estimating accuracy varies from chart to chart, as dictated by current practice in an individual laboratory to meet the demands of its field. For some quantities shown here, the values of absolute accuracy (uncertainty) include an estimate of the limits of systematic errors (both constant and variable [2]) for calibration of typical high-quality interlaboratory standards using the measurement process, equipment, and personnel of NBS. For others only the computed limits of precision are given, reflecting only repeatability under these conditions. In the latter case, the figure usually corresponds to three times the standard deviation of the observations from their average. The references below cover available statistical methods for evaluating and combining various estimates of uncertainty,[3, 4] the various measurement techniques and their useful ranges,[5] and the many factors which must be considered in estimating overall uncertainties.[6] Some charts include shaded bands of uncertainty designated 'Non-NBS State of the Art." These are estimates by various NBS staff members, gleaned from the technical literature, from manufacturers, or from the 1963 URSI survey;[7] any needed corrections will be welcomed. The reader interested in evaluating the accuracy of his own measurements is cautioned that allowance must be made for the inevitable deterioration of accuracy resulting from the sequence of events and environments between an NBS calibration and the point at which the calibrated instrument is used.

The qualitative or quantitative listing of needed improvements in accuracy or extension of range, as shown on charts or facing sheets, is the composite result of staff judgment and of statements made by industry and government agencies. Major contributions came from the Quality Control Project of the Aerospace Industries Association, the Measurement Research Conferences sponsored by AIA and NBS, contractors and laboratories of DoD, NASA, and AEC, and the various NBS Advisory Panels. "Objectives" shown as chart curves or mentioned in text must be regarded as subject to change because of shifting priorities and resources.

All the calibration services on physical quantities presently available from NBS are given in Miscellaneous Publication 250.[8] This also lists the services in precision measurement provided by the Bureau on such items as audiometric earphones, chromaticity of light sources, photographic objectives, gear tooth indexing, gamma-ray sources, magnetic permeability, dielectric constant, and fire endurance of structural columns. Miscellaneous Publication 260 [9] describes the specially prepared reference materials available from stock—stainless steels and hydrocarbons for spectrometer calibration, viscometric oils, radioactive nuclides, alloys and ceramics of certified composition, and many others.

Comments are invited on any aspect of the charts: these may be directed to the editors. Inquiries or suggestions as to the extension of NBS services will be particularly welcome from persons concerned with high-precision measurements in research, development, or calibration, if they foresee difficulty in obtaining calibration accuracy adequate to their needs in the ranges of importance to them.

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[1] Proceedings, National Conference of Standards Laboratories, 1962, *NBS Misc. Publ. 248, available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at $1.75. See papers by W. A. Wildhack, T. R. Young, E. C. Lloyd and B. L. Wilson, J. F. Swindells, F. L. Hermach, A. H. Morgan, R. C. Powell, R. E. Larson, John L. Dalke.*

[2] Ibid., *paper 2.1 by Churchill Eisenhart, paper 5.1 by W. J. Youden.*

[3] *A. G. McNish and J. M. Cameron, pp. 101–104; E. L. Crow, pp. 105–114, IRE Trans. Instr.* **I–9.**

[4] *Chapter 23 of* Experimental Statistics, *NBS Handbook 91, available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at $4.25. A list of other NBS papers on the uncertainties associated with calibrations and meusurements, either general or for specific variables, is available at no charge from the Office of Technical Information and publications, National Bureau of Standards, Washington, D.C., 20234.*

[5] Precision Measurement and Calibration, *NBS Handbook 77 (Feb. 1961), available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402:* Vol. I, Electricity and Electronics, *$6.00;* Vol. II, Heat and Mechanics, *$6.75;* Vol. III, Optics, Metrology, and Radiation, *$7.00.*

[6] *See, for example, R. C. Powell, R. M. Jickling, and A. E. Hess, IRE Trans. Instr.* **I–7**, *270–274 (Dec. 1958).*

[7] URSI National Committee Report, XIV General Assembly, Tokyo, Sept. 1963: Commission 1, Radio Measurement Methods and Standards. *In J. Res. NBS* **68D** *(Radio Science), No. 5 (May 1964).*

[8] Calibration and Test Services of the National Bureau of Standards, *NBS Misc. Publ. 250, available at 70 cents from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. For continuous updating, see the* Federal Register.

[9] Standard Materials Issued by the National Bureau of Standards: A Descriptive List With Prices, *NBS Misc. Publ. 260, available at 35 cents from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Supplementary inserts are issued periodically.*

2. Uncertainty Charts

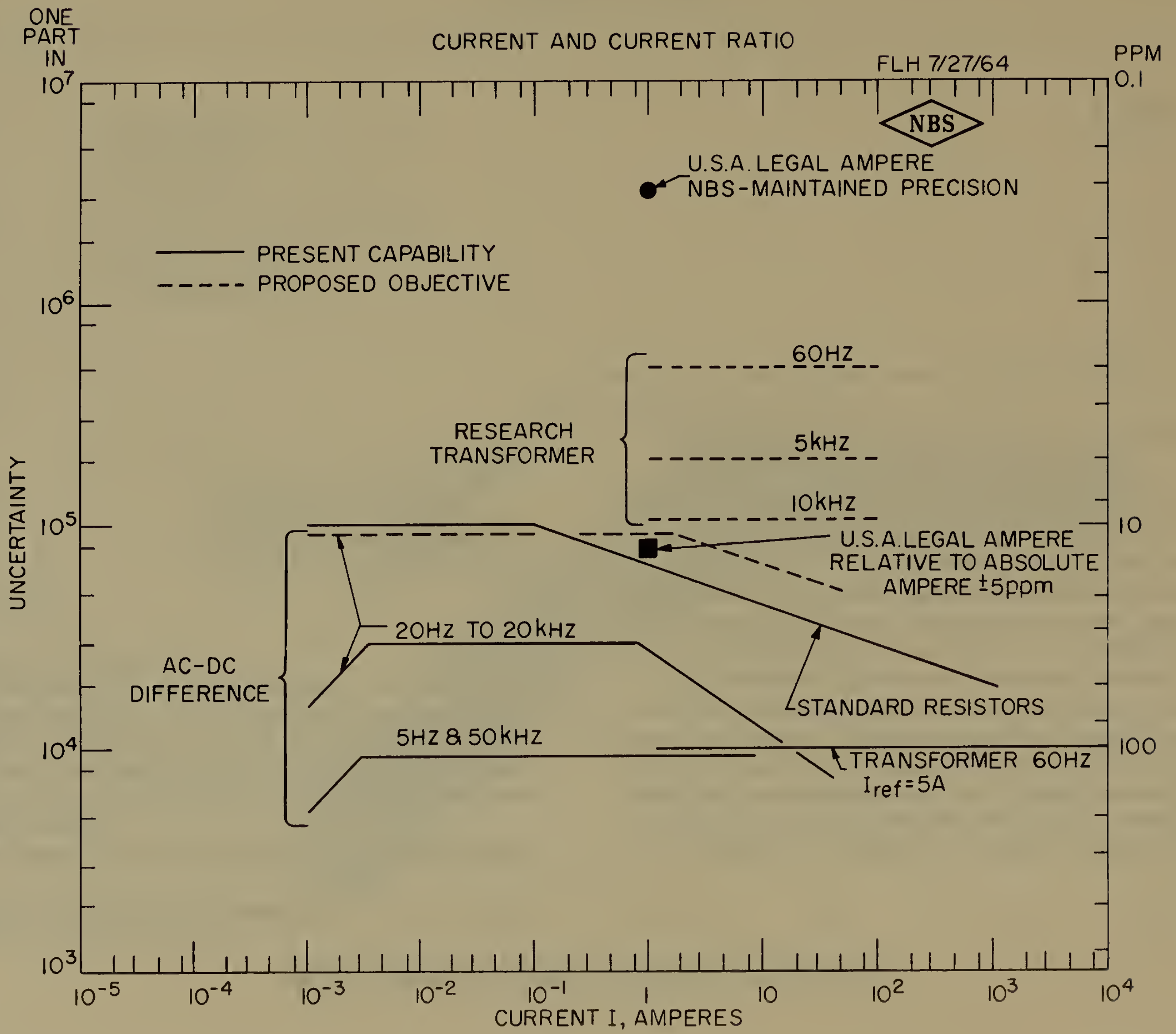
Current and Current Ratio

F. K. Harris, F. L. Hermach, *Section Chiefs*

State of the art: The absolute ampere is realized by a current balance "weighing" to a few parts per million. The NBS (legal) ampere is estimated to be 12 ± 5 ppm above the absolute ampere, and is monitored to within ±0.3 ppm by use of proton gyromagnetic ratio and calibrated coil; d–c values above and below 1 ampere are realized by standard resistors and d–c potentiometer; a–c values are realized with ac–dc transfer standards and the same d–c standards. Estimated accuracies shown are for calibration of ideal reference standards (perfectly stable and unaffected by environment) and include 3 standard deviations plus estimated systematic errors; accuracy of ratio I/I_{ref} is shown for ideal transformers.

Industry needs: Nonmagnetic facility at Gaithersburg to expedite work on absolute ampere, gyromagnetic ratio, and speed of light; accurate measurements are presently possible only 1 to 5 in early morning. More accurate standards for steady-state d–c and a–c measurements.

Short-term objectives: Detailed plans for nonmagnetic facility. Improvements in Pellat-type balance for absolute ampere. Improvement of ac–dc transfer standards. Improvement of a–c ratio and extension to higher currents with transformers and a–c current comparators. D–c current comparator.


CURRENT AND CURRENT RATIO
FLH 7/27/64
NBS
ONE PART IN
10^7
10^6
10^5
10^4
10^3
UNCERTAINTY
PPM
0.1
10
100
U.S.A. LEGAL AMPERE NBS-MAINTAINED PRECISION
PRESENT CAPABILITY
PROPOSED OBJECTIVE
RESEARCH TRANSFORMER
60HZ
5kHZ
10kHZ
U.S.A. LEGAL AMPERE RELATIVE TO ABSOLUTE AMPERE ±5ppm
20HZ TO 20kHZ
AC-DC DIFFERENCE
STANDARD RESISTORS
5HZ & 50kHZ
TRANSFORMER 60HZ $I_{ref}=5A$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
CURRENT I, AMPERES

High-Frequency Current (Coaxial Systems)

N. V. Frederick, *Project Leader*, Standards

Existing capability: There are at present no reference standards for high-frequency current.

Five-year objective: Two approaches to the current-measurement problem have been established recently. One approach uses thin-film thermocouples and the other uses the electrodynamic ammeter. The Electro-Technical Laboratory of Japan has developed such an ammeter; the uncertainty of their measurements as compared to their thermo-ammeter corresponds to

$$s=\left[\frac{\sum_{i-1}^{n}(E_i-\overline{E})^2}{n-1}\right]^{1/2}$$

$$\overline{E}=\frac{1}{n}\sum_{i=1}^{n}E_i, n=9$$

$$E_i=\frac{i_i-i_i}{(I_i+i_i)/2}$$

I_i=the ith current indication of the electrodynamic ammeter

i_i=the ith current indication of the thermo-electric ammeter

I_i and i_i are read simultaneously.

In general the precision and absolute accuracy of the electrodynamic ammeter are limited by the ability to make precise mass length, and time measurements, and to make accurate evaluations o the electric-field boundary-value problems presented by the geometr of the instrument. Serious limitations to precision and sensitivit are set by building vibrations and environmental thermal stability

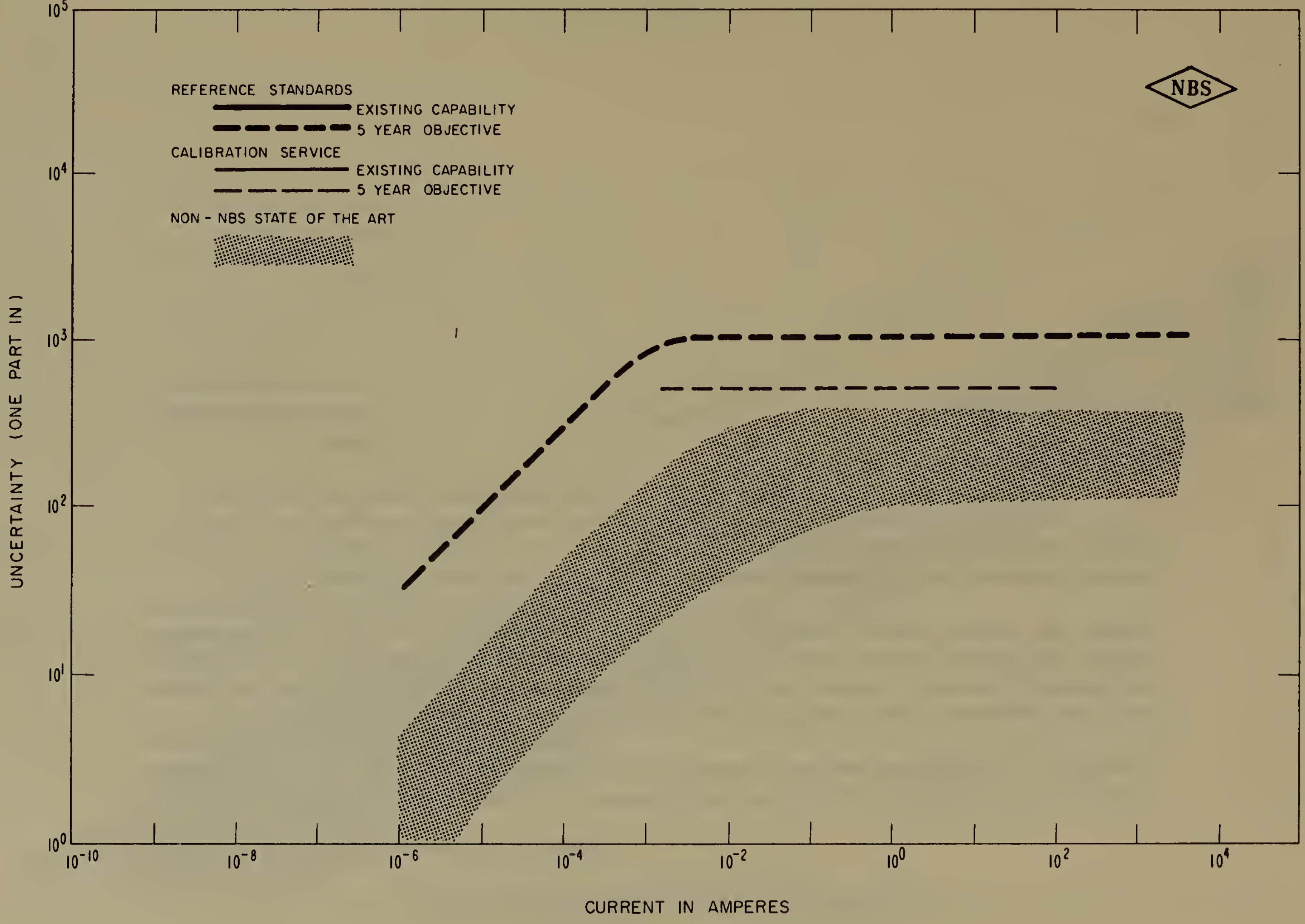
The instrument is expected to operate between 1 MHz an 1 GHz for currents of 1 to 100 amperes. It is hoped that thin-film thermocouples will supply a means of extending the measuremen range below 1 ampere over the frequency range 1 to 300 MHz.

State of the art: The Japanese and Russian electrodynami ammeters operate in the VHF and lower UHF bands at current around 100 amperes, giving uncertainties of about 1 part in 200 to 50

Reference:

"Research Highlights of Radio Standards and Measurements," *Electr Technical Laboratory of Japan.*

HIGH FREQUENCY CURRENT
(COAXIAL SYSTEMS)



Time Delay (Waveguide Systems)

D.A. ELLERBRUCH, *Project Leader*, Standards

General: Time delay, the time for an electromagnetic wave to travel through a device, is given in seconds, but time-delay standards should not be confused with standards of time. The primary reasons for this measurement are twofold:

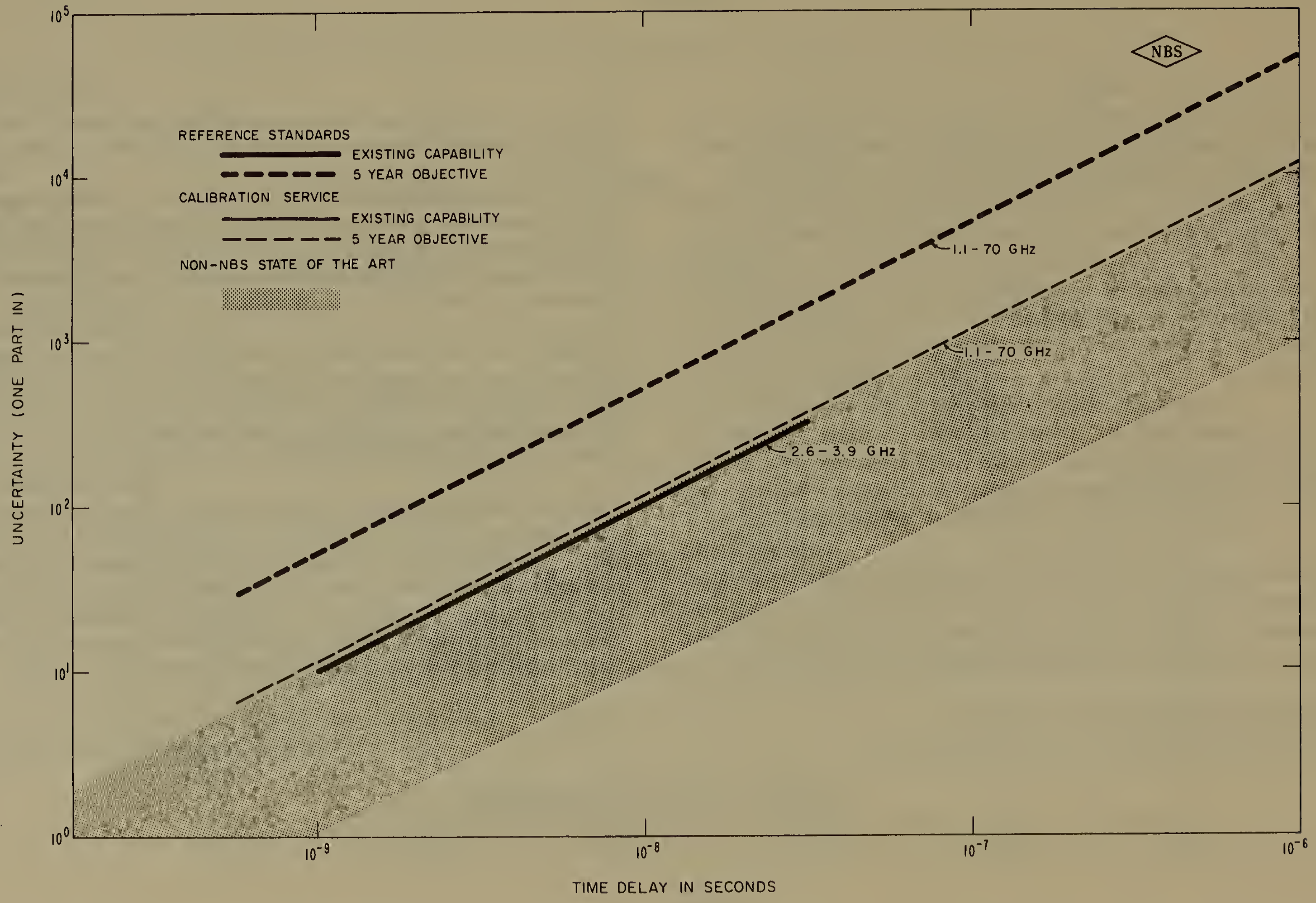
1. It is a measure of phase slope. Any phase slope variation over a frequency band indicates the phase distortion a device or network under test will introduce. Industry has indicated an interest in either phase slope measurements (time delay) or swept-frequency phase data. Where narrow band equipments are involved, time-delay measurement appears to offer the greatest measurement accuracy in the microwave region.

2. Industry has indicated an interest in the measurement of absolute phase through a network or device. Although no technique now exists for determining the absolute phase shift through use of both time delay and phase data, the possibility will be investigated.

State of the art: The band is based partly on the following:

Organization	*Uncertainty*	*Time delay*
Commercial laboratory	2×10^{-10} sec	To 10^{-7} sec.
Instrument manufacturer	2×10^{-9} sec	To 3.6×10^{-7} sec.

TIME DELAY
(WAVEGUIDE SYSTEMS)



Frequency and Time Interval

R. C. Mockler, *Section Chief*, Standards
A. H. Morgan, *Section Chief*, Dissemination Research
D. H. Andrews, *Section Chief*, Broadcast Services
J. H. Shoaf, *Project Leader*, Dissemination

General: The term "precision," when used in connection with the NBS frequency standards, refers to the extent to which a measurement of frequency is reproducible. Used in this sense the measure of precision would include contributions from both the standard itself and whatever source of frequency is being measured. The most commonly used measure of precision for NBS measurements of frequency is the standard deviation of the mean associated with the comparison data.

The term "uncertainty" refers to the degree to which the atomic frequency standard approaches the value of the idealized resonance frequency for the cesium atom in its unperturbed state. This uncertainty figure is consistent with the values obtained by other reliable standards laboratories in foreign countries (i.e., England, Switzerland, etc.).

The lower limit for short time intervals (reciprocal frequency) is of course limited by equipment and techniques for determining the end points of a time interval. Time interval measurements are based upon the atomic definition of the second as adopted by the Twelfth General Conference of Weights and Measures in October 1964.

Existing capability: The curve for existing capability of signal sources is based primarily on cesium beam standards (i.e., 6 parts in 10^{12} accuracy).

The curves for existing capabilities for calibration services represent, in general, the announced services available. Calibration service for special requests, where extended frequency ranges or slightly lower uncertainties are necessary, may be made contingent upon demands.

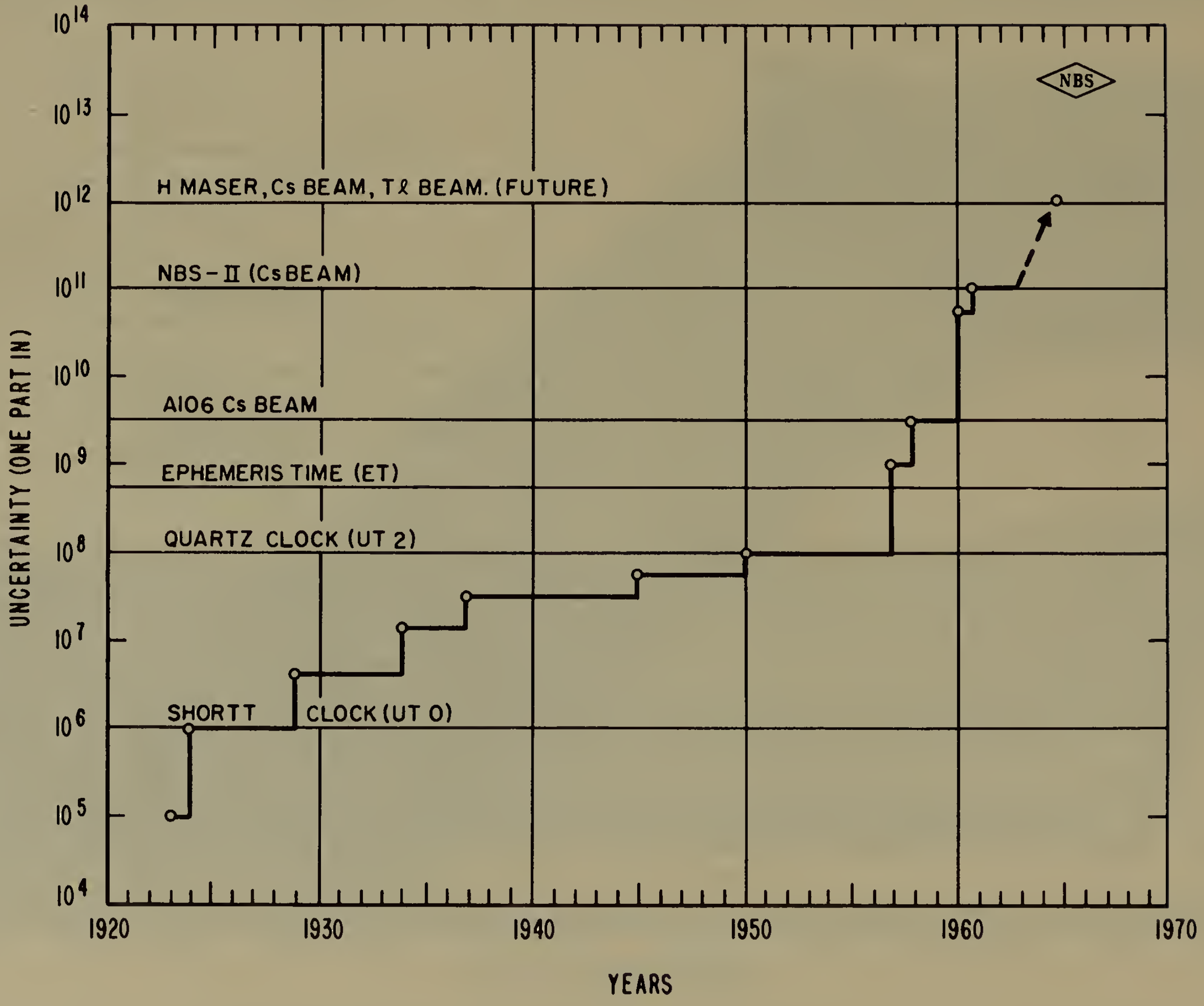
The lower limit on the range for calibration of cavity resonators is, of course, based on the nature of resonant devices (i.e., limited in general to the microwave region). The limitation on accuracy for resonance frequency is the uncertainty of resettability of cavity wavemeters, etc. (dial graduations, coarse verniers, etc.).

Five-year objectives: The curve for future objectives is based on improved techniques and better cesium standards as well as other atomic standards such as the thallium beam or hydrogen maser. Approximately one order of magnitude less uncertainty may be achieved.

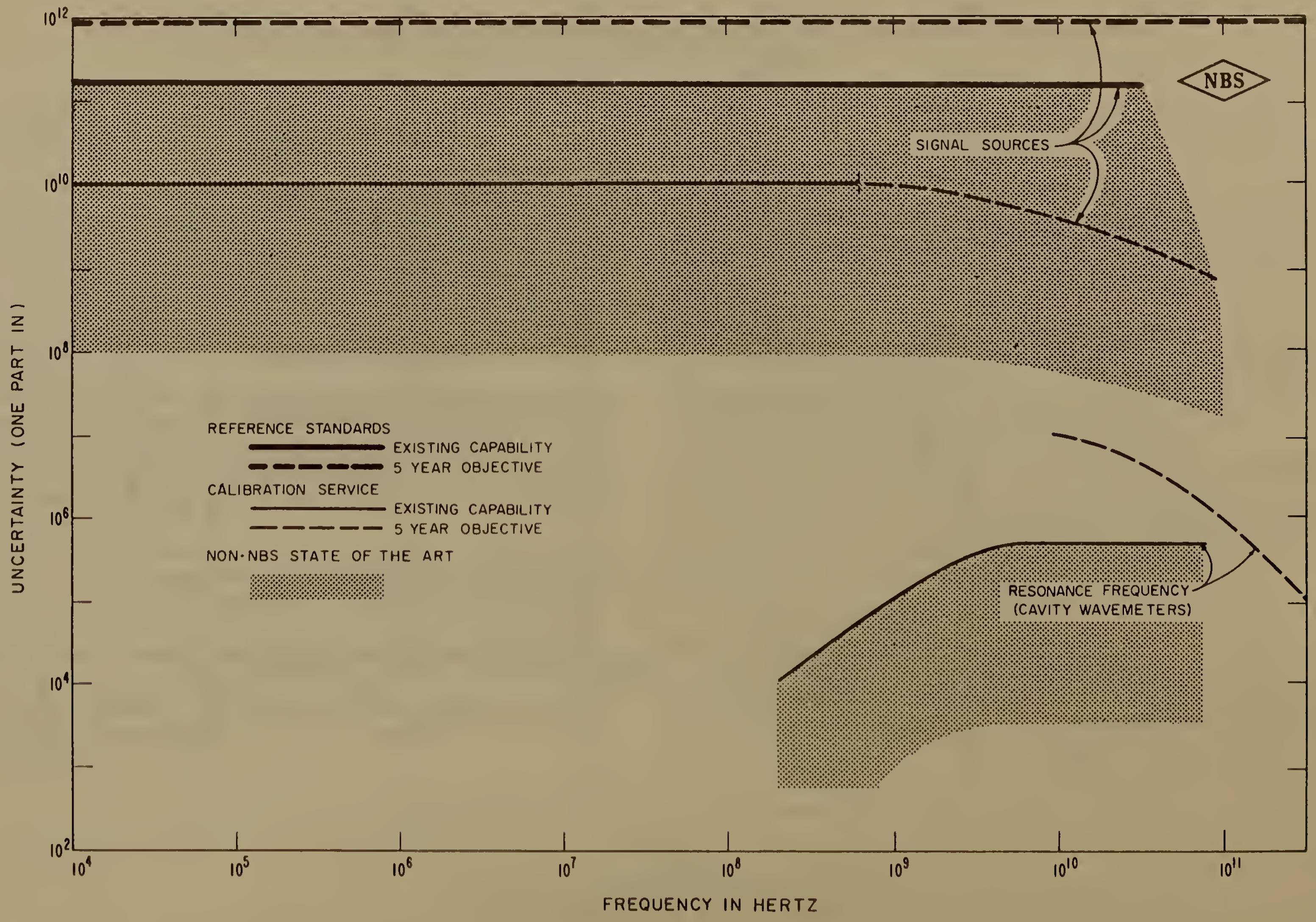
It is planned to eliminate the cavity resonator calibration service below *X*-band in the near future.

State of the art: The existing capabilities also represent the upper limit of the non-NBS state of the art. The width of the band is determined by the uncertainty range of high-quality standards.

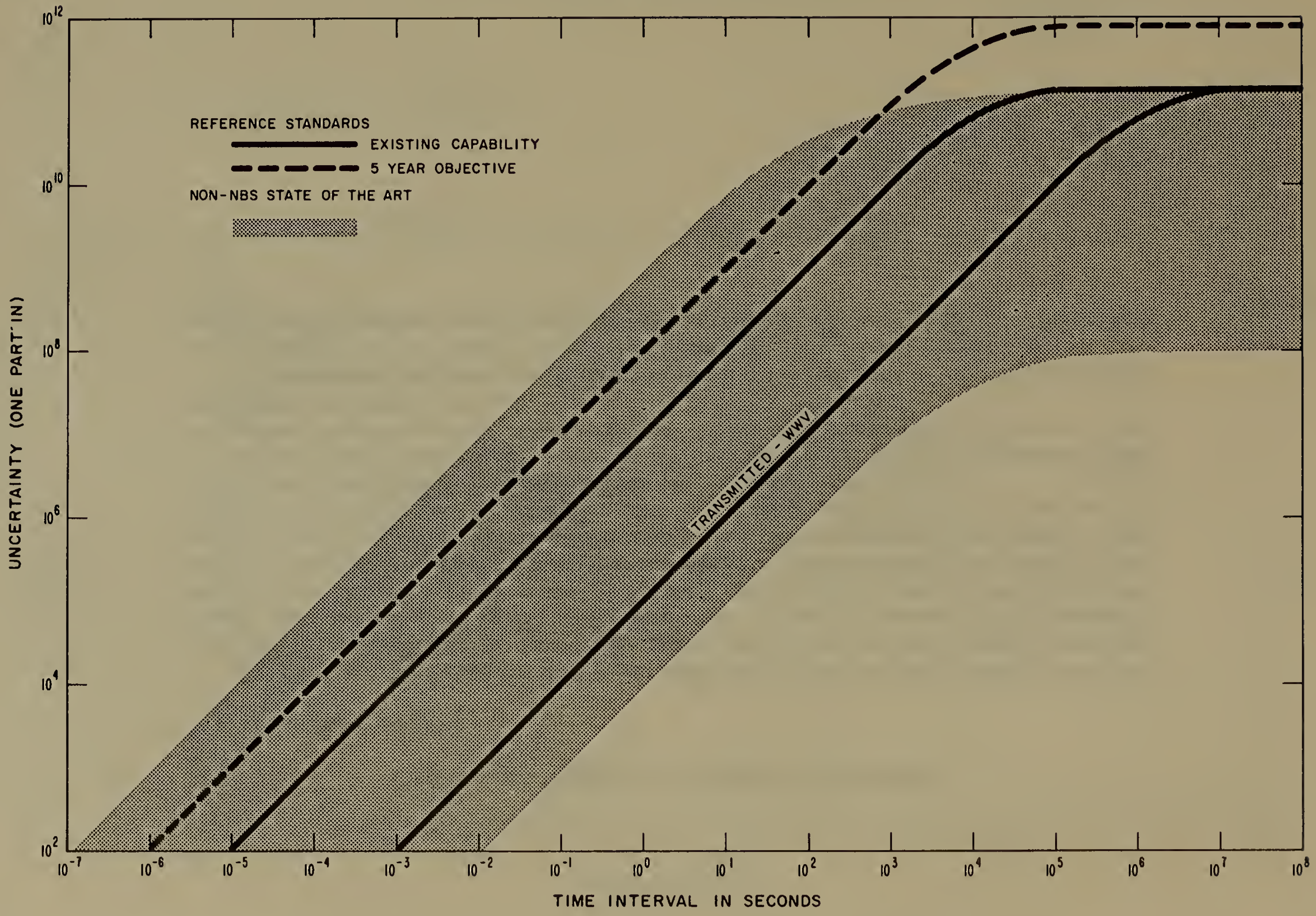
IMPROVEMENTS IN THE ACCURACY
OF THE U.S. FREQUENCY STANDARD
(USFS)



FREQUENCY


NBS
SIGNAL SOURCES
RESONANCE FREQUENCY (CAVITY WAVEMETERS)
REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE
CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE
NON·NBS STATE OF THE ART
UNCERTAINTY (ONE PART IN)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
FREQUENCY IN HERTZ

TIME INTERVAL



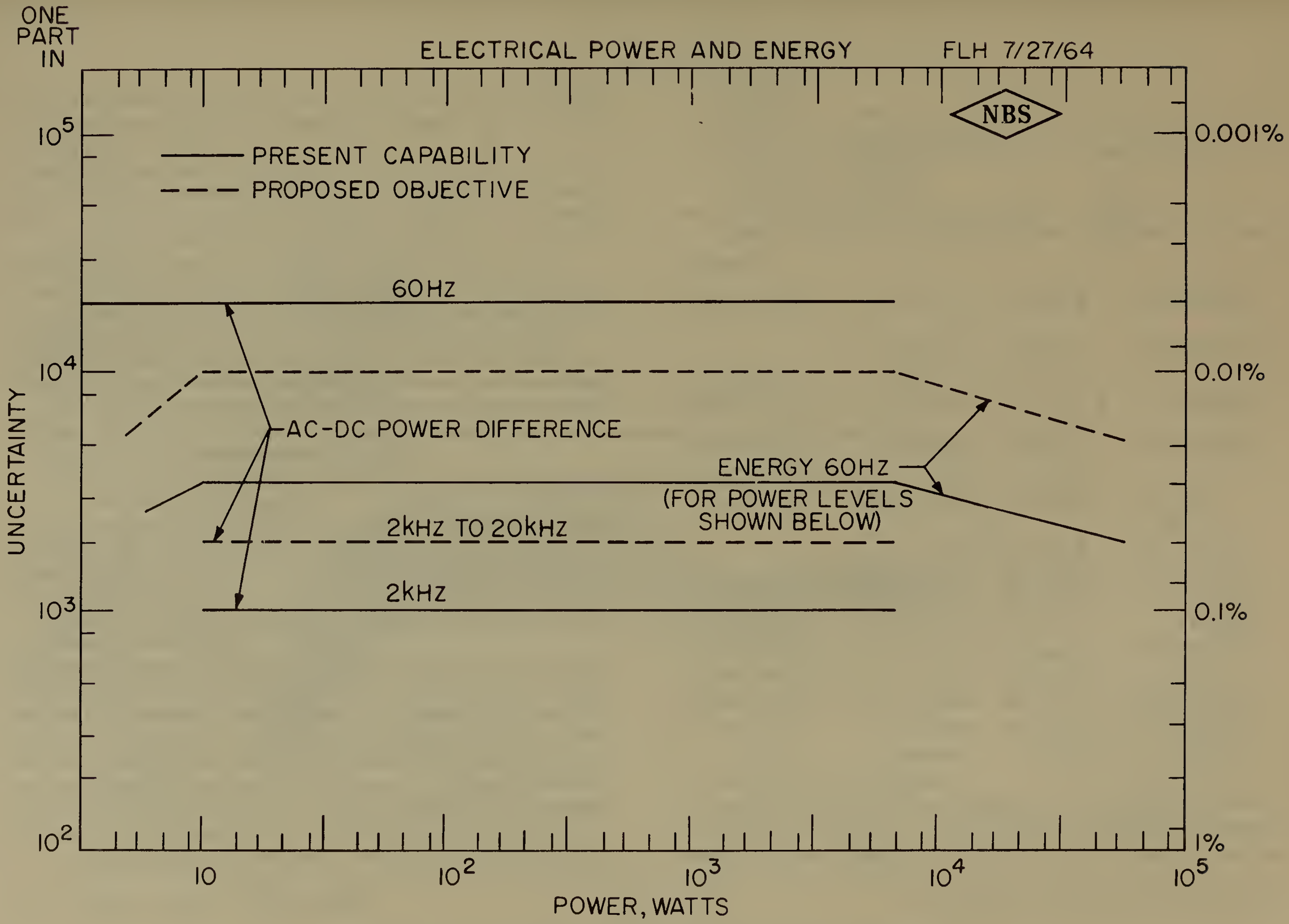
Power and Energy at Audio Frequencies

F. L. Hermach, *Section Chief*

State of the art: NBS does not offer power calibration service; d–c power measurements are made with d–c potentiometer, standard cell, resistor, and voltage divider. Accurate a–c power measurements are made with ac–dc transfer wattmeter and these d–c standards; NBS, determines only the ac–dc differences of such wattmeters. Energy measurements are made by comparison with a bank of four standard watthour meters, maintained as a working standard for energy and calibrated periodically with the NBS transfer wattmeter and NBS standard-frequency signals. Estimated accuracies shown are for calibration of ideal standards (perfectly stable and unaffected by environment), and include 3 standard deviations plus estimated systematic errors.

Industry needs: Improved accuracy of energy measurements at 60 Hz and extension to high frequencies. Power measurements above 1 kHz. Pulses of 5 kilojoules to develop very high temperatures for thermal research.

Short-term objectives: Ac–dc transfer measurement of power difference to within ±0.05 percent for 10 to 5000 W at 2 to 20 kHz. Energy measurements to within ±0.01 percent at 60 Hz. Develop capacitor discharge techniques for high-energy pulses of 300 kA at 100 kV for 5μ sec to 5 percent.


ELECTRICAL POWER AND ENERGY
FLH 7/27/64
NBS
ONE PART IN
UNCERTAINTY
10^5
10^4
10^3
10^2
0.001%
0.01%
0.1%
1%
PRESENT CAPABILITY
PROPOSED OBJECTIVE
60 HZ
AC-DC POWER DIFFERENCE
ENERGY 60 HZ
(FOR POWER LEVELS SHOWN BELOW)
2kHz TO 20kHz
2kHz
10
10^2
10^3
10^4
10^5
POWER, WATTS

High-Frequency Power (CW Coaxial Systems)

P. A. Hudson, *Project Leader*, Standards

I. S. Berry, *Project Leader*, Dissemination

General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. Individual uncertainties are assigned from direct observations or by estimates of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch. At levels below 100 μW, measurement uncertainties increase rather rapidly due to thermal drifts and other causes.

Existing capability: Reference standards for high-frequency power measurement are of calorimetric type and have relatively long time constants (e.g., 20 to 30 min). The reference standards instruments and their ranges are as follows:

1. Bolometer bridge, 100 μW to 100 mW (calibrated against the dry load calorimeter).
2. Dry load calorimeter, 50 mW to 5 W.
3. Twin-joule flow calorimeter, 5 to 100 W.

All reference standards employ d–c substitution techniques.

It is possible to generate or standardize a low power level accurately (i.e., with uncertainty less than ± 1 percent) using directional coupler techniques, thus making it possible to calibrate microwatt and sub-microwatt power meters with acceptable uncertainties.

The range of the above standards also can be extended to higher power levels by use of directional couplers. The total range of interest extends from 10^{-8} to 10^{5} W.

Working standards for performing HF power calibration measurements consist of calorimeters [1] and bolometer bridges [2, 3, 4] together with precision directional couplers.[5] These working standards are periodically intercompared with the previously mentioned reference standards.

Calibration services are presently available only for coaxial CW rf calorimeters having Type N connectors. The uncertainty stated on reports of calibration is 1 to 2 percent, depending upon the repeatability and SWR of the calorimeter undergoing calibration.

State of the art: Some of the information on which the state-of-the-art band is based follows:

Reference	*Uncertainty*	*Range*	*Frequency*
Required maximum measurement uncertainties based on calibration requirements.	1 part in 200	10^{-4}–10^{-2} W	100–300 MHz.
	1 part in 200	10^{-2} W	500 and 1000 MHz.
	1 part in 200	10^{-2} W	100, 300, 500, 1000 MHz.
	1 part in 100	10^{-3}–10^{-2} W	To 1000 MHz.
	1 part in 100	10^{-3}–10^{-2} W	220–250 MHz.
	1 part in 100	10–150 W	200, 300, 500 MHz.
	1 part in 50	8. 10^{-3}–8 W	400 MHz.
Manufacturer	1 part in 100	5–125 W	30–1000 MHz.
Aerospace standards lab.	1 part in 50 to 70.	10^{-4}–10^{-2} W	10–1000 MHz.
	1 part in 100	1–50 W	100–1000 MHz.
Aerospace base	1 part in 30	20–100 W	100–500 MHz.

References:

[1] *Hudson, P. A., and C. M. Allred,* A dry, static calorimeter for RF power measurement, *IRE Trans. Instr.* **I-7**, *292 (1958).*

[2] *U.S. Patent No. 2,883,620.*

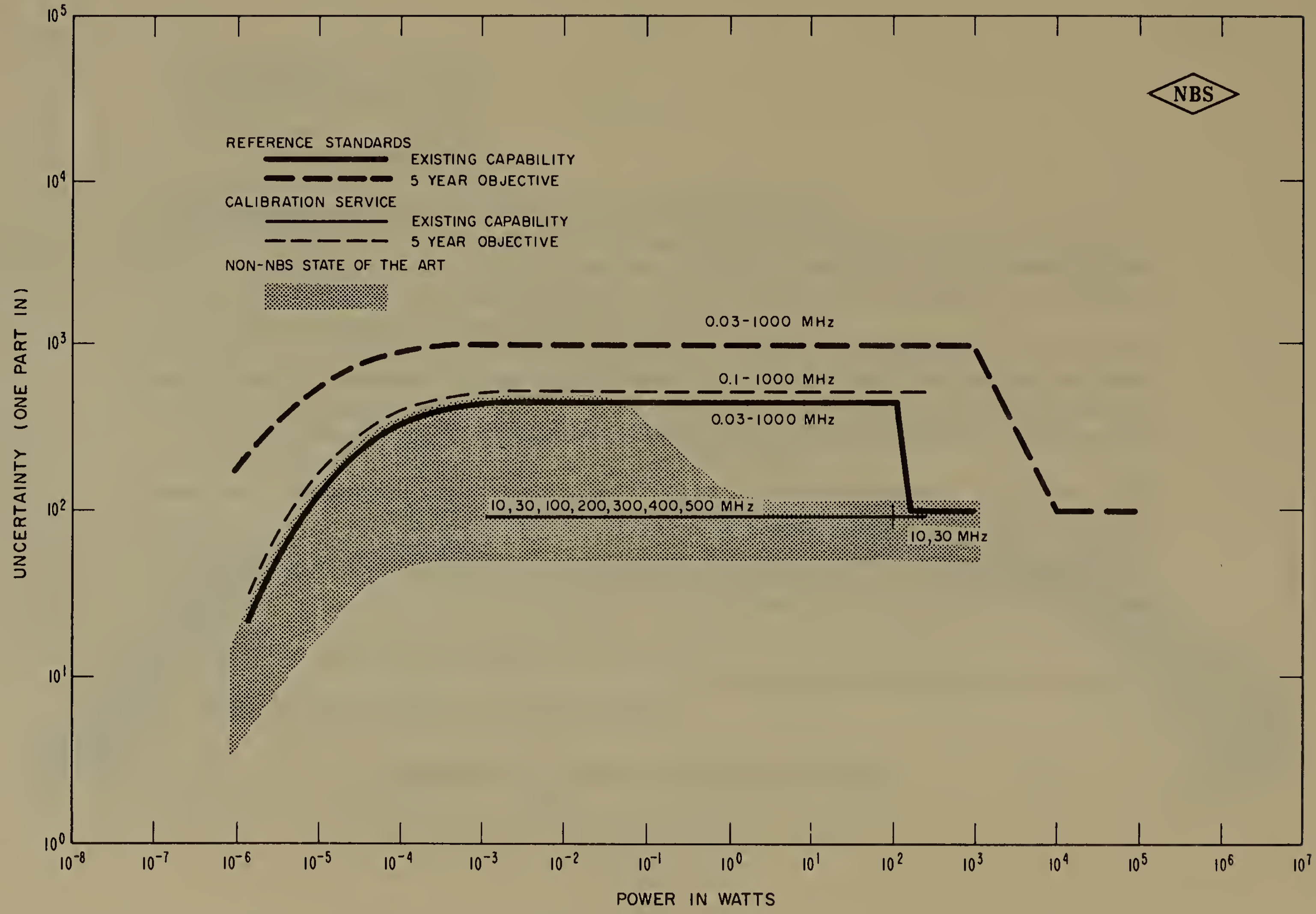
[3] *U.S. Patent No. 2,997,652.*

[4] *Engen, G. F.,* A self-balancing d-c bridge for accurate bolometric power measurement, *J. Res. NBS* **59**, *101 (1957).*

[5] *Hudson, P. A.,* A precision RF power transfer standard, *IRE Trans. Instr.* **I-9**, *280 (1960).*

(Pages 13 and 14 deleted.)

HIGH FREQUENCY POWER
(CW COAXIAL SYSTEMS)



Microwave Power (Coaxial Systems)

N. T. LARSEN, *Project Leader*, Low-Power Standards

R. F. DESCH, *Project Leader*, Dissemination

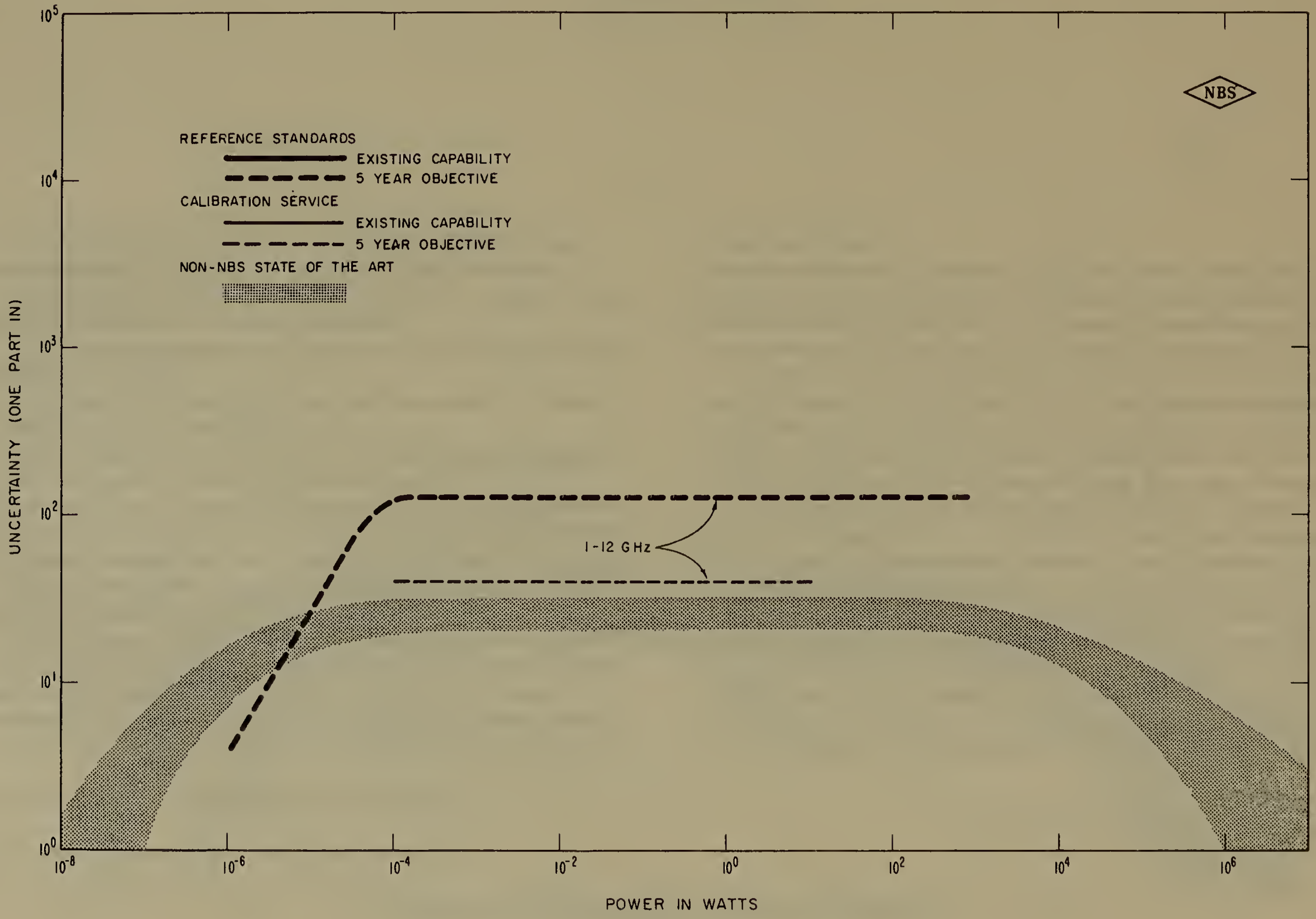
L. B. ELWELL, *Project Leader*, High-Power Standards

Five-year objective: It is planned to fabricate a coaxial reference standard calorimeter covering a frequency range of 1 to 12 GHz from 1 to 100 mW using a single size of coaxial transmission line. Evaluation of the calorimeter will be performed over each frequency band of interest. With this calorimeter, coaxial working standard bolometer units for low power levels can be calibrated. Low-power calibration services can be provided by using these working standards. The power range can be increased by utilizing attenuators and directional couplers.

A coaxial calorimeter for use as a reference standard is planned for this frequency range, covering power levels up to a few hundred watts. This will enable calibrations of bolometer units or thermoelement units in combination with directional couplers or attenuators to be intercompared at power levels above those attainable by low-power bolometric techniques. Calibration services at higher power levels will become available based upon this work.

State of the art: The band representing the non-NBS state of the art illustrates the estimated limits of commercial microwave power-measuring instruments based upon manufacturers' claims. The lower edge of the band corresponds to measurements made at the highest and lowest frequencies; the upper edge corresponds to those made in the middle frequencies.

MICROWAVE POWER
(COAXIAL SYSTEMS)



Microwave Power (Waveguide Systems)

N. T. Larsen, *Project Leader*, Low-Power Standards

L. B. Elwell, *Project Leader*, High-Power Standards

R. F. Desch, *Project Leader*, Dissemination

General: Calorimetric reference standards used in low-power measurements are not suited for general-purpose power measurement, as they require specially built bolometer mounts. In addition, the labor involved in a single measurement amounts to about 8 man-hours.

The uncertainty is here defined as the limit of error (plus or minus) in the measurement.

Existing capabilities: Reference standards are limited in power range as shown because they are inherently differential devices with a practical range of about 1 to 100 mW. The bolometric technique most generally used is extended by the use of calibrated attenuators. At higher power levels, other techniques are used.

Five-year objective: The projection of standards and calibration services above 1 W is based upon:

(a) A static high-power calorimeter being developed for measurements from 10 to 1000 W.

(b) The use of calibrated low-power meters in combination with calibrated attenuators or directional couplers.

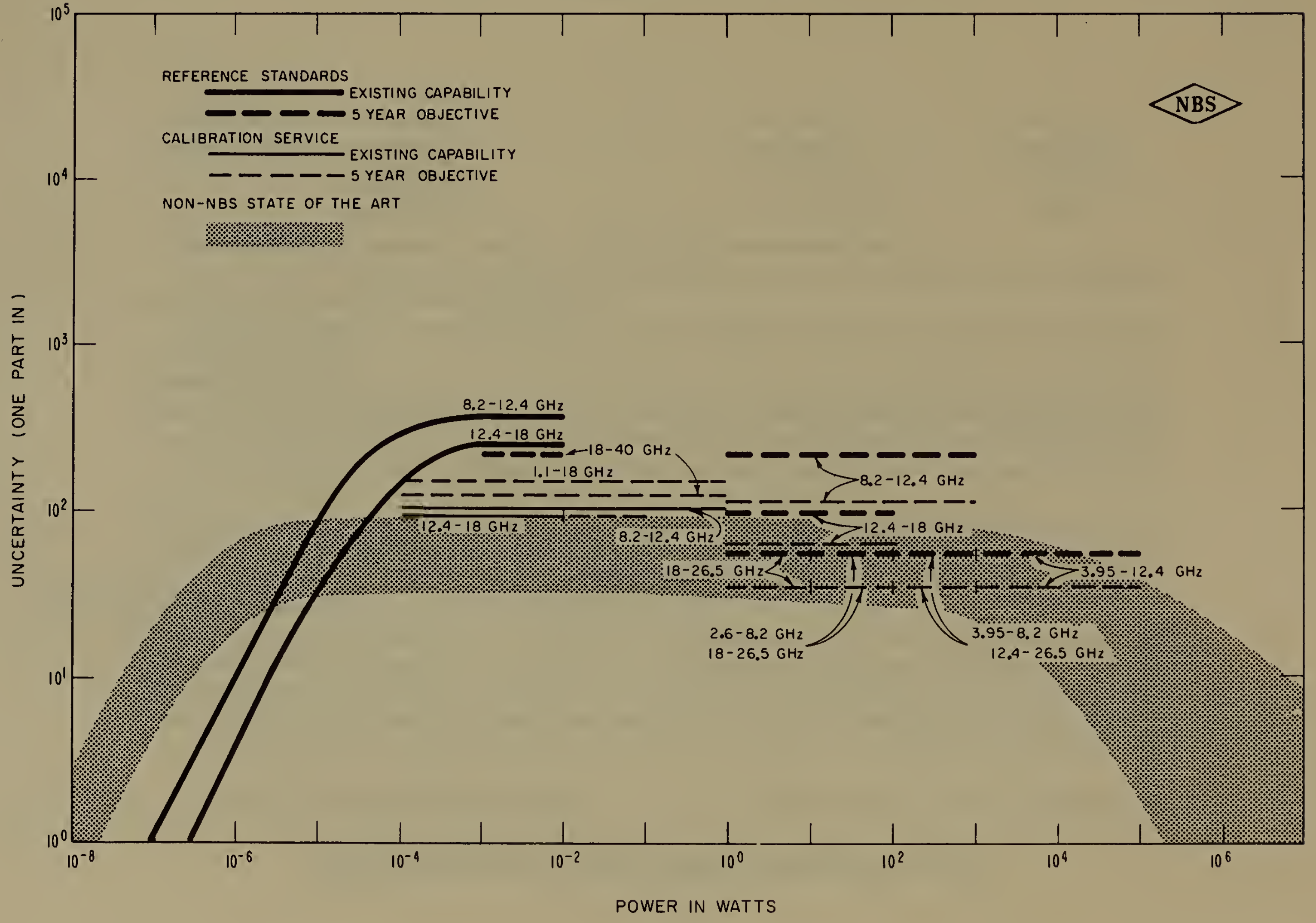
(c) The electron beam microwave power meter technique with an expected range of 10 W to the limitation of the waveguide.

(d) New techniques developed as the result of further study.

Not being a continuous-reading device, the high-power calorimeter is limited in application. With it, the total energy applied in a known time (approximately 3 min) is measured. The two other techniques mentioned have less limited application. We expect an uncertainty of a few percent with the electron beam technique. Its power range is expected to be 10 W to the limits of the waveguide. It should have decreasing value as a standard with increasing frequency, because of limitations presented by the decreasing physical sizes of the waveguides. The frequency range of the standards is, in general, limited by the narrow bandwidth of the waveguide. The design, development, and evaluation of each particular measurement technique must be repeated for each waveguide, size, and type. The calibrations are now performed at spot frequencies in a waveguide band. Applications exist, however, for swept-frequency calibrations.

State of the art: The non-NBS state of the art curve represents an estimate of the limit of the capabilities of modern commercial power-measuring instruments. It is based on manufacturers' claims. The lower edge of the band corresponds to measurements made at the highest and lowest frequencies. The upper edge corresponds to the middle frequencies.

MICROWAVE POWER
(WAVEGUIDE SYSTEMS)



High-Frequency Power (Pulse Coaxial Systems)

P. A. Hudson, *Project Leader*, Standards P. A. Simpson, *Project Leader*, Dissemination

General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. Individual uncertainties are assigned from direct observations or by estimation of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch.

Existing capability: The reference standard is a sampling-comparison system employing a solid-state radio frequency switch. The measuring system is moderately complex. A measurement is accomplished by comparing peak pulse power to accurately known continuous wave power of the same frequency. The continuous wave power is measured in terms of d–c power.

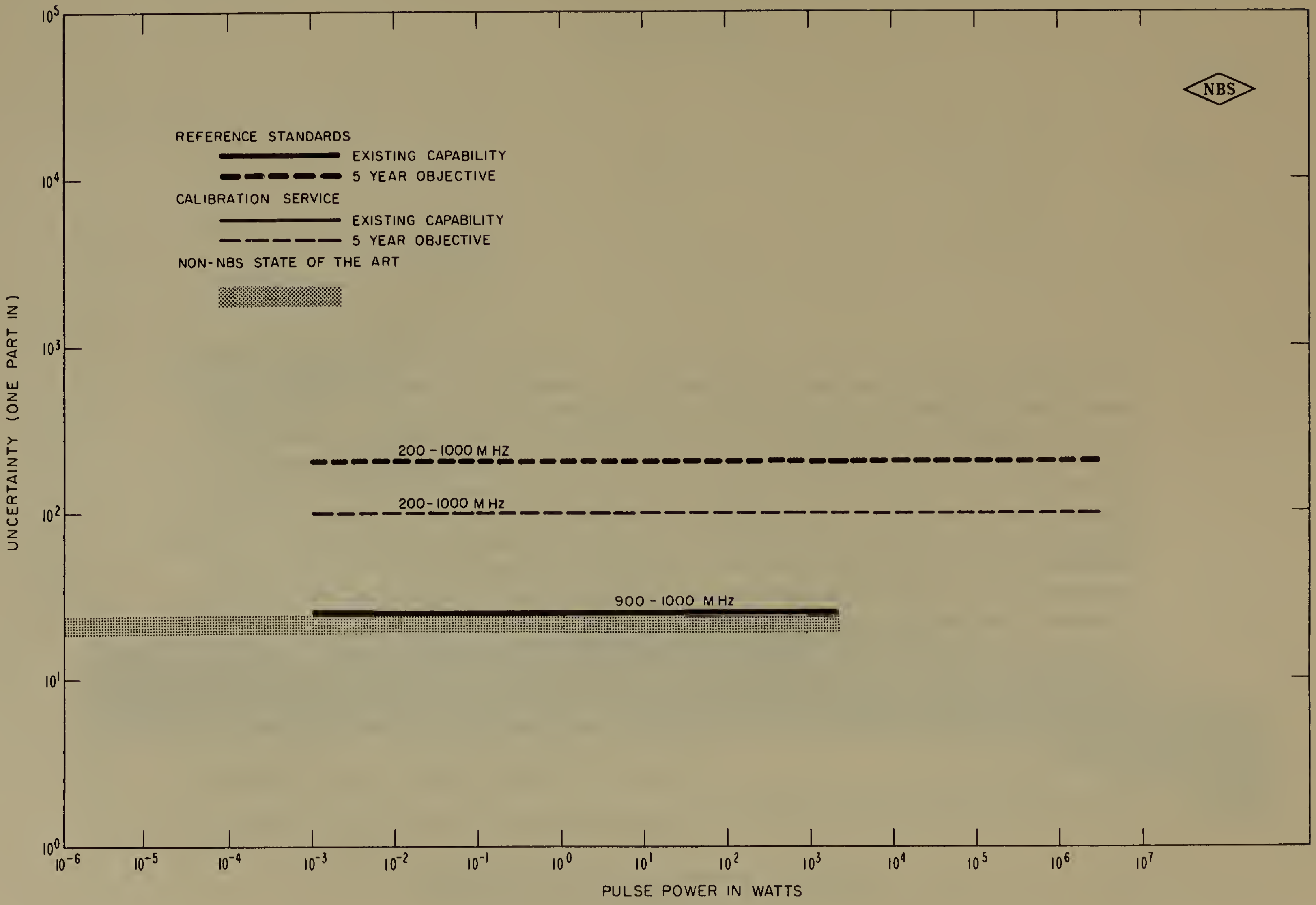
The range of the basic sampling-comparison method for peak pulse power measurement extends from 20 mW to 2 W. The upper limit is set by the power-handling capability of the switch. The total range of interest extends from 10^{-6} to 10^{6} W. Measurement and standardizing can be accomplished throughout the total range by using the basic system in conjunction with calibrated directional couplers.

Five-year objective: A calibration service is now under development for peak pulse powers up to 5 kW at frequencies around 1000 MHz.

State of the art: The upper limit of the non-NBS state of the art coincides with the capability of the present U.S. reference standard. Other typical uncertainties follow:

Organization	*Uncertainty*	*Range*
Commercial standards laboratory	1 part in 20 to 30	1 μW–0.5 W.
Russian standards laboratory	1 part in 30	mW levels.
U.S. commercial instruments	1 part in 10	1 mW–2 kW.

HIGH FREQUENCY POWER
(PULSE; COAXIAL SYSTEMS)



Pulse Power (Waveguide Systems)

N. T. Larsen, *Project Leader*, Low-Power Standards

R. F. Desch, *Project Leader*, Dissemination

L. B. Elwell, *Project Leader*, High-Power Standards

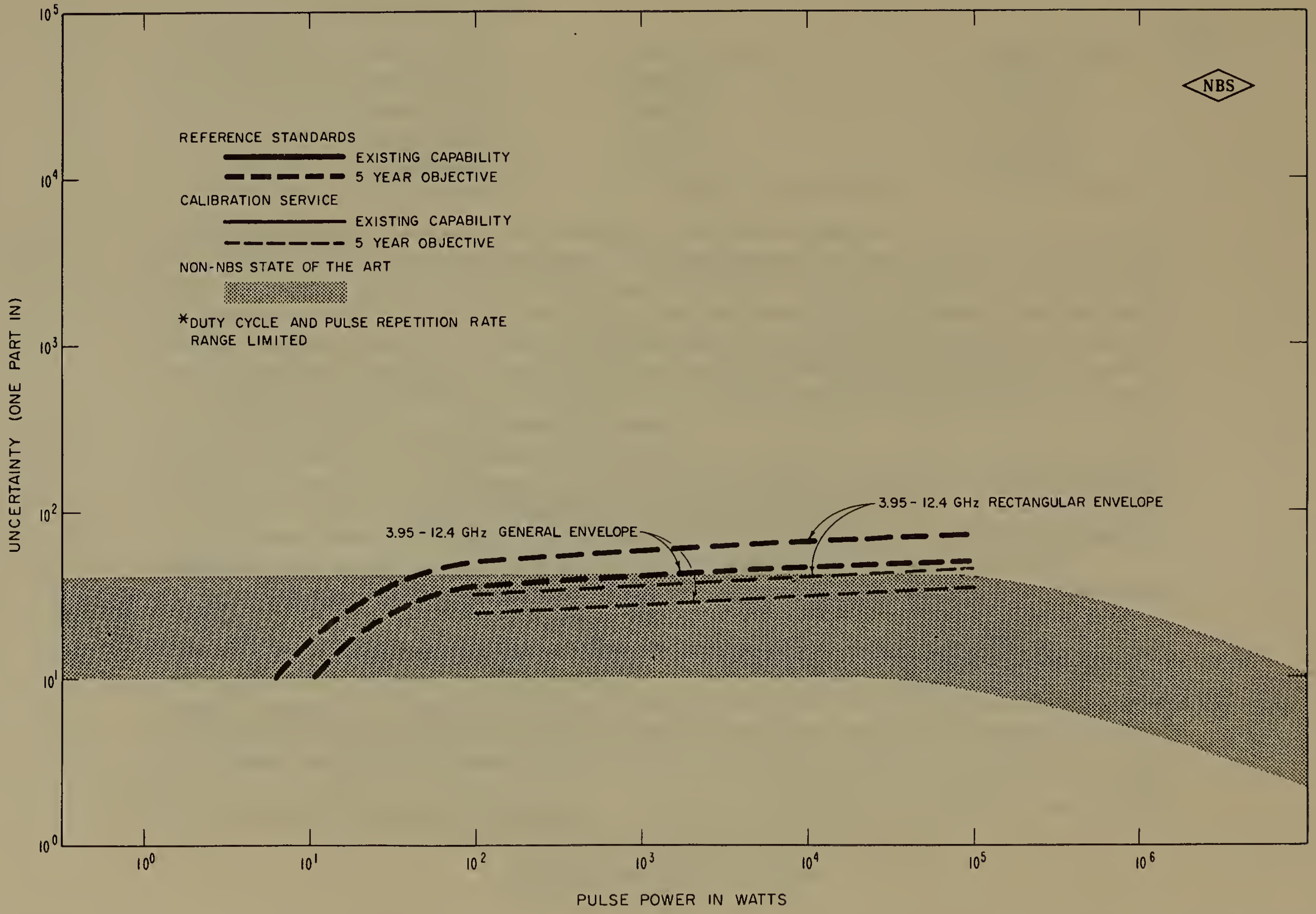
General: The design, development, and evaluation of a standard must, in general, be repeated for each waveguide size. The effects upon a measurement due to different repetition rates, duty cycles, modulation waveforms, and power levels must be considered.

Five-year objective: The projected standardization of the measurement of peak pulse power rectangular waveguides is based on completing the development of the electron-beam technique. Decreased uncertainty at higher power levels shown on the chart is characteristic of this technique.

The chart also represents further investigation of existing techniques—for example, measurement by comparing a demodulated waveform with an average power measurement. At present, a technique in coaxial lines has been developed for use below 1 GHz. The peak pulse power is measured by sampling the pulse for a short interval. This sample is compared to a similar sample from a known CW power source.

State of the art: The non-NBS state of the art band is an estimate of the capabilities of commercial equipment and of microwave laboratories. The lower limit of the band represents uncertainties of available commercial equipment. The upper limit represents the possible capabilities of microwave laboratories.

PULSE POWER
(WAVEGUIDE SYSTEMS)



High-Frequency Noise

M. G. Arthur, *Project Leader*, Standards H. E. Taggart, *Project Leader*, Dissemination

Existing capability: At present NBS has neither reference standards nor calibration service for random or impulse noise in the high-frequency range. Instruments and techniques for calibrating random noise generators and for measuring noise figure are under development. While noise has the units of power per unit bandwidth, it is often expressed as effective noise temperature, since the power per unit bandwidth is equal to Boltzmann's constant times the effective noise temperature.

Five-year objective: The uncertainties stated for the five-year objectives are for the worst-case situations; they are the sums of the magnitudes of individual contributions to uncertainty.

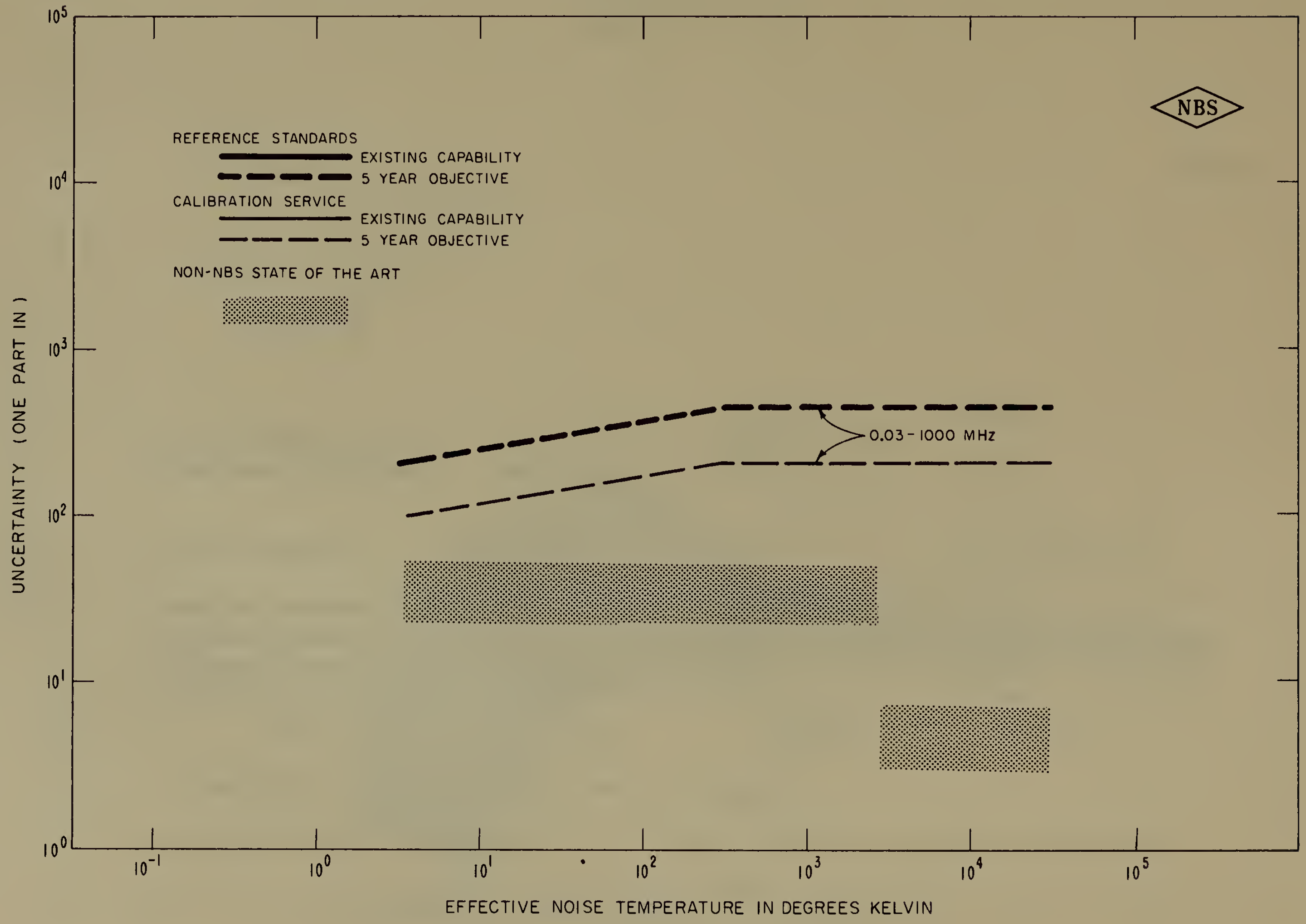
The lower temperature limit (approximately 4 °K) for the random noise standards is determined by cryogenic techniques which we intend to apply during the five-year period. The upper temperature limit (29,000 °K) is determined by the maximum ratings of present-day temperature-limited diode noise generators. Calibration service may cover temperature ranges outside these limits, but the need for this is not seen within this period.

State of the art: The non-NBS state of the art bands are based upon the claims of commercial manufactures, statements from other laboratories, and the experience of NBS–BL staff. Since no national reference standard of noise power presently exists, these data are only approximate. Further, noise generators have not been built to cover continuously the temperature range indicated, but there appears to be no reason why this could not be done. The low-temperature section of the band pertains to thermal noise generators. The high-temperature section pertains to shot noise. Typical uncertainties determined by instrument manufacturers follow:

Manufacturer	*Uncertainty*	*Effective noise temperature*	*Frequency range*
I	1 part in 50	77 °K*	0–1 GHz.
I	1 part in 50	373 °K*	0–1 GHz.
II	1 part in 100	300 °K*	0–1 GHz.
II	1 part in 50	2200 °K*	0–1 GHz.
II	1 part in 8	600–29,000 °K**	1 MHz–1 GHz.

*Thermal noise generators, 50 ohms.
**Temperature-limited diode, 50 ohms.

HIGH FREQUENCY NOISE
(COAXIAL SYSTEMS)



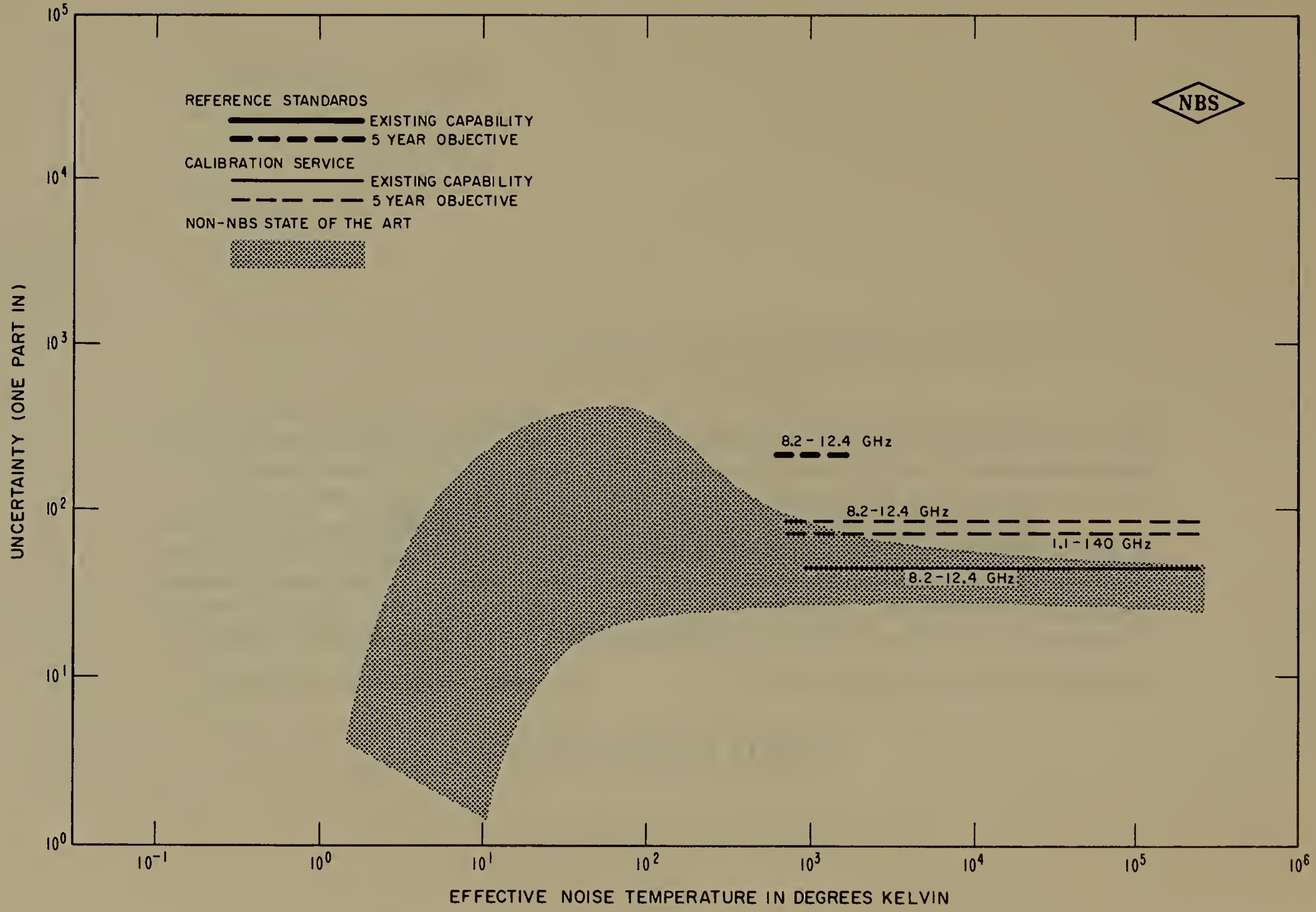
Microwave Noise (Waveguide Systems)

G. F. Engen, *Project Leader*, Standards　　C. K. S. Miller, *Project Leader*, Dissemination

State of the art: The band is based in part on the following:

Organization	*Uncertainty*	*Effective noise temperature*	*Frequency*
Commercial laboratory	0.5 °K	3.5 °K	4.17 GHz.
Commercial laboratory	0.2 °K	2.3 °K	2.39 GHz.
Commercial laboratory	1 °K	21 °K	2.39 GHz.
Commercial laboratory	1 °K	8 °K	2.39 GHz.
Aerospace industry	0. 2 °K	77.5 °K	0.96, 1.3, 2.295, and 9.25 GHz.
USSR standards laboratory	250 °K (2σ)	10,000 °K	1–10 GHz.
USSR standards laboratory	10 °K (2σ)	600–700 °K or 900–1000 °K	1–10 GHz.

MICROWAVE NOISE
(WAVEGUIDE SYSTEMS)



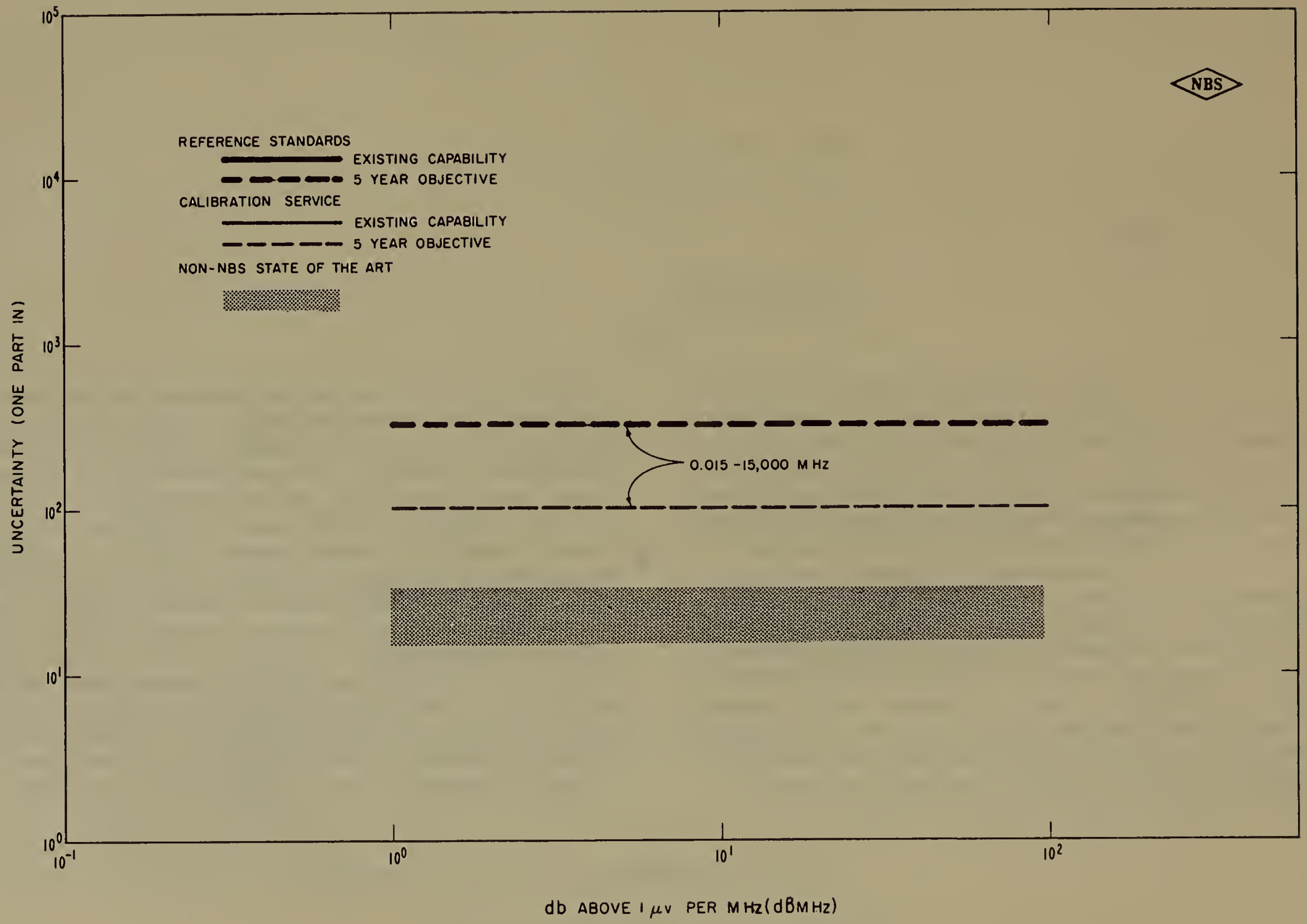
Impulse Spectral Density

M. G. ARTHUR, *Project Leader*, Standards H. E. TAGGART, *Project Leader*, Dissemination

Five-year objective: While impulse spectral density has the units of power per unit bandwidth, it is common practice to express it in decibels above 1 μV per megahertz. An impedance of 50 ohms is assumed. Standards and calibration service for impulse noise will not be pursued until late in the five-year period. Therefore, all information on these quantities is tentative at this time and will be revised as the need demands.

Non-NBS state of the art: Measurement uncertainties claimed by instrument manufacturers are ±0.5 dB over a range of 0 to 100 dB at any frequency from 10 kHz to 10 GHz. Requirements stated by an aerospace company are for a range of 0 to 100 dB with uncertainties of 0.25 dB from 10 kHz to 1 GHz, and 0.5 dB from 1 to 10 GHz.

IMPULSE SPECTRAL DENSITY



D–C Voltage and Voltage Ratio

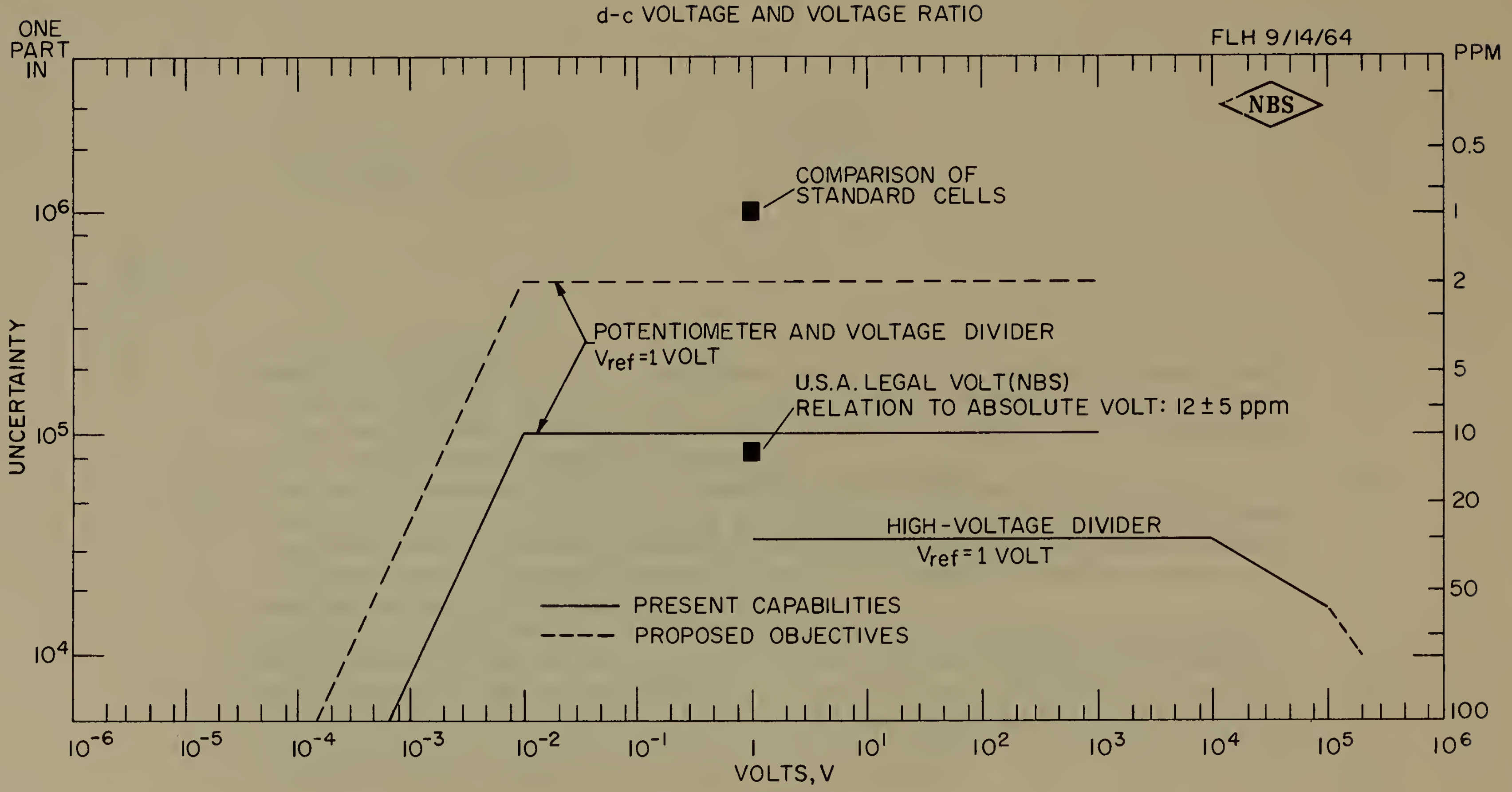
W. Hamer, F. K. Harris, F. L. Hermach, F. R. Kotter, C. Peterson, *Section Chiefs*

Mrs. B. A. Wickoff, *Project Leader*

State of the art: The absolute volt is realized by passing a "weighed" ampere through a Thomas-type 1-ohm resistor to measure emf of standard cells. The USA legal volt is estimated to be 12±5 ppm above the absolute volt; it is monitored in terms of the USA legal ohm and ampere to within ±1 ppm. Standard cells are calibrated to within ±1 ppm, relative to legal volt. Measurements above and below 1 volt are made with ratio standards (potentiometers and voltage dividers); estimated accuracies shown are of ratios V/V_{ref}, and include 3 standard deviations plus estimated systematic error, for calibration of ratio standards assumed to be ideal (perfectly stable and unaffected by environment). A calibration service is available for determination of the ratio factor of pulse voltage dividers under single-pulse conditions. The calibrating pulse has a rise time of about 1 μsec, a length of about 12.5 μsec, and an amplitude of from 20 to 100 kV. The accuracy depends on the performance of the divider being calibrated and is in the range of 1 to 3 percent.

Industry needs: More accurate legal volt, closer to absolute volt. Voltage balance analogous to Rayleigh current balance. Improved standard cells, lower temperature coefficient, not requiring hand carrying. Stable reference at 1000 V. Precision d–c dividers accurate to within ±2 ppm of ratio under full voltage (to 1 kV). Measurement of pulse voltages in microsecond range up to 200 kV. Measurement of 100 kV to within ±10 ppm or better for atomic energy-level scale. USA embarking on high-voltage d–c transmission; needs improved techniques of measurement.

Short-term objectives: Techniques and equipment for measuring Zener diode voltages. Study of voltage balance for absolute measurement. Study pressure and temperature coefficients, effect of D_2O, in standard cells. Attain accuracy to within ±2 ppm for potentiometers and for voltage dividers under full voltage (to 1 kV). Improvement of the accuracy of high-voltage pulse-amplitude measurement to 0.5 percent and extension of the range to 300 kV.


d-c VOLTAGE AND VOLTAGE RATIO
FLH 9/14/64
NBS
ONE PART IN
UNCERTAINTY
10^6
10^5
10^4
PPM
0.5
1
2
5
10
20
50
100
COMPARISON OF STANDARD CELLS
POTENTIOMETER AND VOLTAGE DIVIDER
V_{ref} = 1 VOLT
U.S.A. LEGAL VOLT (NBS)
RELATION TO ABSOLUTE VOLT: 12 ± 5 ppm
HIGH-VOLTAGE DIVIDER
V_{ref} = 1 VOLT
PRESENT CAPABILITIES
PROPOSED OBJECTIVES
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
10^6
VOLTS, V

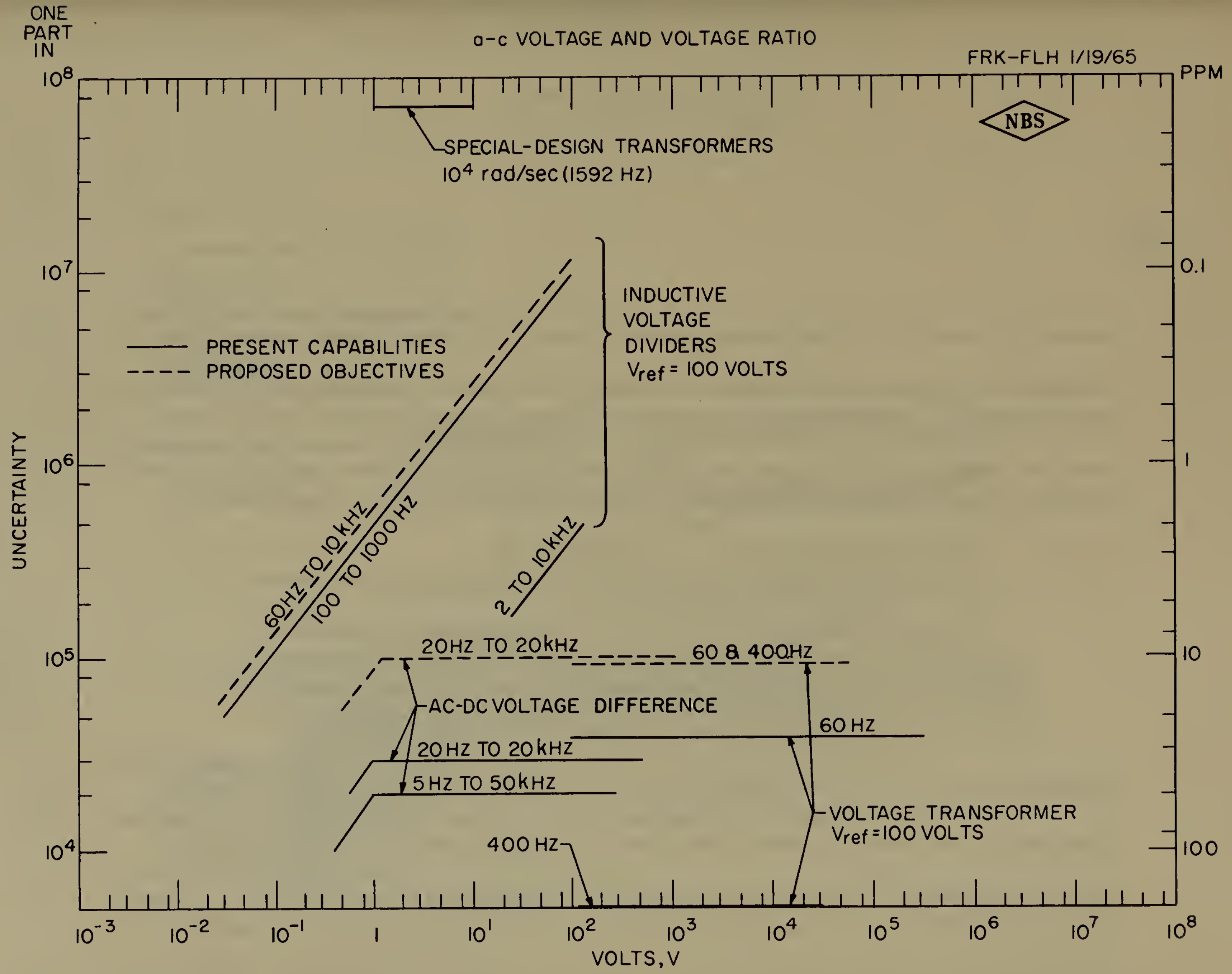
A–C Voltage and Voltage Ratio

F. L. Hermach, F. R. Kotter, W. W. Scott, Jr., *Section Chiefs*

State of the art: A–c voltage measurements at power and audio frequencies are made with d–c potentiometers, ac–dc difference standards, and a–c voltage dividers. Estimated accuracies shown are for calibration of ideal reference standards (perfectly stable and unaffected by environment) and include 3 standard deviations plus estimated systematic error; accuracy of ratio V/V_{ref} is shown for ratio standards (transformers and dividers).

Industry needs: Developments in electronic standards demanding more accurate measurements. Ac–dc transfer standards needed for peak and average values as well as improved transfer standards for rms values. Better calibration accuracy for voltage transformers 60 to 400 Hz. Extension of low-voltage dividers to 10 kHz. USA moving to higher a–c transmission levels; need for calibration of transformers and capacitor voltage dividers.

Short-term objectives: Improved ac–dc transfer via thermal voltage converters and differential thermocouple principle. High-voltage transformers to within ±10 ppm, 60 to 400 Hz. Low-voltage dividers 60 Hz to 10 kHz. Ac–dc transfer standards for peak and average values. Study of capacitor dividers.



a-c VOLTAGE AND VOLTAGE RATIO

High-Frequency Voltage (CW Coaxial Systems)

M. C. Selby, *Project Leader*, Standards F. X. Ries, *Project Leader*, Dissemination

General: The stated uncertainty is the estimated maximum deviation from an algebraic mean based on (1) agreement between independent analytically sound methods, (2) reproducibility, and (3) a certain safety factor.

The major existing limitations on accuracy are (1) the dynamic instability of the electronic equipment, e.g., power sources, and (2) ambient temperature variations.

Existing capabilities: The reference standards and instruments used to cover the ranges shown are as follows:

Thermal voltage converter: 0.1 to 300 V, 30 kHz to 30 MHz
Voltage bridges: 20 mV to 1.2 V, 30 kHz to 1000 MHz
Cathode ray technique: 5 to about 250 V, 30 kHz to 40 MHz
Voltage bridge and attenuator: 1 to about 250 V, 30 kHz to 100 MHz;
1 to 100 V, 30 kHz to 300 MHz
Micropotentiometers: 0.1 to 10^5 μV, 30 kHz to 700 MHz; 10 to 10^5 μV,
700 to 1000 MHz

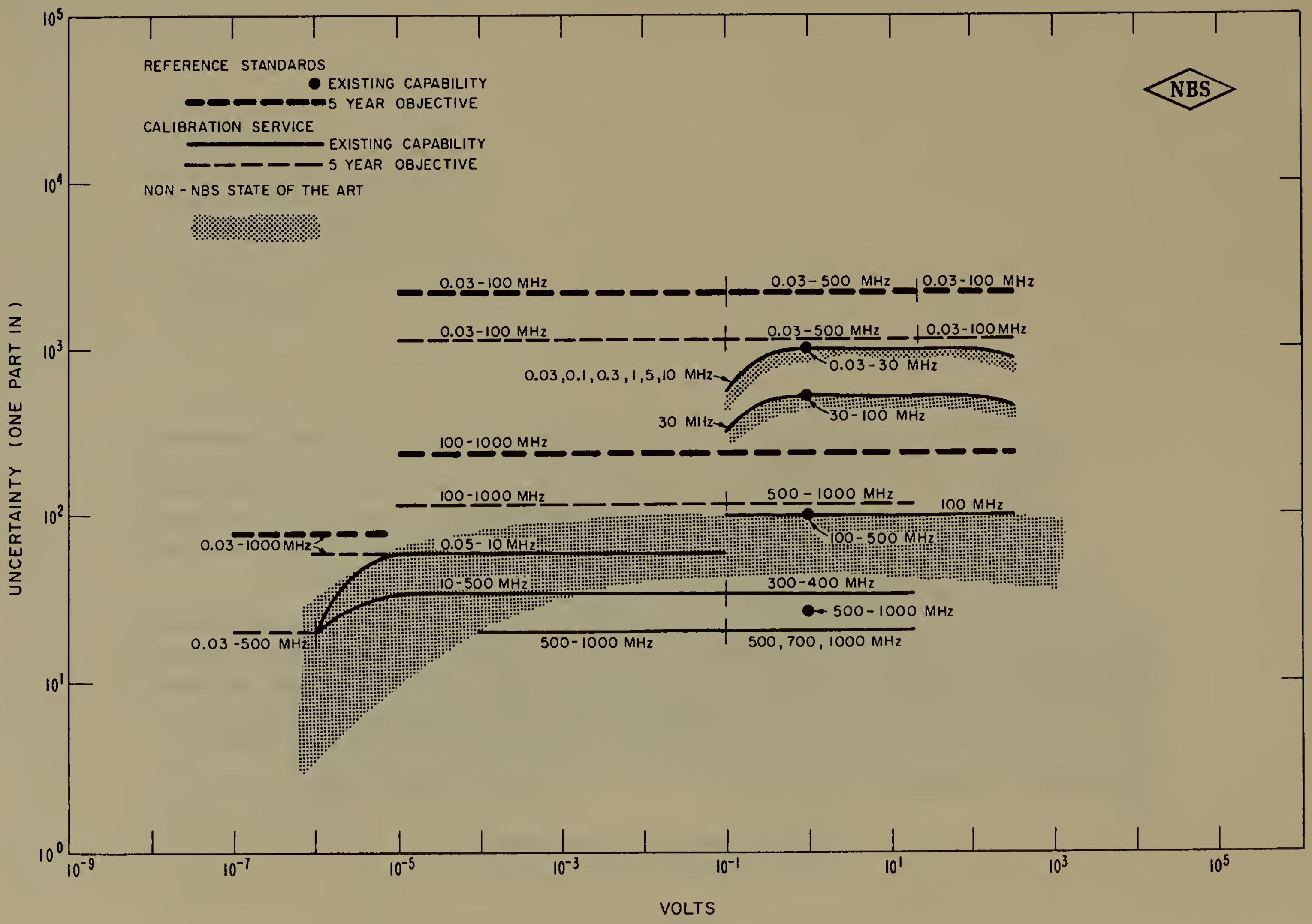
Five-year objective: The basic principles of existing techniques seem applicable to the nonexisting ranges, but the instrumentation and elimination of additional sources of error (negligible at lower frequencies) will require considerable thought and effort.

State of the art: The state of the art bands are based on (1) NBS capability, (2) claims of other laboratories, both foreign and domestic, and (3) claims and specifications of commercial instruments.

Reference:

IRE Technical Committee Report on the State-of-the-Art of Measuring Sine-Wave Unbalanced RF Voltage, *Proc. IRE* **51**, *No. 4, 575–580 (Apr. 1963).*

HIGH FREQUENCY VOLTAGE
(CW, COAXIAL SYSTEMS)



Microwave Voltage (CW)

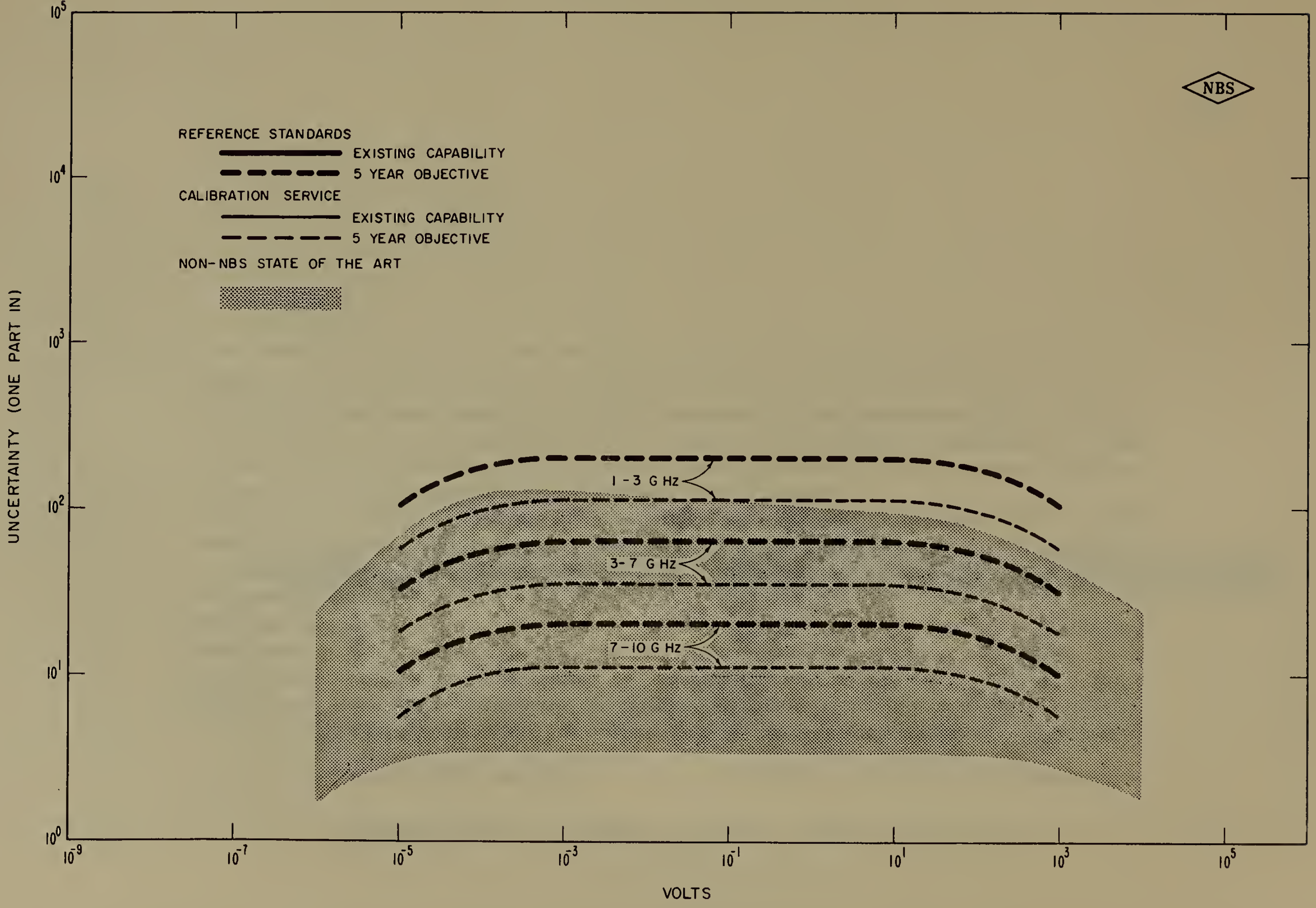
M. C. Selby, *Project Leader*, Standards F. X. Ries, *Project Leader*, Dissemination

Existing capability: No standards presently exist at NBS for CW voltage above 1 GHz.

State of the art: The non-NBS state of the art band is based on claims of other laboratories and claims and specifications of commercial instruments. The upper and lower limits of this band represent uncertainties at frequencies ranging from 1 GHz to 15 GHz respectively. Typical data on which the band is based follow:

Organization	*Uncertainty*	*Voltage range*	*Frequency*
Instrument manufacturer	1 part in 60	0.2–1 V	1 GHz.
Electronic manufacturer	1 part in 10	0.5 mV–1 V	3.5 GHz.
Commercial laboratory	1 part in 5	0.2–3 V	2 GHz.
Research laboratory	1 part in 40	0.05–10 V	3–10 GHz.
Instrument manufacturer	1 part in 5	0.1 mV–25 V	2–10 GHz.

MICROWAVE VOLTAGE (CW)



High-Frequency Voltage (Pulse Coaxial Systems)

P. A. HUDSON, *Project Leader*, Standards P. A. SIMPSON, *Project Leader*, Dissemination

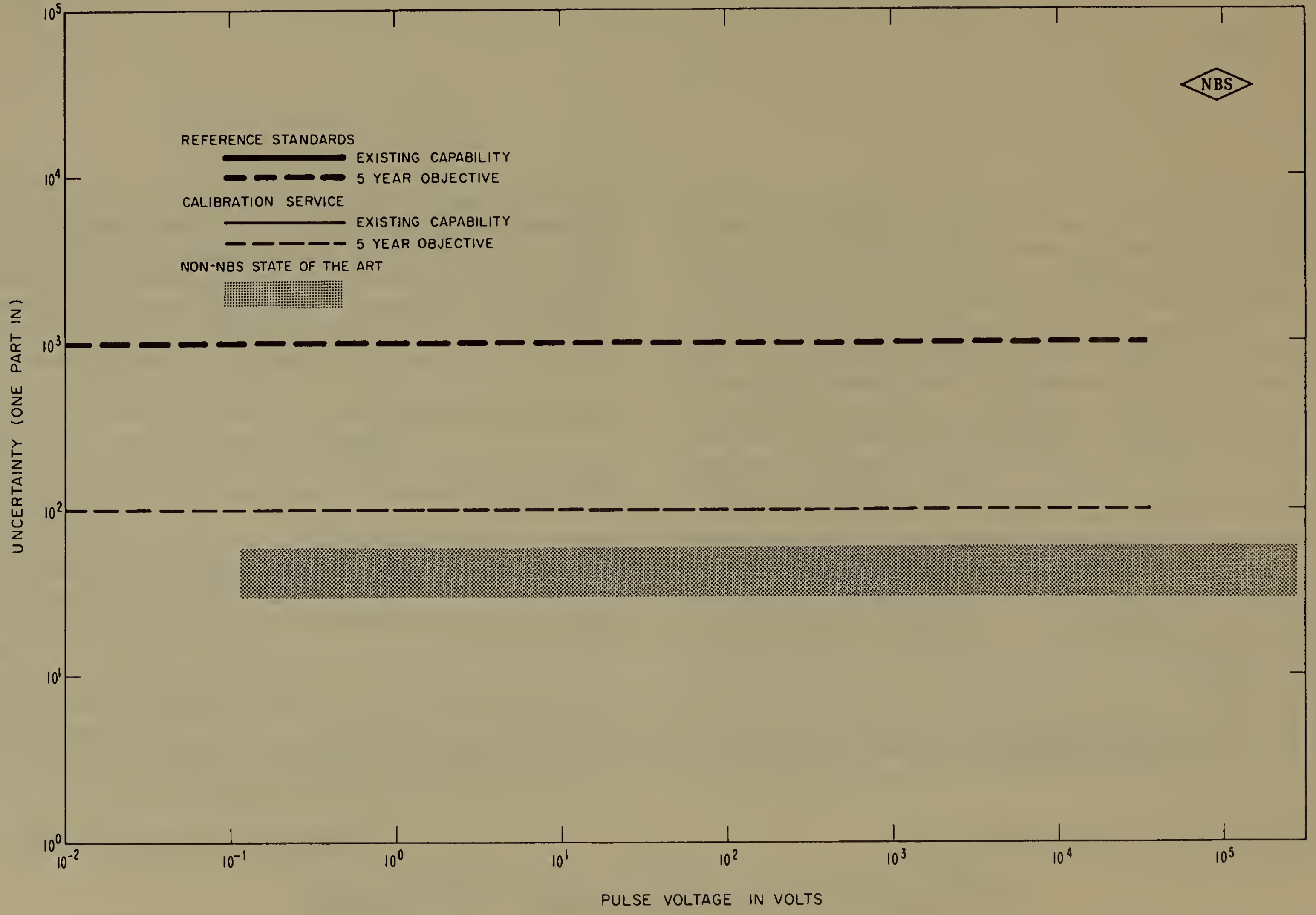
General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. The individual uncertainties are assigned from direct observations or by estimation of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch.

Existing capability: At present, NBS has only a limited service for the ratio factor of pulse voltage dividers under single-pulse conditions (see p. 30).

Five-year objective: It is expected that standards will be developed for the measurement of pulse risetimes and other quantities needed in fast-pulse instrumentation.

State of the art: The non-NBS state of the art band is derived from manufacturers' advertisements, accuracies quoted in scientific papers, and direct communications. Uncertainties of 1 part in 30 to 50 for peak pulse voltages of 1 to 350 kV are needed for linear accelerator work. U.S. commercial instrument manufacturers claim 1 part in 20 to 50 for peak pulse voltages of 0.1 to 1 kV.

HIGH FREQUENCY VOLTAGE
(PULSE; COAXIAL SYSTEMS)



High-Frequency Field Strength (Near-Field Region)

F. M. Greene, *Project Leader*, Standards

H. E. Taggart, *Project Leader*, Dissemination

General: The near-field region of a simple transmitting antenna is here considered to extend out to a distance of about one wavelength from the antenna.

Calibrations are made in terms of sinusoidally time-varying (CW) electric or magnetic field components parallel to the axis of the antenna.

Power density represents average power flow at any point in the field, i.e., the real part of the Poynting vector.

The pulse factor is the quantity by which the CW calibration factor is multiplied to obtain the pulse calibration, for specified pulse characteristics.

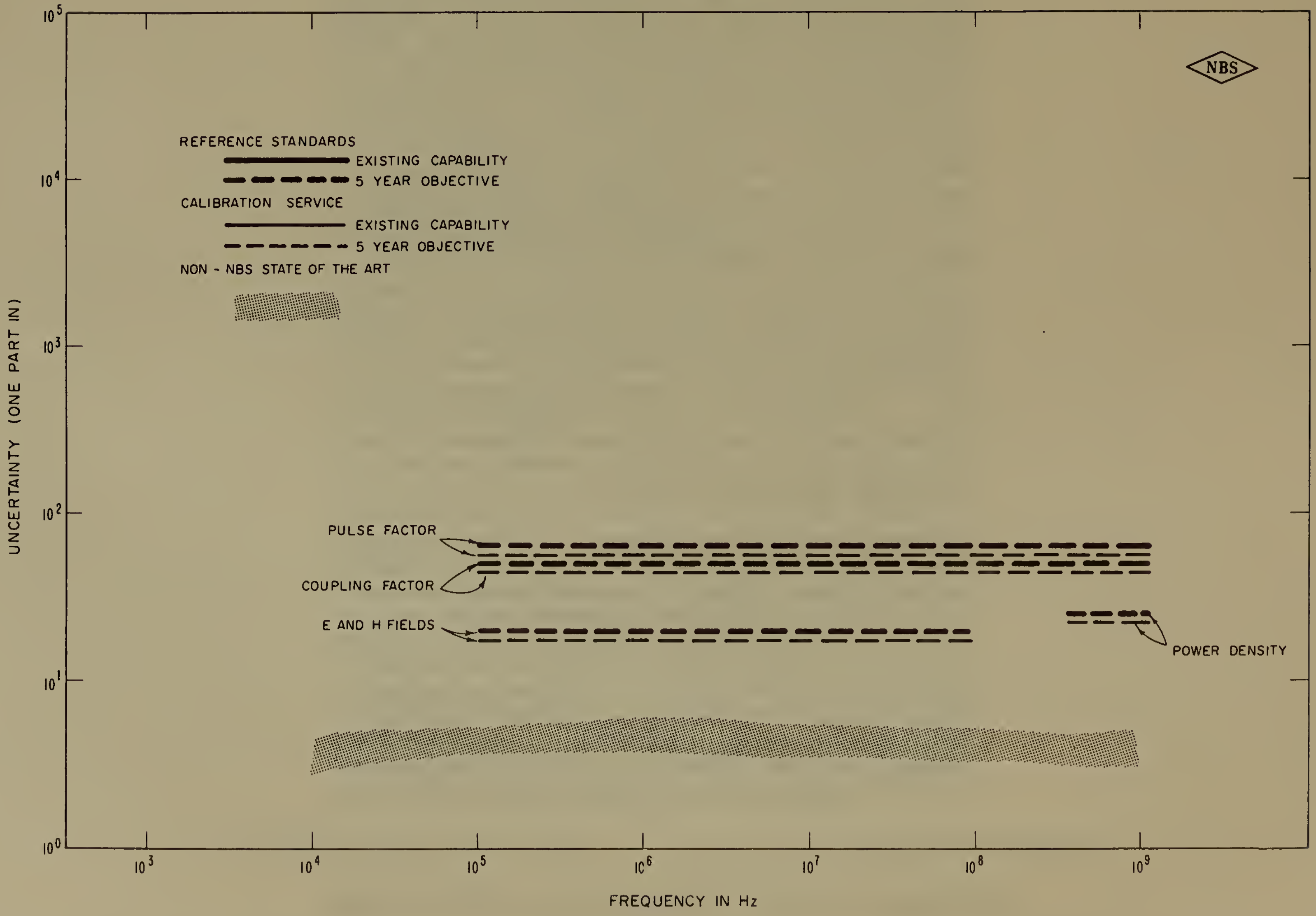
The coupling factor is the attenuation introduced between the measuring antenna and the receiver to permit a high-level field measurement in terms of a low-level calibration.

Existing capabilities: There are no existing NBS capabilities in the near-field region areas listed.

Five-year objectives: The proposed uncertainty of the E and H field standards (five-year objective) is 1 part in 20, or 5 percent, as indicated by the ordinate of the chart. The uncertainty statements represent our best estimate of the present needs that can be realized in the time specified. The anticipated sources of systematic errors are similar to those listed for the loop and dipole antenna standards under *High-Frequency Field Strength.* The proposed frequency range for E and H field standards is shown as 0.1 to 100 MHz. Measurements at lower frequencies than this may be difficult to achieve because of greater sensitivity requirements for the H field and because of a higher impedance requirement on voltmeters to minimize loading of short dipoles. There may be difficulty in measuring H fields at frequencies higher than 100 MHz because of increasing uncertainty in the frequency corrections for loop antennas. Power-density standards are not shown below 300 MHz because of the uncertainty of the requirements at the present time. We anticipate an increasing complexity in measuring power density with decreasing frequency in the near zone. Also, the actual usefulness of power-density measurements at these lower frequencies has not been fully analyzed. Pulse-factor and coupling-factor standards are shown over the range from 0.1 to 1000 MHz to complement the E, H, and power-density standards. The proposed calibration uncertainty is essentially the same as that of the standards, and is as shown on the chart. The proposed frequency range of calibration is essentially the same as that for the standards as that outlined above.

State of the art: The present state of the art is shown by the shaded area on the chart. It is an estimate based entirely on discussions with personnel of other laboratories, and has an uncertainty of the order of 2 to 3 dB. Field strength is often stated as a coefficient or gain, i.e., a numeric.

HIGH FREQUENCY FIELD STRENGTH, NEAR FIELD REGION



High-Frequency Field Strength (Antenna Coefficient)

F. M. Greene, *Project Leader*, Standards H. E. Taggart, *Project Leader*, Disseminatio

General: Antenna coefficients are determined for the types of antennas discussed below, in the frequency range 30 Hz to 1000 MHz. In general, the *antenna coefficient* is a *calibration factor*, i.e., a *proportionality constant*, by which the indication of the field-strength meter must be multiplied to obtain the magnitude of the unknown field strength, E or H, parallel to the axis of the antenna at a given frequency. Some instruments are direct-reading, so that the *antenna coefficient* is essentially unity. In other types of instruments, the coefficient can be expressed either as a factor or in decibels, relative to an arbitrary reference incorporated in the instrument design. Calibrations are made for sinusoidally time-varying (CW) fields only.

Field-strength meters employing shielded loop antennas are used over the frequency range from 30 Hz to about 30 MHz and measure magnetic field strength, H. However, it is standard practice to express the calibration in terms of the electric field, E, that would exist in the case of a free-space plane wave ($E=120\pi H$).

At frequencies in the range 30 to 1000 MHz, field-strength meters generally employ half-wave dipoles. These are calibrated in terms of the component of electric field, E, parallel to the axis of the dipole.

Certain types of field-strength meters use a short (vertical) rod antenna, working against the metal case of the instrument, to measure vertically polarized electric field strength. However, NBS has no facilities, at present, for calibrating this particular type of antenna.

The "*standard-antenna*" method is used to evaluate the component of field strength parallel to the axis of a receiving antenna in terms of (a) the voltage induced in the antenna by this component of the field, and (b) the dimensions and form of the antenna.

The "*standard-field*" method is used to generate a known field in terms of (a) the current flowing at reference terminals of the antennas, (b) the dimensions and form of the transmitting antenna, (c) the distance to the point at which the field is to be evaluated, and (d) the effect of the ground.

Existing capability: The available accuracy of the reference standards and calibration services is given by the ordinate. In the case of the existing reference standards for loop antennas below 5 MHz, e.g., the uncertainty shown is 1 part in 30, or 3 percent. In general, the specified uncertainty in the reference standards is twice the average percentage difference between the "*standard-antenna*" and "*standard-field*" techniques of evaluation. The principal systematic errors involved in existing standards result from uncertainties in the following:

(a) *Loop antennas:* current distribution, proximity effects, linear dimensions, distributed capacitance.

(b) *Dipole antennas:* current distribution, end effect, crystal voltmeter, ground effect, linear dimensions.

As stated above, the uncertainty in the field-strength standards is determined from the difference between the *standard-antenna* and *standard-field* techniques of evaluation. However, in the normal calibration of field-strength meters it is often more convenient or practical to use one technique than the other. For example:

(a) The *standard-field* technique is used below 30 MHz for the calibration of loop antennas.

(b) Above 30 MHz the *standard-antenna* technique is used for calibrating dipole antennas.

In (a), the sensitivity and accuracy of the standard-antenna technique are not sufficient at present for use in regular calibrations. In (b), the uncertainty and nonuniformity of the ground properties, and difficulties in accurately determining them, preclude the use of the standard-field technique above 30 MHz, except as an intercomparison with the standard-antenna technique at spot frequencies, during initial development of the standards.

The accuracy available in calibration is as shown on the accompanying chart.

Loop antenna standards and calibration services are not available above 30 MHz for the following reasons: (a) uncertainty of frequency corrections, (b) uncertainty in evaluating proximity effects, and (c) no demand for service for these reasons.

Dipole antenna standards and calibration are not available below 30 MHz because of (a) cumbersome length of self-resonant antennas, (b) uncertainty in evaluating close electrical proximity to the ground, and (c) no demand for service for these reasons.

Five-year objectives: The planned improvement in reference standards and calibration service in the next five years as is follows:

(a) *Loop antennas* (magnetic field). It is proposed to reduce the uncertainty from 3 percent to 2 percent over the range from 30 Hz to 5 MHz; and from 5 percent to 2 percent over the range 5 to 30 MHz.

(b) *Dipole antennas* (electric field). There is a definite need for reduction of uncertainty in this area over the frequency range 30 to 1000 MHz. It is proposed to reduce the uncertainty from 12 to 6 percent over the next five years.

State of the art: The state of the art is shown by the shaded area on the chart. It is based on considerations of (a) NBS capability, (b) roundrobin calibrations of instruments performed by NBS and other leading laboratories, and (c) claims made by other standards laboratories, both foreign and U.S., and both government and private.

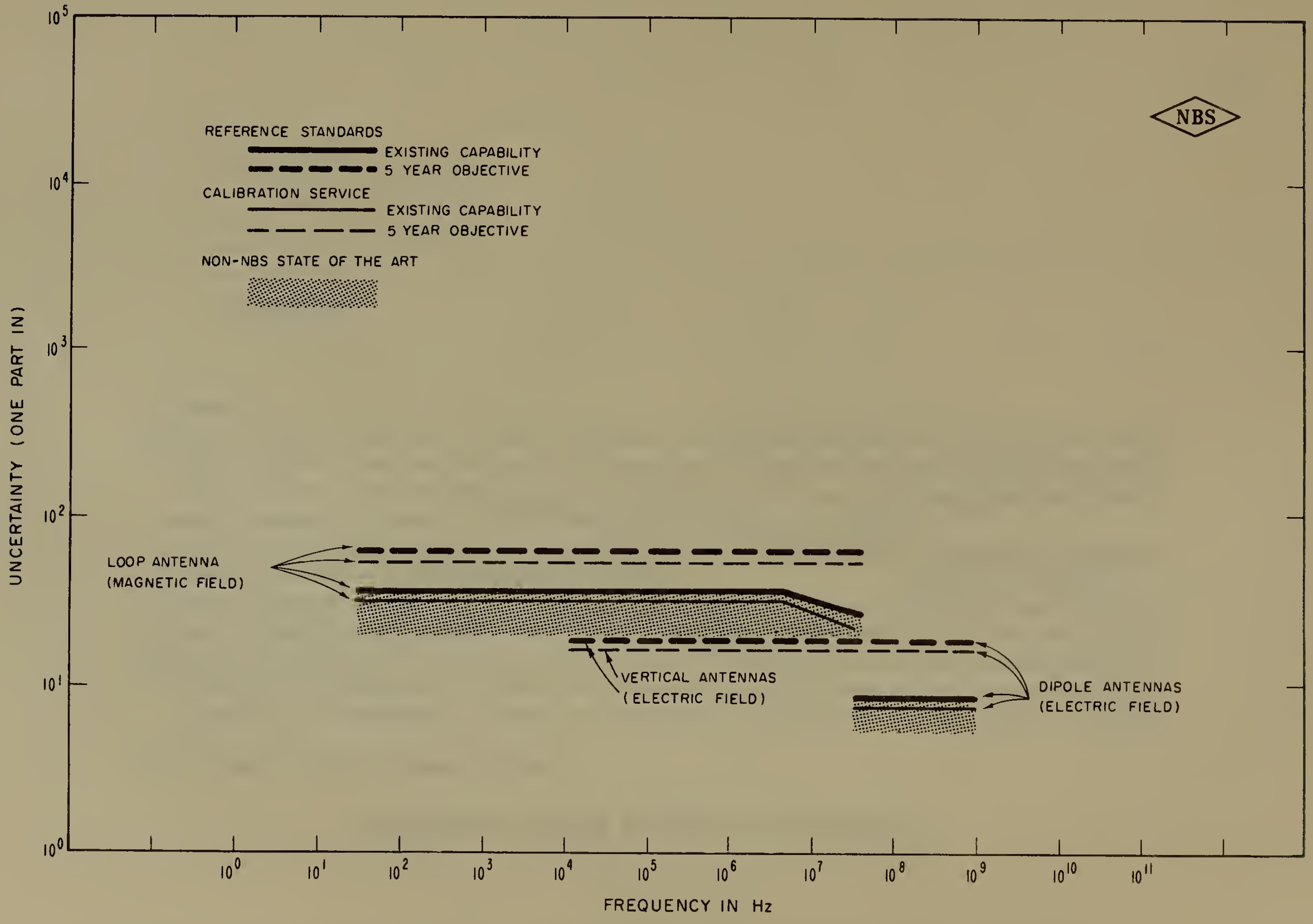
The ranges covered are as follows:

30 Hz to 30 MHz. Standard-field technique for calibrating loop antennas (magnetic field). Accuracy: 30 Hz to 5 MHz—3 percent; 5 MHz to 30 MHz—5 percent.

30 to 1000 MHz. Standard-antenna technique for calibrating dipole antennas (electric field). Accuracy—12 percent.

The accuracy of the loop-antenna standards is degraded to 5 percent between 5 and 30 MHz from the 3-percent figure that applies to frequencies below 5 MHz. This is because of the increasing uncertainty in evaluating the frequencies above 5 MHz. The limits of applicability of particular operating techniques are described above. In addition, the use of dipole techniques appears to have an upper frequency limit of about 1000 MHz. This is because of the difficulty in accurately measuring current and voltage (as such, necessary to this technique) at frequencies much above 1000 MHz.

HIGH FREQUENCY FIELD STRENGTH
(ANTENNA COEFFICIENT)



Microwave Field Strength (Horn Gain)

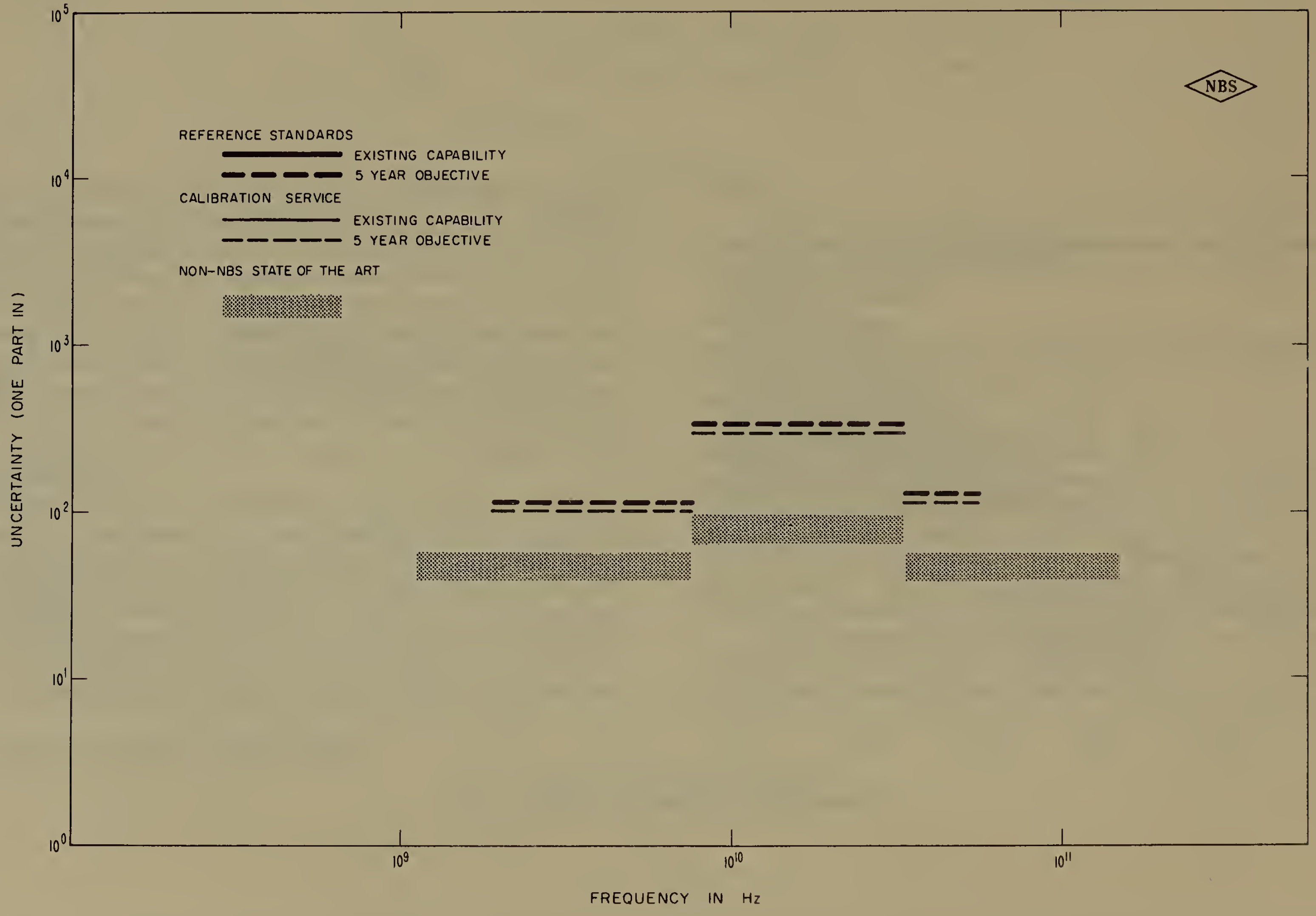
R. R. Bowman, *Project Leader*, Standards

General: The uncertainty of horn gain calibrations depends on waveguide size. At long wavelengths the calibration uncertainty is imposed by the dimensions of the anechoic chamber, while at sufficiently short wavelengths the uncertainty is imposed by the small waveguide dimensions. A more detailed graph, therefore, would show a different uncertainty for each frequency band. Since the variations are not great over the indicated range of frequencies, only three levels suggesting the limits of the uncertainties are shown.

Five-year objectives: Achievement of the objectives is contingent on the availability of a finished anechoic chamber by the end of Fiscal Year 1965.

State of the art: Standard gain horns provided by industry are usually not calibrated experimentally. These horns are constructed to dimensions specified in Naval Research Laboratory Report No. 4433. The limits of error established by NRL Report 4433 are ±0.3 dB, or about 7 percent.

MICROWAVE FIELD STRENGTH
(HORN GAIN)



Calibration of Standard Resistors

H. Krider, D. Ramaley, *Project Leaders*

All resistors having nominal values up to 10^{12} ohms are calibrated by comparison with NBS working standards. By means of accurately established ratios, these working standards are evaluated periodically in terms of the legal unit of resistance maintained with a highly stable group of Thomas-type 1-ohm resistors. The legal unit approximates very closely the defined unit, the absolute ohm. Resistors having values of 10^{10} ohms and above may be calibrated in terms of the units of capacitance and time using the capacitor discharge method.

Precision resistors in oil, at 25.0 °C, Wenner Bridge: In the range 10^{-4} to 10^{3} ohms, the solid points on the accompanying chart indicate currently *available* accuracies (uncertainties) listed in the fee schedule for measurements in terms of the legal unit. The total uncertainties are based on estimated limits of systematic error, plus three times the standard deviation for random errors. These total uncertainties pertain to calibration measurements made for the public by established methods on commercially made, high-quality standard resistors, and at an established fee. The open circles indicate the maximum attainable accuracy (minimum uncertainty state-of-the-art measurements) which can be made by painstaking procedures with great effort on "ideal" resistors.

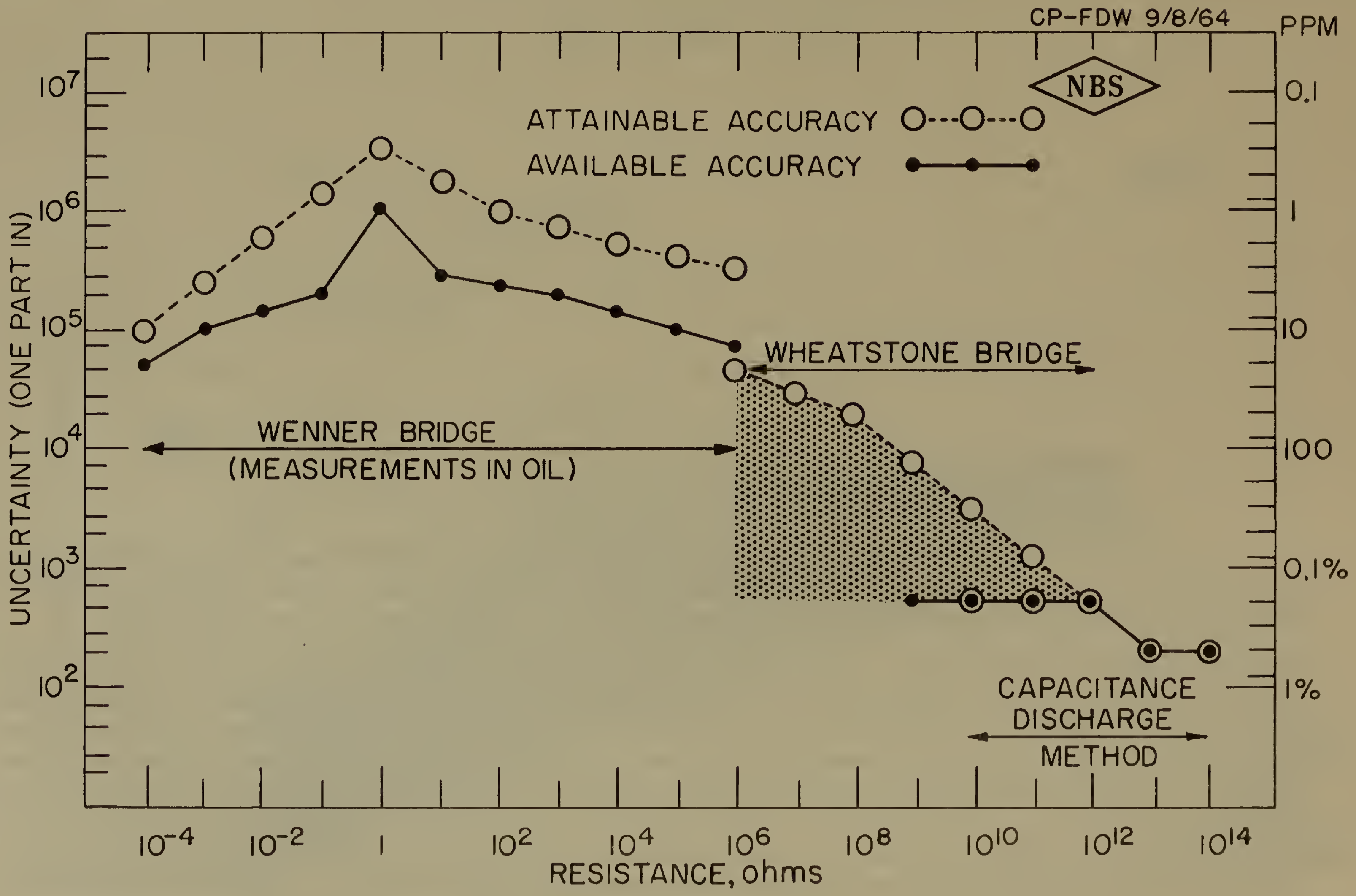
Two-terminal resistors, 10^{3} to 10^{12} ohms, in air, Wheatstone Bridge: Open circles connected by dotted line show accuracy attainable under ideal conditions. In range 10^{3} to 10^{12} ohms, available accuracy depends largely on the characteristics of the resistor being calibrated and will be in the shaded area. High-quality wire-wound resistors up to 10^{8} ohms having reasonably low temperature coefficients may be calibrated regularly with an uncertainty not exceeding a few hundredths of one percent. Acceptable metal film or deposited carbon "standards" 10^{8} to 10^{12} ohms are calibrated with a stated uncertainty of 0.2 percent.

Resistors 10^{10} ohms and above, capacitance discharge method: In this area the attainable and the available accuracies coincide; "ideal" resistors do not exist.

Short-term objectives:

1. To increase the available accuracy in the calibration of 10^{4} ohm standards approaching the characteristics of "ideal" resistors.
2. To increase the attainable accuracy in high resistance measurements.

CALIBRATION OF STANDARD RESISTORS



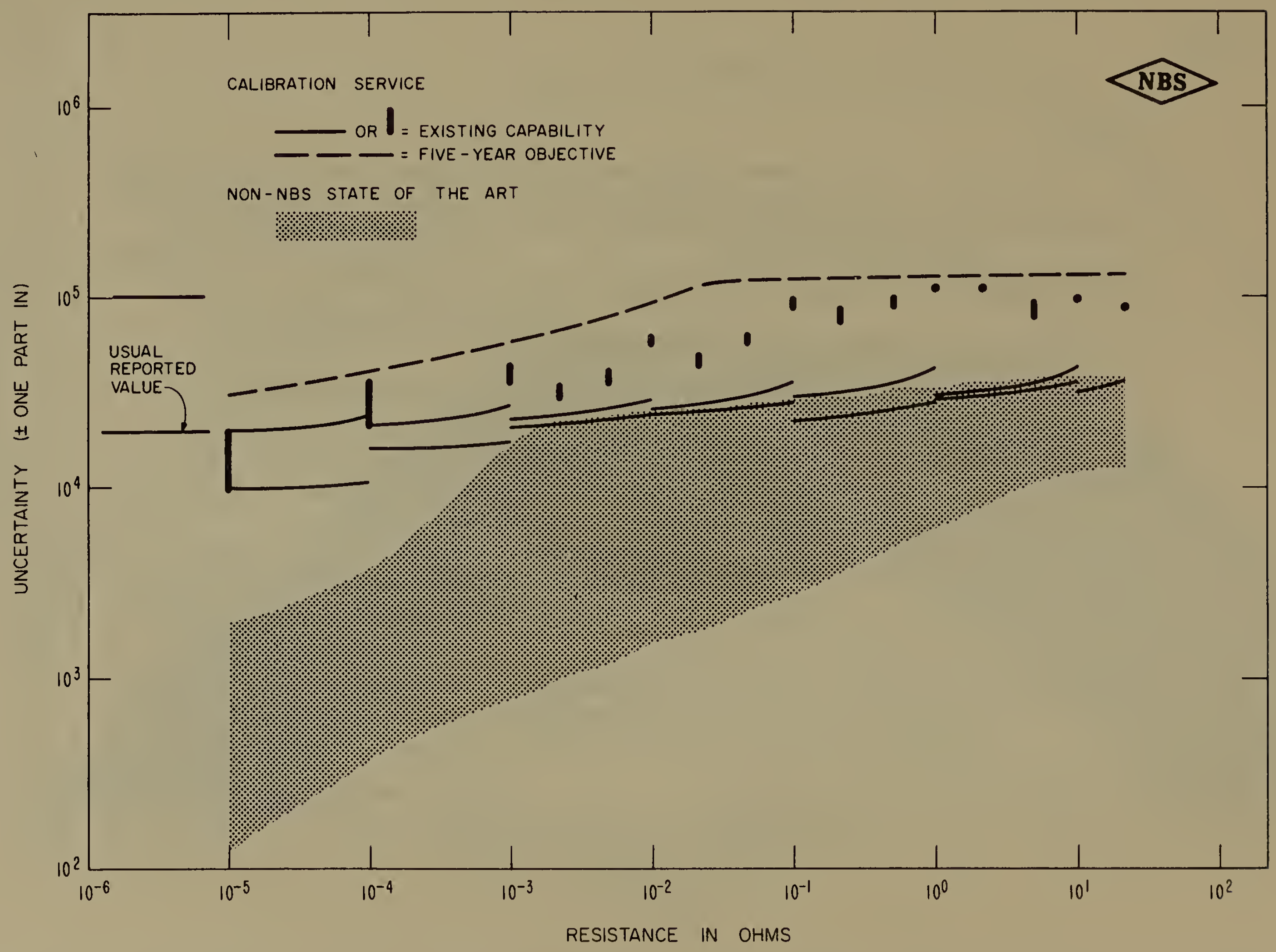
DIRECT CURRENT RESISTANCE (Shunts)

P.H. Lowrie, Jr. - Project Leader, Dissemination

Existing Capabilities: Current shunts are normally measured at both 20% and 100% of rated current. (In general, rated current varies inversely with resistance value.) At the NBS Boulder Laboratories, shunts may be measured at currents up to 1000 amperes. The solid lines indicate the measurement capabilities at reduced (upper line) and rated (lower line) currents. Certain values of resistance (multiples of 1, 2, and 5 ohms) can be measured with smaller uncertainties, as shown by the bars and dots. The upper end of the bars correspond to measurements at 20% of rated current, and the lower ends correspond to measurements made at 100% of rated current. The increased uncertainty at 100% of rated current is the result of heating of bridge components.

This graph shows measurement capabilities rather than reported values of uncertainty. The value reported reflects the dependence of the shunt undergoing calibration upon the ambient conditions as well as the capabilities of the measurement system.

DIRECT CURRENT SHUNTS



High-Frequency Resistance

A. E. Hess, *Project Leader*, Standards R. N. Jones, *Project Leader*, Dissemination

General: The limiting factors in high-frequency measurements are as follows:

The accuracy of low resistance measurements is limited by the uncertainty in connector contact resistance, about 1mΩ, and by the uncertainty in series inductance, about 1 pH, as well as by loss of measuring resolution, about 1 ppm at 100Ω.

The accuracy of high resistance measurements is limited by measuring instrument resolution and by the uncertainty of shunt capacitance, about 1 fF.

Existing capability: The following three instruments are used to determine HF resistance:

1. Woods twin-T bridge: 5 to 250 MHz, 25 to 10,000 ohms.

2. NBS self-calibrating twin-T bridge: 1.5 MHz, 100 to 10,000 ohms.

   Both instruments are used to measure conductance (resistance) in terms of capacitance, thus are limited by the accuracy to which high-frequency capacitance is known.

3. A 2½-meter slotted line: 50 to 1000 MHz, 1 to 2500 ohms.

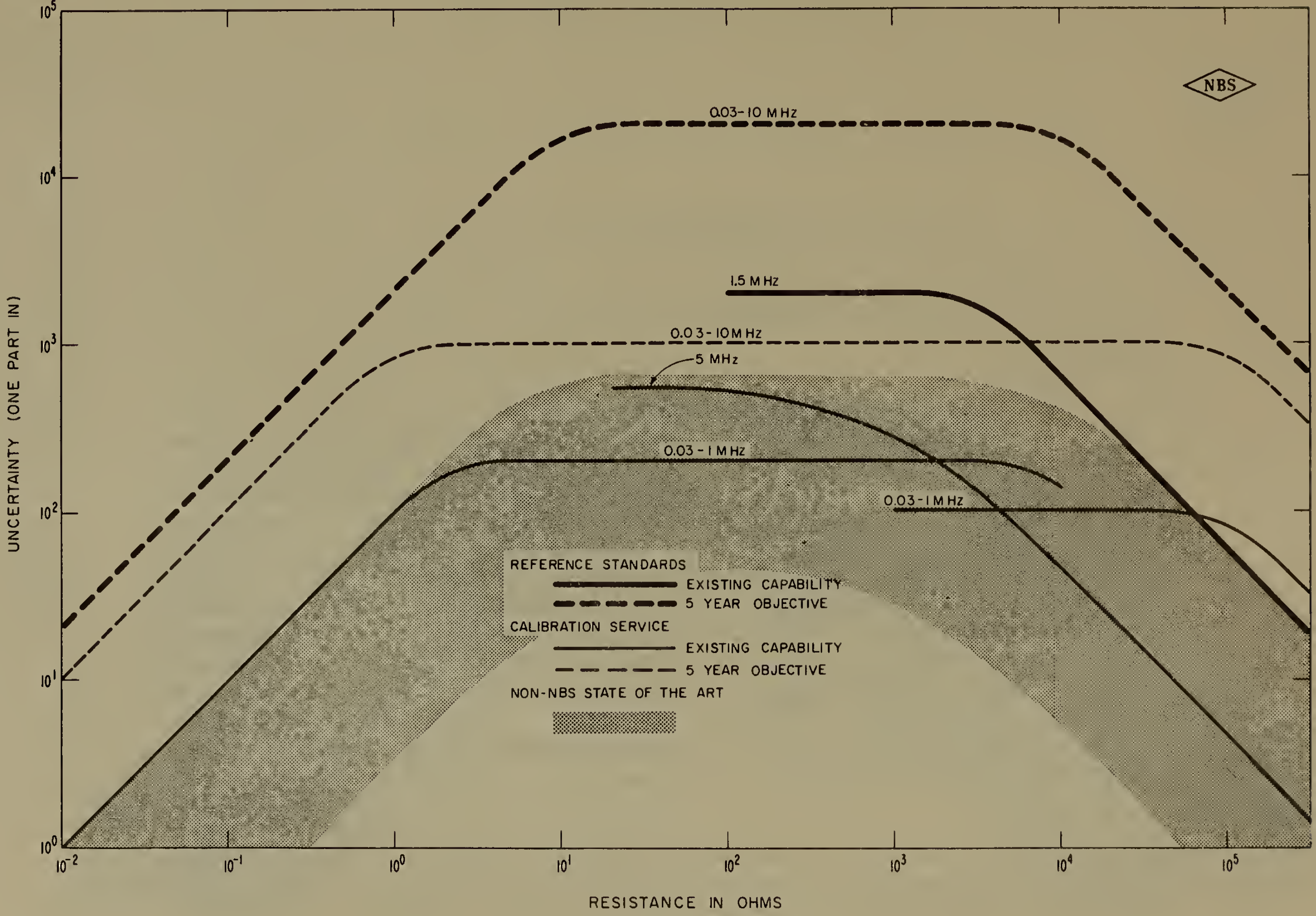
   Resistance may be determined from slotted-line measurements of standing wave ratio in terms of the characteristic impedance of the line and phase shift.

The value of resistance from 30 kHz to 1.5 MHz is in part determined by interpolation between the measured d–c and rf values.

For calibration service, calibrated Maxwell impedance bridges and ratio admittance bridges are used in addition to the previously mentioned instruments. High-precision coaxial connectors are used to obtain the lowest uncertainty of resistance measurements.

(*continued*)

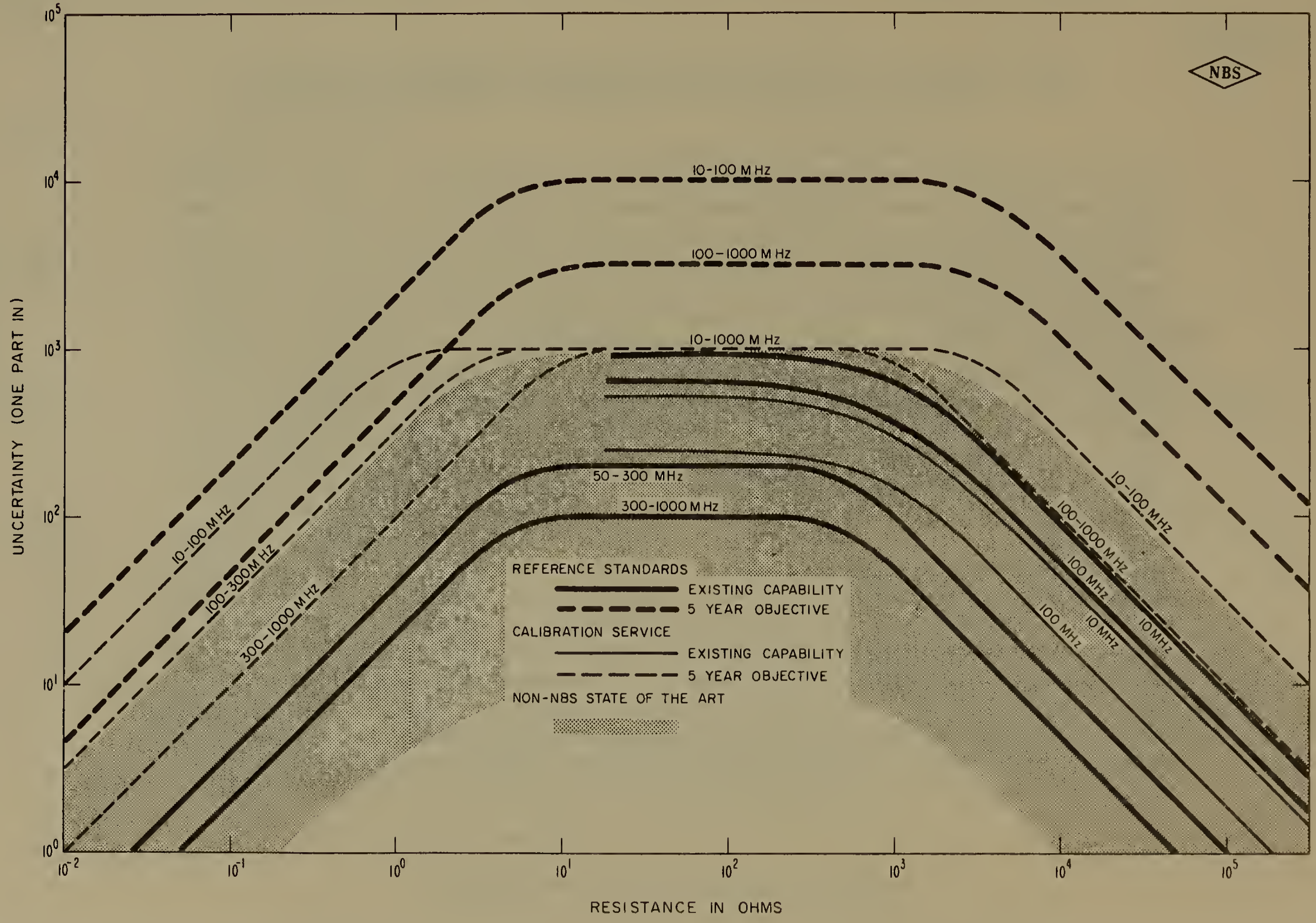
HIGH FREQUENCY RESISTANCE (0.03 TO 10 MHz)
LOW-PHASE-ANGLE RESISTORS



State of the art: The upper limits of the non-NBS state of the art bands indicate the least reported resistance-measuring uncertainty at the lower frequencies. The lower limits of the bands indicate the increased uncertainty in resistance measurement at the higher frequencies. Typical data used in determing the state of the art follow:

Organization	*Uncertainty*	*Range (ohms)*	*Frequency (MHz)*
Military standards laboratory, England.	1 part in 300–900	20–300	3–300.
Manufacturer I	1 part in 50–100	50–100	0.05–5.
Manufacturer I	1 part in 40–800	10–1000	0.4–60.
Manufacturer I	1 part in 10–25	3–700	25–1500.
Manufacturer II	1 part in 30	2–2000	50–500.
Manufacturer III	1 part in 20–40	15–1000	0.5–250.
Manufacturer IV	1 part in 50–100	1–100,000	0.015–5.
Manufacturer V	1 part in 30–50	250–25,000	1–50.
Manufacturer's standards laboratory.	1 part in 500+0.05Ω	0–1300	0.5–20.
Aerospace standards laboratory.	1 part in 400	10	0.1–50.

HIGH FREQUENCY RESISTANCE (10 TO 1000 MHz)
LOW-PHASE-ANGLE RESISTORS



Calibration of Standard Capacitors

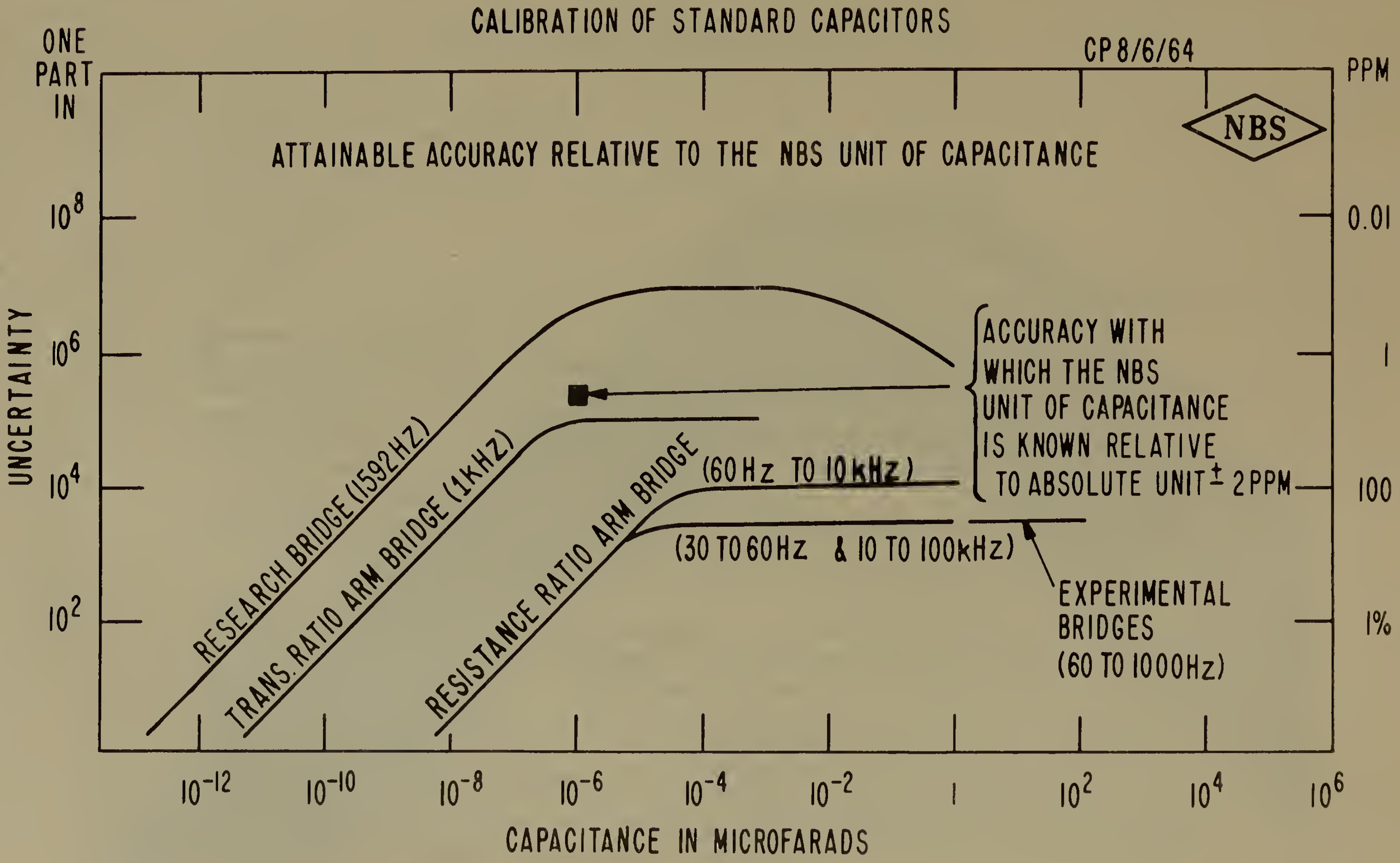
J. J. Morrow, T. L. Zapf, *Project Leaders*

Standard capacitors are calibrated by comparison with NBS working standards of capacitance. These working standards generally are components incorporated into various a–c bridge structures. Other individual portable standards having nominal values on the decimal scale are used as reference standards for calibrating the bridges used in everyday calibration work. These reference standards have values ranging from 1 picofarad (pF) to 10 micofarads (μF). At the low end of this scale the 1–pF and 10–pF standards are hermetically sealed capacitors of NBS design and construction. At the upper end the standards are high-grade polystyrene capacitors of commercial origin. The 1–pF standard is evaluated by comparison with the NBS computable capacitor; its value is projected upwards by means of accurate 1:10 ratios established with close-coupled transformer-type ratio arms.

The accompanying chart indicates the accuracies which have been attained at NBS in measurements employing various types of a–c bridges. It is not feasible to show on this chart the widely varying accuracies available in the fee schedule calibration of many different types of commercial standard capacitors covering 12 orders of magnitude. As an indication of what may be expected, it can be stated that the lowest value standard currently accepted for calibration is a three-terminal air capacitor having a nominal value of direct capacitance 0.001 pF; this is calibrated with a total uncertainty of 0.3 percent, the total consisting of the estimated limits of systematic error plus three times the standard deviation caused by random variations. The least uncertainty (0.002 percent at a frequency of 1000 Hz) pertains to the calibration of modern, hermetically sealed, three-terminal standards having low temperature coefficients of capacitance. At intermediate values of capacitance, the uncertainty of measurement at 1000 Hz is 0.02 percent. Polystyrene capacitors of good quality, 10 to 100 μF, can be calibrated with an uncertainty of 0.5 percent at frequencies in the range 100 to 1000 Hz. No capacitors are accepted for calibration at test frequencies less than 65 Hz, although some experimental work has been done at low frequencies.

Short-term objectives:

1. To improve capabilities for measurement of large values of capacitance.
2. To decrease the uncertainty in knowledge of loss factor.


CALIBRATION OF STANDARD CAPACITORS
CP 8/6/64
NBS
ATTAINABLE ACCURACY RELATIVE TO THE NBS UNIT OF CAPACITANCE
ONE PART IN
UNCERTAINTY
10^8
10^6
10^4
10^2
PPM
0.01
1
100
1%
RESEARCH BRIDGE (1592HZ)
TRANS. RATIO ARM BRIDGE (1KHZ)
RESISTANCE RATIO ARM BRIDGE
(60 Hz TO 10 kHz)
(30 TO 60 Hz & 10 TO 100 kHz)
ACCURACY WITH WHICH THE NBS UNIT OF CAPACITANCE IS KNOWN RELATIVE TO ABSOLUTE UNIT ± 2 PPM
EXPERIMENTAL BRIDGES (60 TO 1000 Hz)
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^2
10^4
10^6
CAPACITANCE IN MICROFARADS

High-Frequency Capacitance

L. E. Huntley, *Project Leader*, Standards R. N. Jones, *Project Leader*, Dissemination

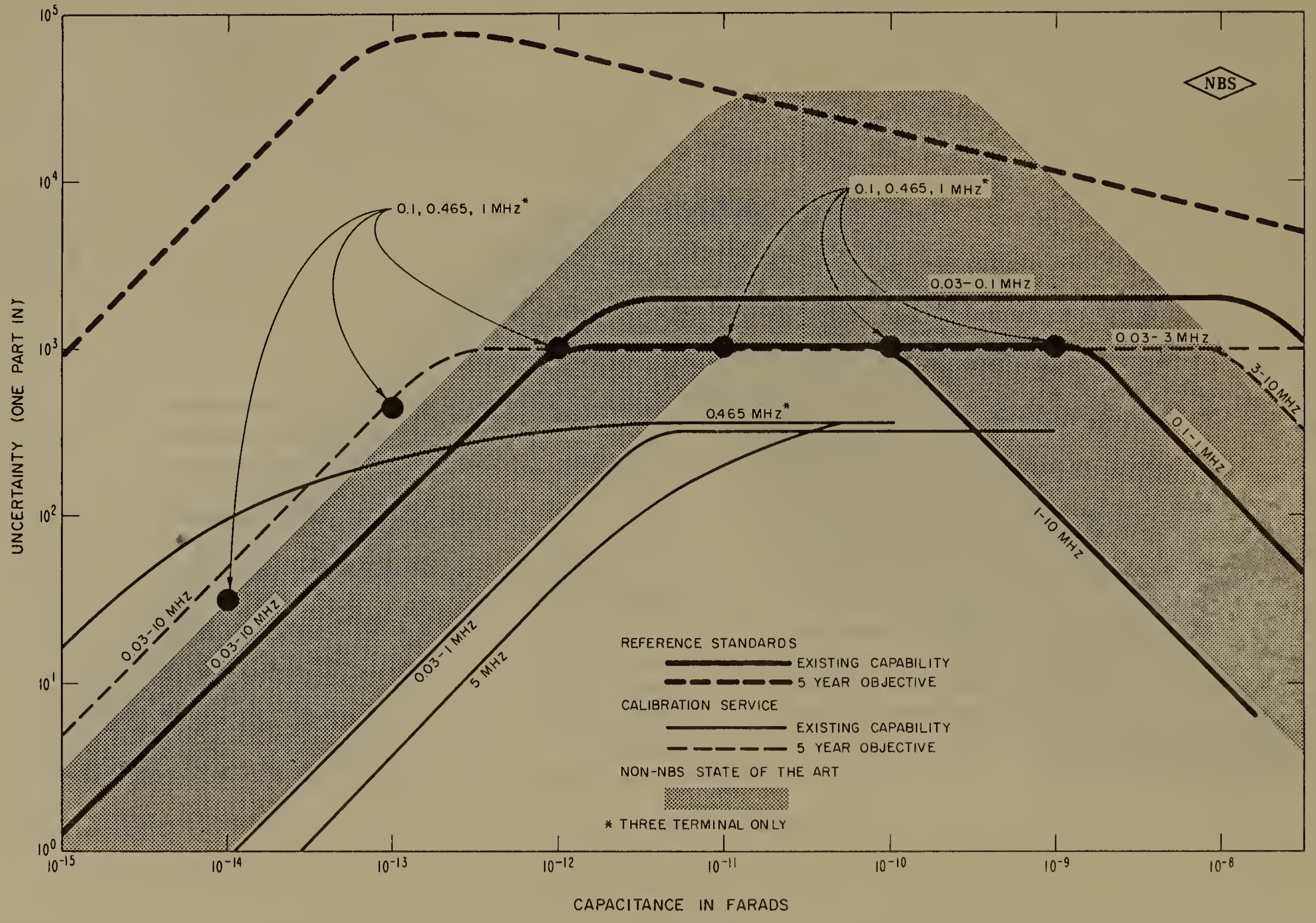
General: The chart shows the uncertainty in measuring capacitance at various frequencies. In most cases, two like capacitors can be compared with a precision which is one or two orders of magnitude greater than the accuracy which may be assigned to the measurement of either. At the lower frequencies (below about 50 MHz), the accuracy obtainable is limited primarily by the accuracy with which frequency corrections to capacitance standards can be evaluated. At frequencies above 50 MHz, where slotted-line measurements are practical, the accuracy obtainable depends upon the quality of the slotted line. At any frequency, the lowest two-terminal capacitance which can be measured to a given accuracy is determined by the connector uncertainty, which in the case of capacitors equipped with precision coaxial connectors is the uncertainty in the fringe capacitance or other reference capacitance.

Existing capability: The low-capacity limits of the curves are determined by the uncertainty of the reference capacitance (about 1 fF). The high-capacity limits of the curves are determined by the uncertainty in frequency corrections. Above 100 MHz, additional restrictions are encountered due to errors associated with slotted-line measurements.

State of the art: The non-NBS state of the art bands apply only to the measurement of two-terminal capacitors, since the problems encountered in measuring three-terminal capacitors are somewhat different. (The calibration service offered for three-terminal capacitors is about at the level of the state of the art in that area.) The upper limits of the state of the art bands represent the lower frequencies, while the lower limit represents the higher frequencies. Typical data used to determine the state of the art follow:

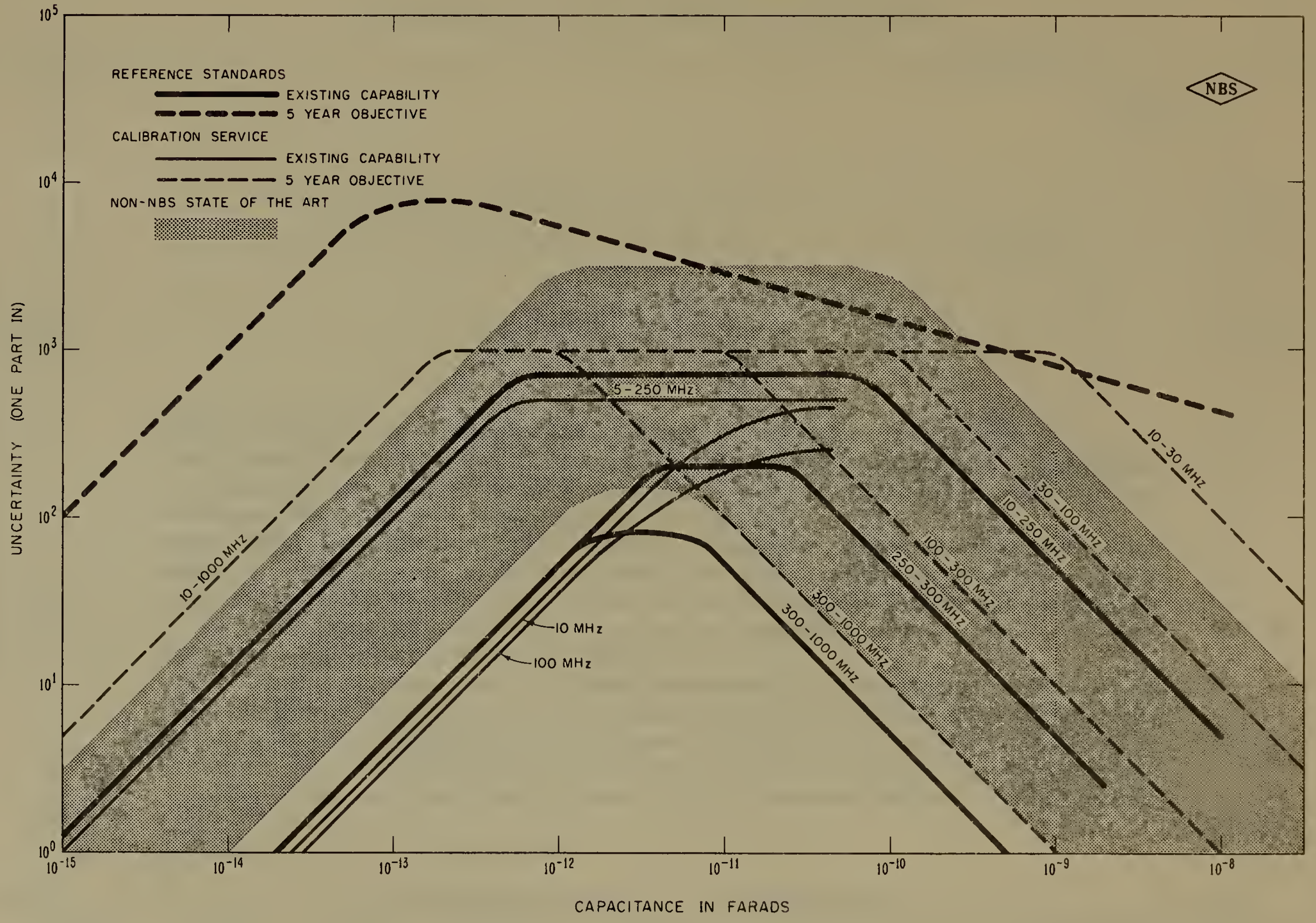
(*continued*)

HIGH FREQUENCY CAPACITANCE (0.03 TO 10 MHz)
(LOW-LOSS CAPACITORS)



Organization	*Uncertainty*	*Capacitance range*	*Frequency*
University laboratory	1 part in 4000	200 pF (3-terminal)	1 MHz.
University laboratory	1 part in 5000	400 pF (3-terminal)	1 MHz.
University laboratory	1 part in 500	200 pF	1 MHz.
Military standards laboratory	0.001 pF	"All practical cases"	5–50 MHz.
Commercial stds. laboratory	1 part in 1600	92 pF	1 MHz.
Commercial stds. laboratory	0.01 pF	to 200 pF	10 MHz.
Instrument manufacturer	1 part in 1000+1 pF	100–1150 pF	1 MHz.
University laboratory	1 part in 800	40 pF (3-terminal)	50 MHz.
University laboratory	1 part in 800	80 pF (3-terminal)	50 MHz.
University laboratory	1 part in 900	40 pF	50 MHz.
Commercial stds. laboratory	1 part in 1000	130 pF	20 MHz.
Commercial stds. laboratory	0.01 pF	to 200 pF	10 MHz.

HIGH FREQUENCY CAPACITANCE (10 TO 1000 MHz)
(LOW-LOSS CAPACITORS)



Calibration of Standard Inductors

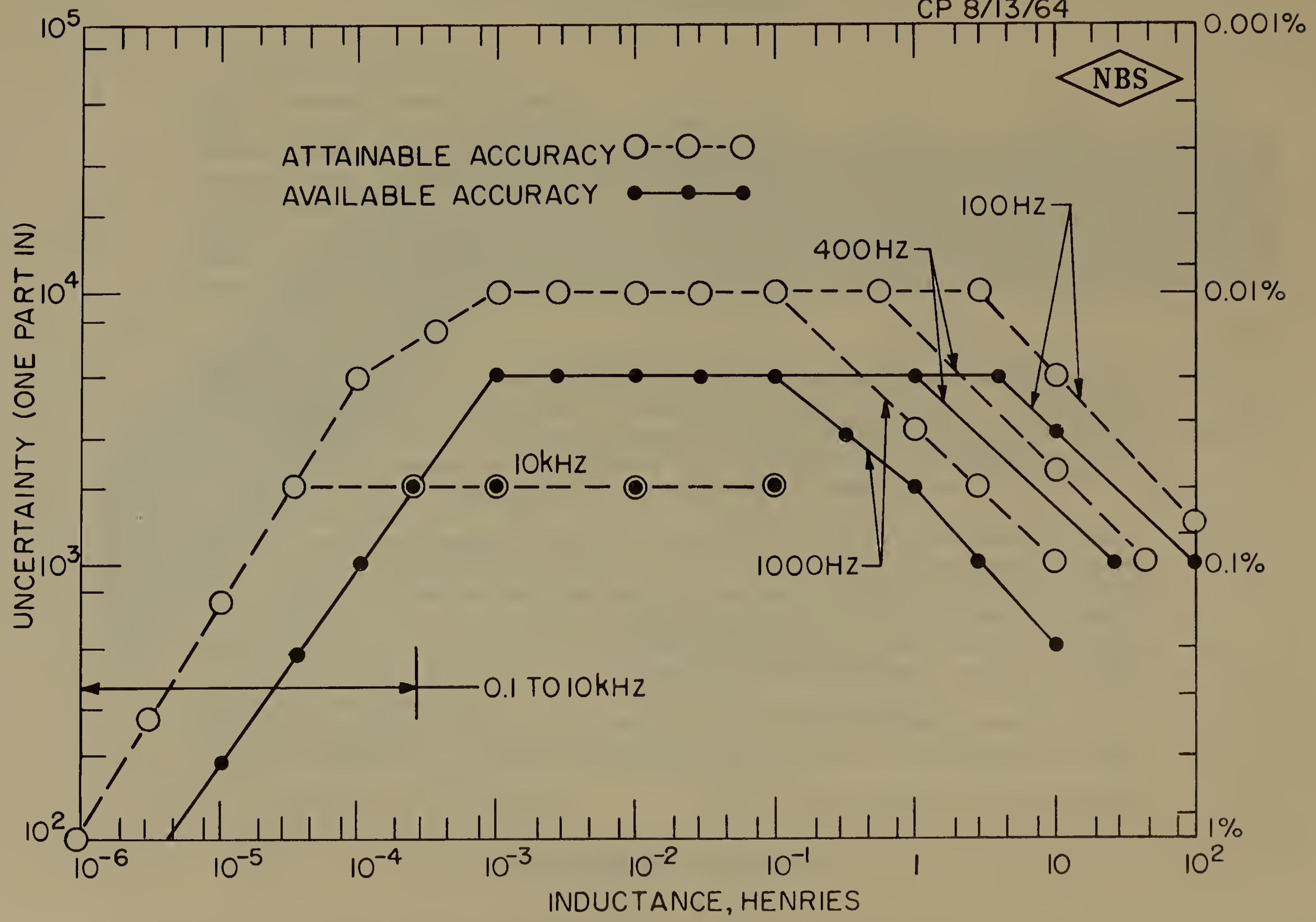
J. J. Morrow, T. L. Zapf, *Project Leaders*

Standard inductors having nominal values of 50 microhenries or more are calibrated by comparison with NBS working standards. These working standards are calibrated periodically using a Maxwell-Wien bridge. Standards of lower nominal value, inductors of odd value, and mutual inductors intended for use in a-c bridge measurements are calibrated directly with the Maxwell-Wien bridge. (Mutual inductors used in magnetic measurements are calibrated by comparison with working standards of mutual inductance using direct current.)

On the accompanying chart the solid points indicate currently available accuracies (uncertainties) in the calibration of commercially available standard inductors, by established calibration procedures, at established fees. Under more closely controlled environmental conditions, and with greater effort, measurements on "ideal" inductors can be made with attainable accuracies (uncertainties) approaching those indicated by the open circles.

NBS is not aware of any urgent requirement for increased accuracy in inductance measurements. Some interest in enhanced accuracies at low values of inductance has been indicated. Investigations presently under way will eventually increase capabilities in this area.

CALIBRATION OF STANDARD INDUCTORS



CP 8/13/64

High-Frequency Inductance

C. A. Hoer, *Project Leader*, Standards R. N. Jones, *Project Leader*, Dissemination

Existing capability: The existing calibration service is provided with a Maxwell-type bridge, a Woods-type dual-admittance bridge, resonance techniques, and as negative capacitance on a resistive arm admittance bridge.

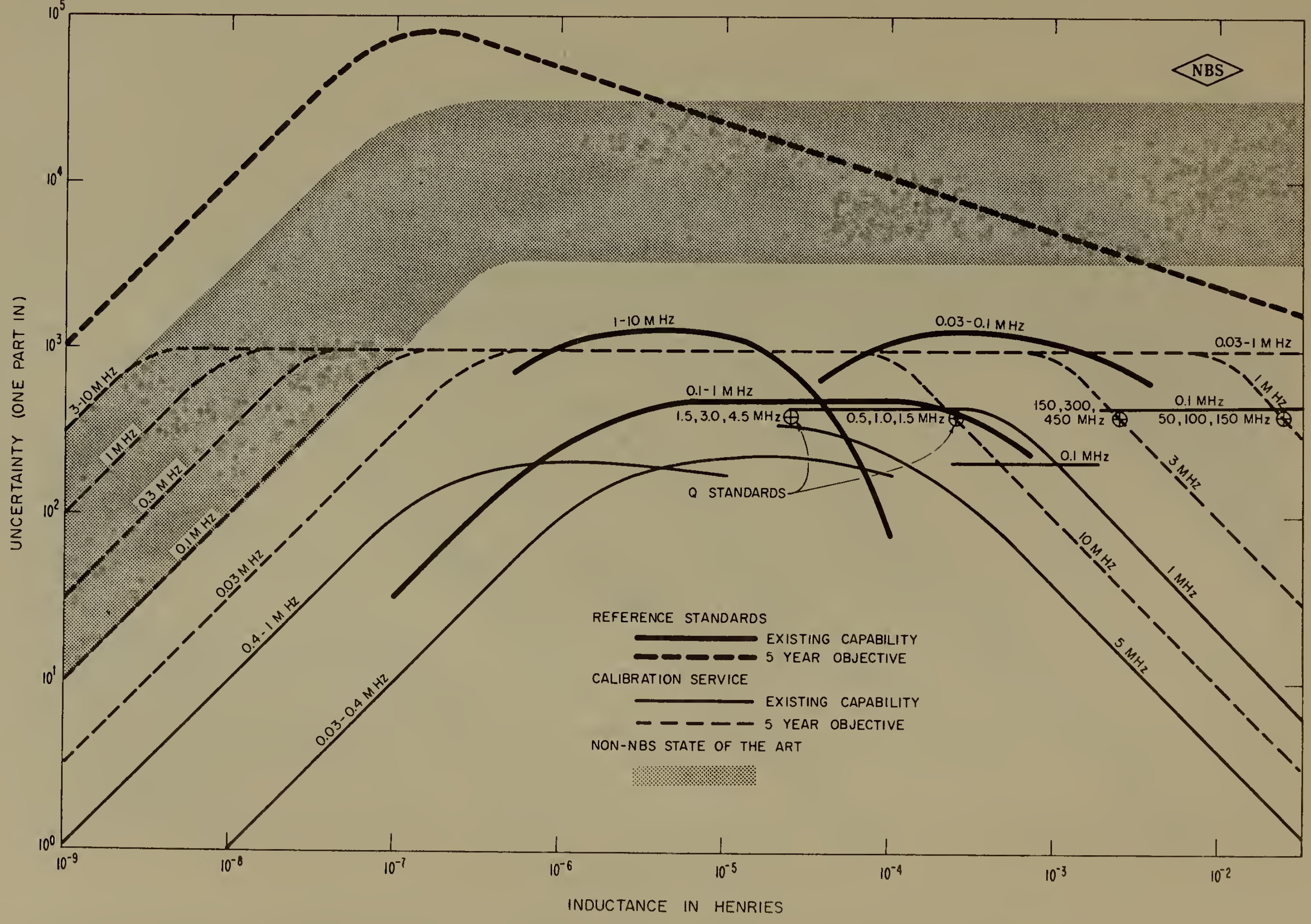
The existing reference standards are a slotted line (50 to 500 MHz), a twin-T capacitance bridge (5 to 250 MHz), and a transcomparator (100 kHz to 30 MHz). These reference standards are essentially instruments for comparing an unknown inductor with either the calculated inductance of a length of precision air coaxial line or with the calculated capacitance of a precision variable coaxial capacitor. The general pyramid shape of the accuracy curves is determined by residual resistance or resolution of inductance on the low inductance side and by shunt capacitance on the high inductance side.

State of the art: The shaded band on the chart represents the non-NBS state of the art of low loss inductance measurements at optimum frequencies for specified values. The upper limit of the band represents the precision with which two inductors may be compared, while the lower limit of the band represents the best accuracy with which an inductor may be measured. For clarity, the bands shown are for the lower frequencies only. Typical data used to determine the state of the art follow:

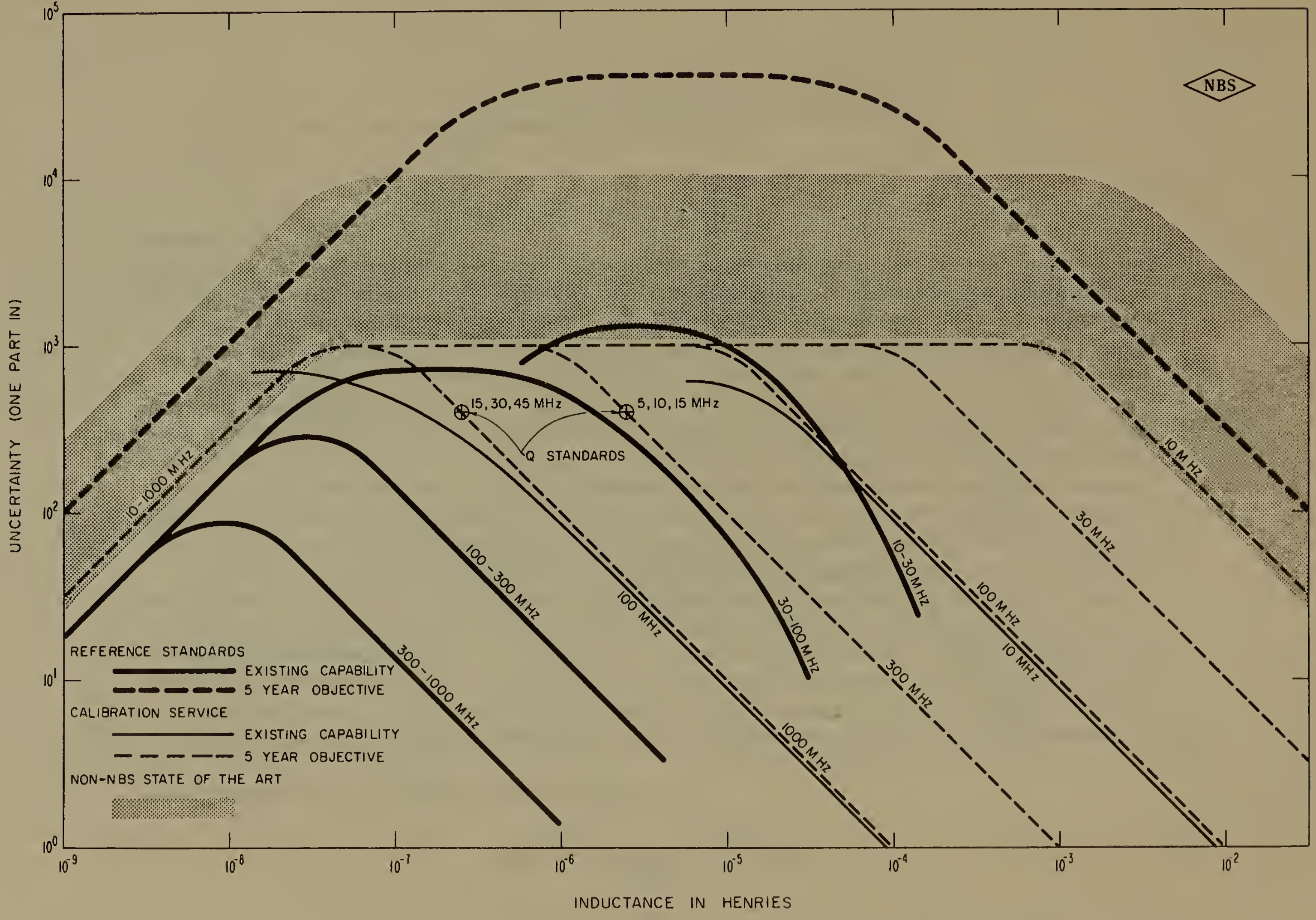
Organization	*Uncertainty*	*Inductance range*	*Frequency*
Commercial standards laboratory	1 part in 6000	10^{-3} H	1 MHz.
Commercial standards laboratory	1 part in 4000	10^{-4} H	3 MHz.
Commercial standards laboratory	1 part in 900	10^{-5} H	10 MHz.
Instrument manufacturer	1 part in 11,000*	$2 \cdot 10^{-5}$ H	100 kHz.
Instrument manufacturer	1 part in 50	10^{-9} H	1000 MHz.
Commercial standards laboratory	1 part in 1000	$5 \cdot 10^{-6}$ H	10 MHz.
Military standards laboratory (England)	1 part in 800	10^{-8} H	250 MHz.
Military standards laboratory (England)	1 part in 1000	10^{-5} H	10 MHz.

*Comparison precision.

HIGH FREQUENCY INDUCTANCE (0.03-10 M Hz)
(LOW-LOSS INDUCTANCE)



HIGH FREQUENCY INDUCTANCE (10-1000 M Hz)
(LOW-LOSS INDUCTANCE)



Magnetic Flux Density

I. L. Cooter, F. K. Harris, *Section Chiefs*

State of the art: Rubidium magnetometers are generally used for precision measurement of flux densities below 1×10^{-3} tesla.[1] A flux density of approximately 1×10^{-3} tesla was established in an air-cored solenoid at NBS in 1964.[2] From the measured coil constant and the accuracy of determining the current, the value of the flux density thus established is known with a probable error subjectively estimated to be ±5 ppm. For precision measurements of fields greater than the earth's field, which is about 5×10^{-5} tesla, proton resonance magnetometers[3] are generally used.

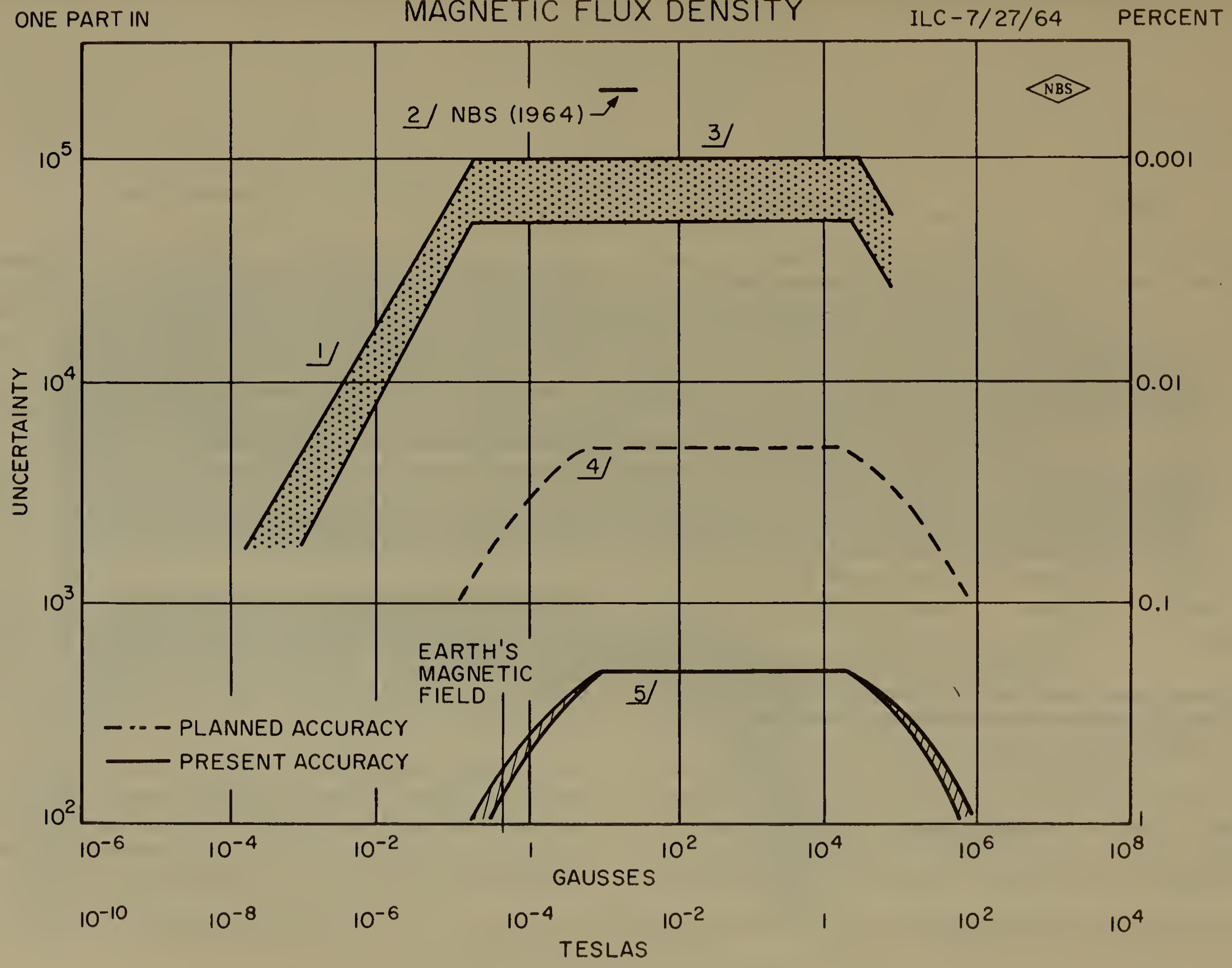
Magnetic fields that are constant and homogeneous over a volume as large as the measuring probe may be measured by means of the rubidium and proton resonance magnetometers. However, most commercial and routine magnetic measurements use the search coil or Hall-effect methods.[5] These methods generally use the field of a permanent magnet as a reference or calibration standard. Permanent magnet standards vary widely in size, shape, air gap dimensions, guides and stop arrangement for the probe, temperature control, etc. Therefore, the value of the field in the gap of each standard is reported to an accuracy depending on its individual merit.

Industry needs: As permanent magnet standards are improved, more accuracy will be required.

Short-term objectives: Improvements in the method for determining the area-turns of search coils and in ballistic detection should result in increased accuracy of the measurement of flux densities for industrial applications. It is expected that the uncertainty of measuring flux density will be reduced to within ±0.1 percent in the near future, and eventually to the planned accuracy line shown.[4]

References refer to correspondingly numbered areas on the chart.

MAGNETIC FLUX DENSITY



High-Frequency Attenuation

W. R. Ives, *Project Leader*, Standards

D. H. Russell, *Project Leader*, Dissemination

General: The uncertainties are given for both attenuation difference and insertion loss. Attentuation difference applies to variable attenuators. Insertion loss applies to cases where the circuit has to be broken to insert a device. In general, uncertainties cannot be predicted for either method when nonprecision connectors are used.

The uncertainty for small values of attenuation approaches a fixed fraction of a decibel. Thus, as the attenuation to be measured decreases, the uncertainty must increase. For example, if the uncertainty and the measured attenuation were the same, the uncertainty would be 1 part in 1. The dropoff at large values of attenuation is caused by the constantly decreasing signal-to-noise ratio.

The uncertainty is given as a part of the total measured range. For example, 1 part in 10^4 for 80 dB attenuation would give a total uncertainty of 0.008 dB.

The chart represents all errors added in magnitude as the worst possible case. For a general discussion of accuracy and systematic errors, see the reference noted.

Existing capabilities: The frequency range 1 to 300 MHz is based on the use of a waveguide-below-cutoff attenuator at the measuring frequency. Limitations in accuracy are due primarily to uncertainties in producing and measuring small increments of linear displacement, and to uncertainties in the rf conductivity and the diameter of the waveguide. The frequency range 300 to 1000 MHz is based on a heterodyne system and has an additional error and limitation in total measuring range due to mixer nonlinearity.

Five-year objective: Future planning is based primarily on completion of a new 30-MHz reference standard now under development.

State of the art: Data for the state-of-the-art bands are based on NBS experience in attenuation measurements, information from other standards laboratories, and instrument manufacturers' claims and specifications such as the following:

Manufacturer	*Uncertainties*	*Range*	*Frequency*
I	1 part in 10,000	0–60 dB	30 MHz.
I	1 part in 500	0–60 dB	200–1000 MHz.
II	1 part in 1000	0–100 dB	30 MHz.
II	1 part in 200	0–100 dB	30 MHz.
II	1 part in 160	0–60 dB	30–1000 MHz.
III	1 part in 1000	0–100 dB	30 MHz.
III	1 part in 500	0–100 dB	30 MHz.
IV	1 part in 500	0–80 dB	30 and 60 MHz.

Reference:

Allred, C. M., and C. C. Cook, A precision RF attenuation calibration system. *IRE Trans. Instr.* I-9, *No. 2 (Sept. 1960).*

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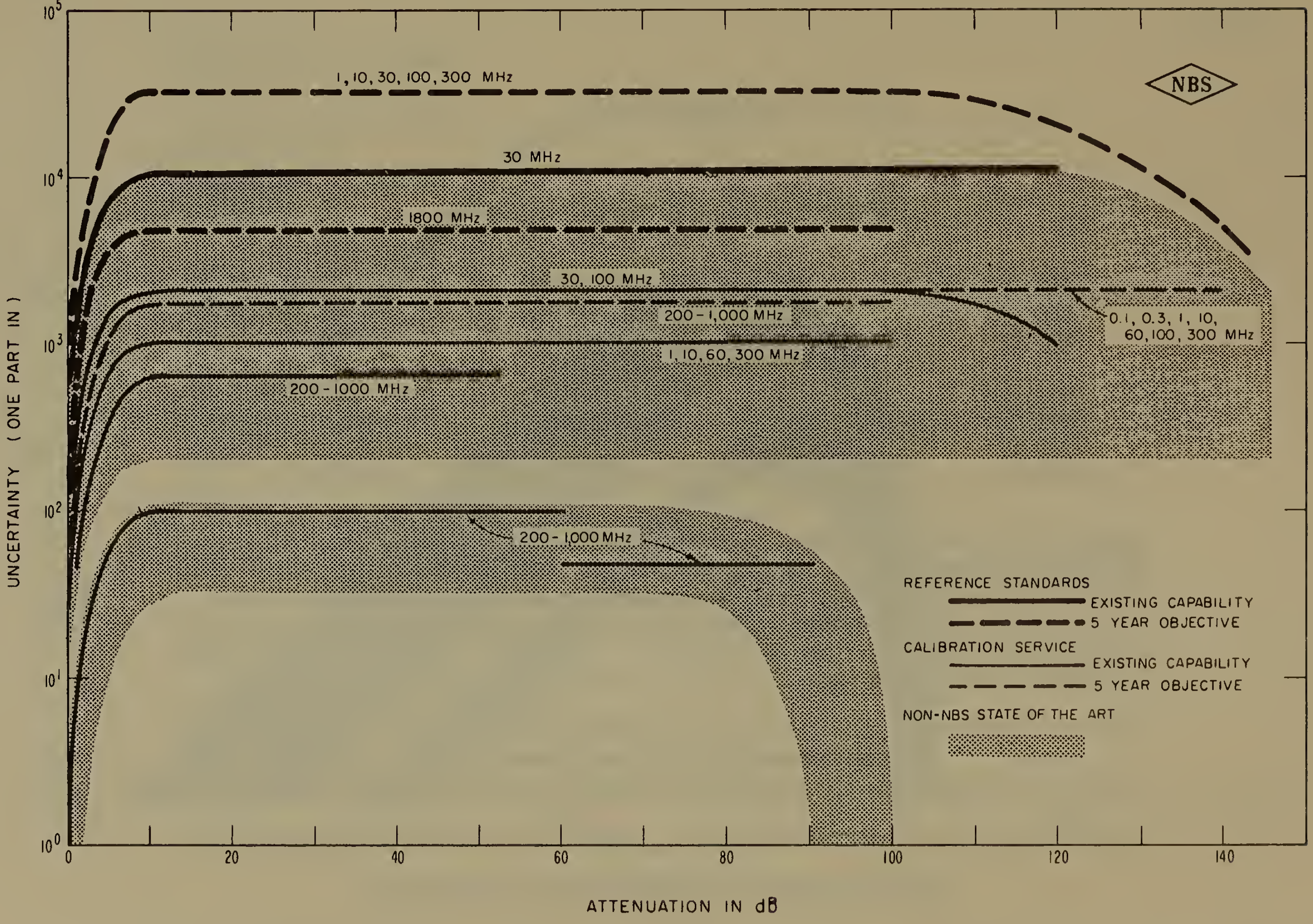
HIGH FREQUENCY ATTENUATION
(COAXIAL SYSTEMS)



Microwave Attenuation (Coaxial Systems)

D. A. Ellerbruch, *Project Leader*, Standards D. H. Russell, *Project Leader*, Dissemination

Existing capability: The power-ratio method is used from 0 to 50 dB and either the IF substitution or modulated subcarrier method is used for the higher attenuations.

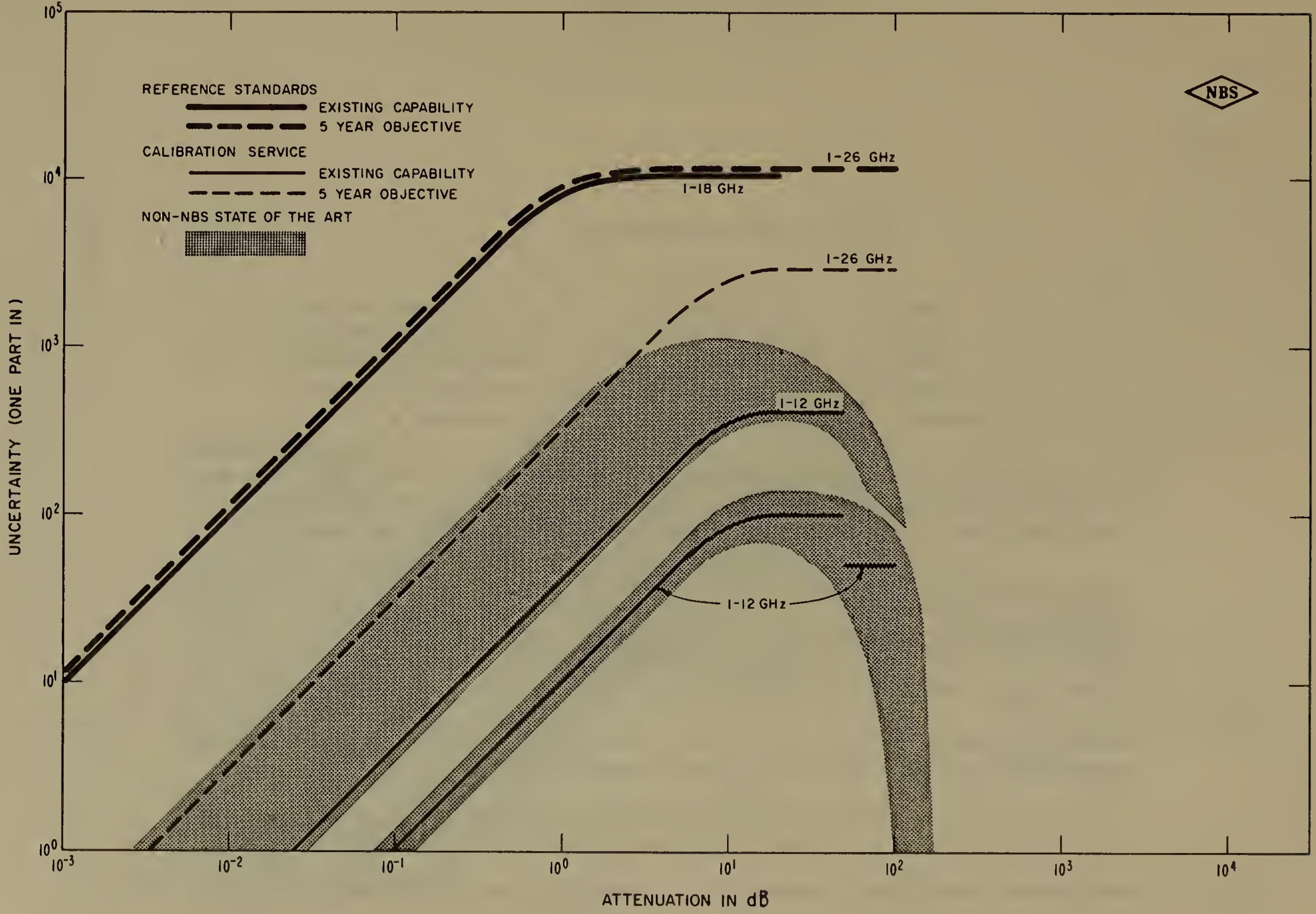
A 30-MHz waveguide-below-cutoff attenuator in conjunction with a diode mixer is considered the reference standard of attenuation.

Five-year objective: The five-year objective for the 1 to 26 GHz frequency range extends the range to 100 dB with decreased uncertainty. A portion of the decreased uncertainty will be due to the use of improved impedance-matching techniques reducing mismatch error.

State of the art: The lower shaded area, representing the non-NBS state of the art for insertion loss measurement, includes uncertainties due to mismatch error. The upper non-NBS state of the art band represents attenuation difference measurements in which mismatch error is not included. Typical data used in determining the state of the art follow:

Organization	*Uncertainty*	*Attenuation*	*Frequency*
Instrument manufacturer	1 part in 500	0–60 dB	1–10 GHz.
Instrument manufacturer	1 part in 160	60–100 dB	1–10 GHz.
Instrument manufacturer	1 part in 160	0–100 dB	1–11 GHz.
Aerospace company	1 part in 160	0–100 dB	1–11 GHz.
Aerospace company	1 part in 160	0.5 dB	2–12 GHz.
Aerospace company	1 part in 1000	30 dB	2–12 GHz.

MICROWAVE ATTENUATION
(COAXIAL SYSTEMS)



Microwave Attenuation (Waveguide Systems)

D. A. Ellerbruch, *Project Leader*, Standards W. Larson, *Project Leader*, Dissemination

General: Mismatch error is the most important limiting factor in the existing capability curve. Highly refined matching techniques must be used to achieve the accuracy represented by the present curve.

Existing capability: The existing capability curve for reference standards represents two different measurement techniques: the power-ratio method from 10^{-3} to 10^{0} dB, and the modulated subcarrier method for the rest of the curve.

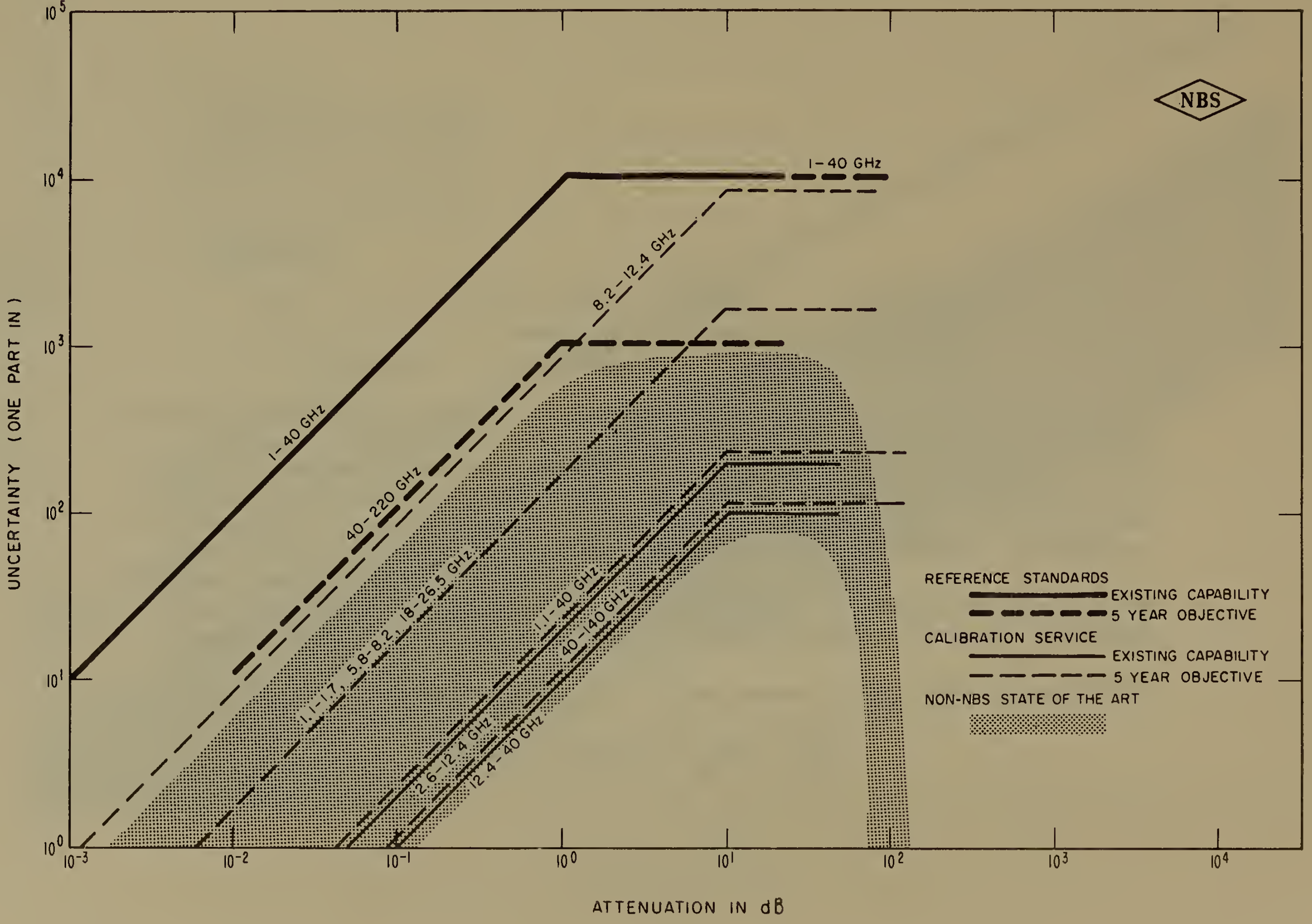
Five-year objective: The five-year objective for the frequency range of 1 to 40 GHz is an extension of the modulated subcarrier method to a range of 100 dB.

The five-year objective for the 40 to 220 GHz range is the development of systems using the 30-MHz IF substitution technique of attenuation measurement. The curve falls far below the existing capability curve because of the many uncertainties, such as source stability and mixer crystal properties, that have not been determined.

State of the art: The non-NBS state of the art band represents the estimated uncertainty of commercial instruments. The frequency range covered by the band extends from about 1 GHz at the upper limit to 40 GHz at the lower limit. Typical data from which the state of the art was determined follow:

Organization	*Uncertainty*	*Attenuation*
Instrument manufacturer	1 part in 600	120 dB.
Instrument manufacturer	1 part in 50	50 dB.
Aerospace industry	1 part in 170	0.5 dB.
Aerospace industry	1 part in 1000	30 dB.

MICROWAVE ATTENUATION
(WAVEGUIDE SYSTEMS)



High-Frequency Phase Shift

W. R. Ives, *Project Leader*, Standards D. H. Russell, *Project Leader*, Dissemination

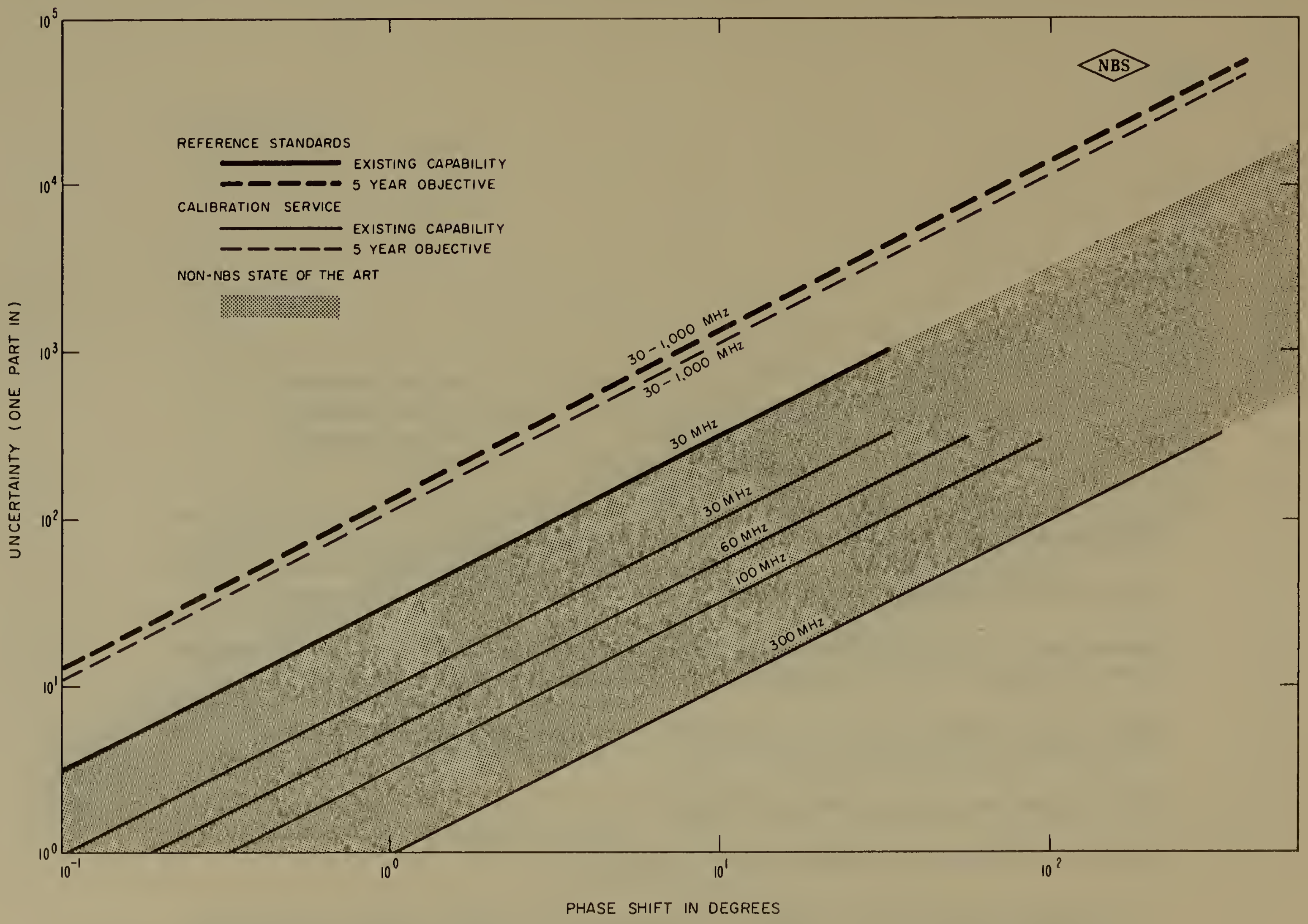
Existing capability: Phase-shift measurements at fixed frequencies are generally reproducible to within ±0.01 (3 standard deviations). A systematic error in the standard, due to mechanical tolerance limitations, increases the uncertainty to an estimated ±0.1°.

The reference standards are limited in range by mechanical considerations. The reference is a precision "trombone" line stretcher with a mechanical travel of 40 inches. This length corresponds to 36° at 30 MHz, 72° at 60 MHz, etc. Measurement of phase shift at frequencies above 300 MHz is based on a heterodyne measuring system possessing a maximum uncertainty of ±0.1°.

State of the art: Data for the state of the art band were based on NBS experience and manufacturers' published specifications, such as the following:

Manufacturer	*Uncertainty*	*Range*	*Frequency*
I	1 part in 100	0–360°	To 400 MHz.
II	1 part in 20	0–360°	0.1–1000 MHz.

HIGH FREQUENCY PHASE SHIFT
(2 PORT COAXIAL DEVICES)



Microwave Phase Shift (Two-Port Waveguide and Coaxial Devices)

D. H. Russell, *Project Leader*, Dissemination, Coaxial
D. A. Ellerbruch, *Project Leader*, Standards
W. Larson, *Project Leader*, Dissemination, Waveguide

General: The uncertainty is determined by summing the individual limits of errors from all sources. This total limit of error is now determined by precision waveguide tolerances, short-circuit displacement measurements, and matching.

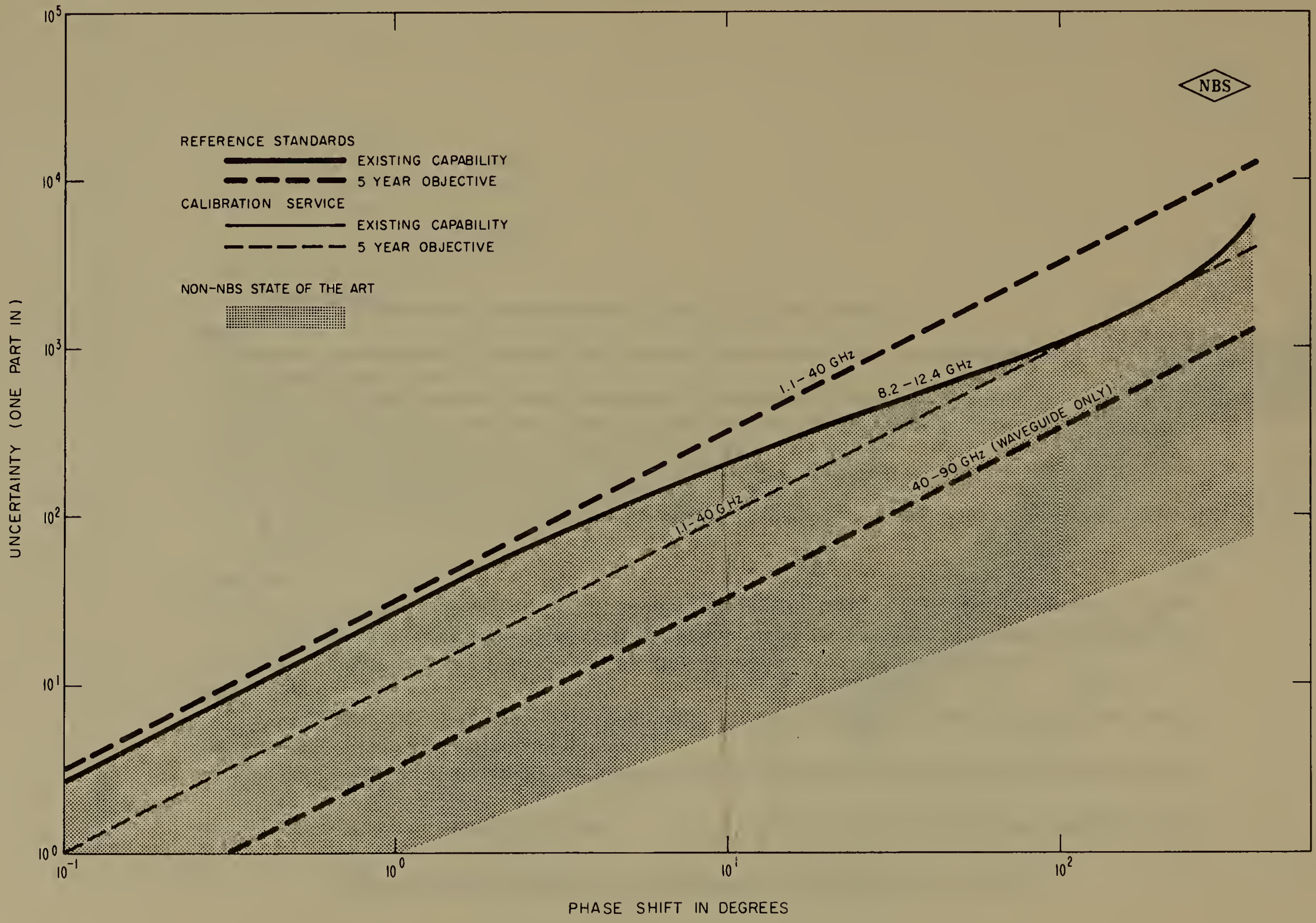
Existing capability: NBS does not yet offer phase-shift calibration services. The measurement capability for *X*-band waveguide devices is shown on the graph along with the range of the state of the art for industry.

The *X*-band reference standard accuracy curves are derived for a modified reflectometer terminated in a sliding short circuit as the standard.

State of the art: The non-NBS state of the art band shown is drawn from personal knowledge and studies of various commercial techniques. Typical data used follow:

Organization	*Uncertainty*	*Phase shift*
Aerospace company	1.5°	To 360°.
Instrument manufacturers	1°+1 percent	To 360°.
Aerospace company	0.3°	To 360°.

MICROWAVE PHASE SHIFT
(TWO PORT WAVEGUIDE AND COAXIAL DEVICES)



Microwave Reflection Coefficient (Coaxial Systems)

W. E. Little, *Project Leader*, Standards R. N. Jones, *Project Leader*, Dissemination

General: The curves are based on reflectometer measurement techniques, using quarter-wavelength short circuits as reference standards.

Existing capability: At present, waveguide-to-coaxial couplers are used on rectangular waveguide systems.

Five-year objective: The future systems are planned to be completely coaxial.

State of the art: The non-NBS state-of-the-art band is based on both reflectometer and improved slotted-line techniques, but is limited to devices equipped with high-precision coaxial connectors.

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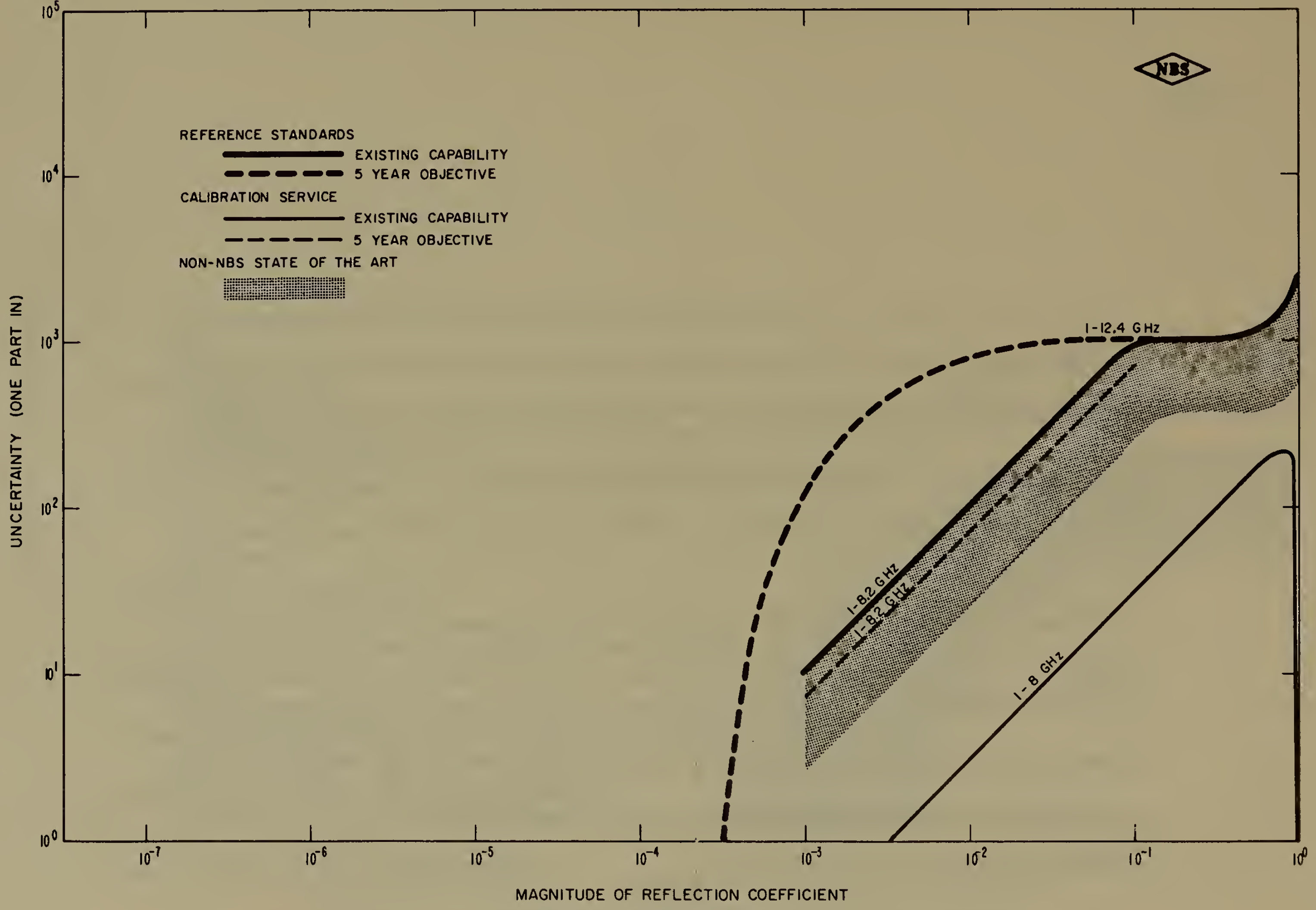
MICROWAVE REFLECTION COEFFICIENT
(COAXIAL SYSTEMS)



Microwave Reflection Coefficient (Waveguide Systems)

W. E. Little, *Project Leader*, Standards B. C. Yates, *Project Leader*, Dissemination

General: The curves are based on reflectometer measurement techniques, using quarter-wavelength short circuits as the reference standards.

Five-year objective: The five-year objective for the 60 to 90 GHz frequency range is to develop a reflectometer and suitable reference standards in rectangular waveguide.

Improvements over the existing capability curve for the 2.6 to 12.4 GHz frequency range are limited by the mechanical precision to which a waveguide can be manufactured and by the stability and accuracy of small power or voltage ratio measurements.

State of the art: The non-NBS state of the art band represents capabilities in the frequency region below 12.4 GHz only.

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R. J. Wescott, Equipment for display of reflection coefficient over a 50 Mc band at 35 Gc, *Proc. IEE* **109**, *Pt. B, Suppl. 23, 693–695 (1962).*

Reflection coefficient measurements with reflectometer systems, *Hewlett-Packard Application Note No. 38, Sec. 4, pp. 25–28.*

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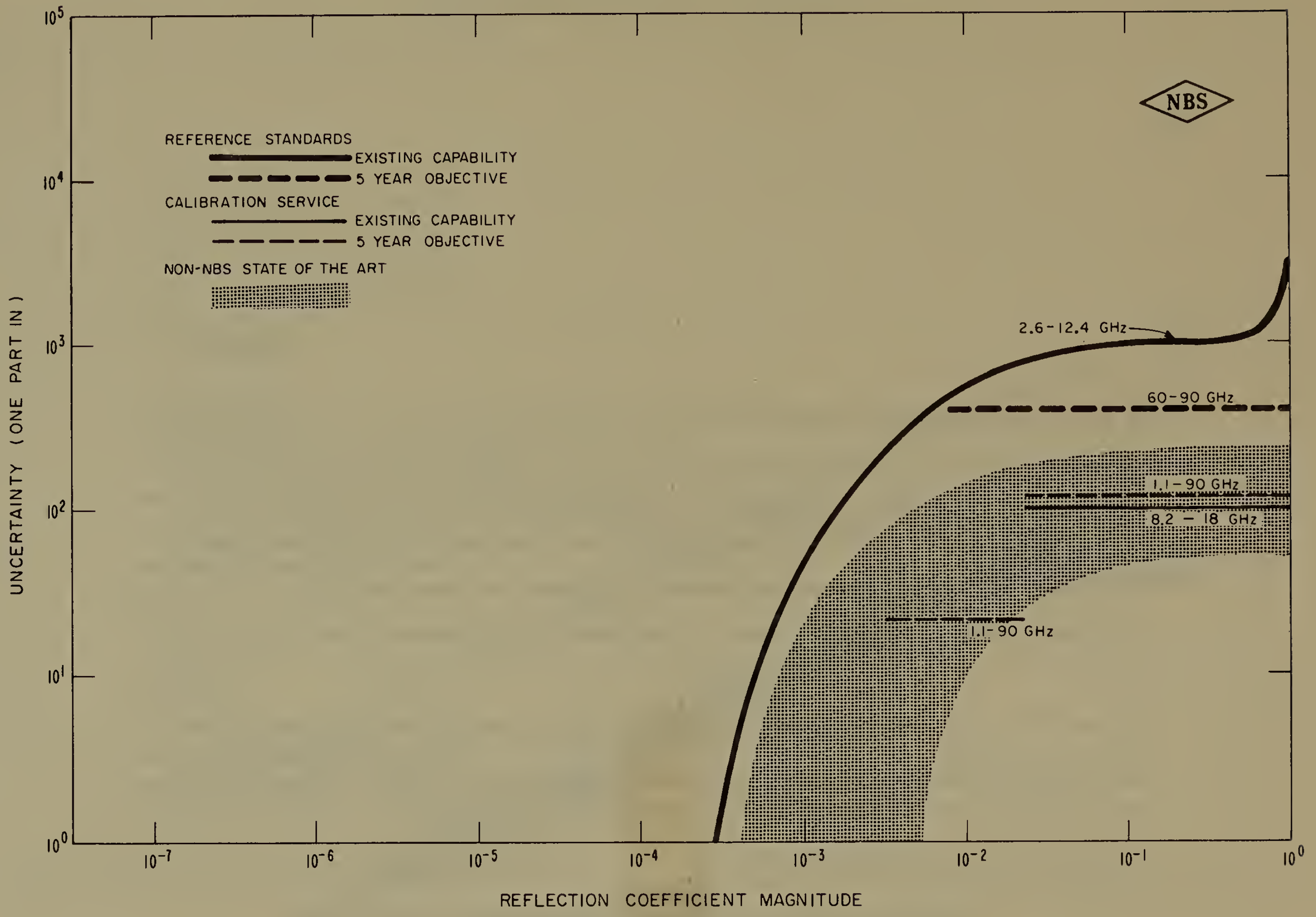
MICROWAVE REFLECTION COEFFICIENT (WAVEGUIDE SYSTEMS)

(MAGNITUDE OF REFLECTION COEFFICIENT)



Microwave Reflection Coefficient (Phase Angle)

W. E. Little, *Project Leader*, Standards B. C. Yates, *Project Leader*, Dissemination

Five-year objective: The NBS five-year objective is based on the present work being done to combine reflectometer and phase-measurement techniques into a single instrument that will measure the complex reflection coefficient.

State of the art: The non-NBS state of the art band is based on slotted-line impedance-measuring techniques

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S. B. Cohn and H. G. Oltman, A precision microwave phase measurement system with sweep presentation, *IRE Convention Record, Pt. 3, 147-150 (Mar. 1961).*

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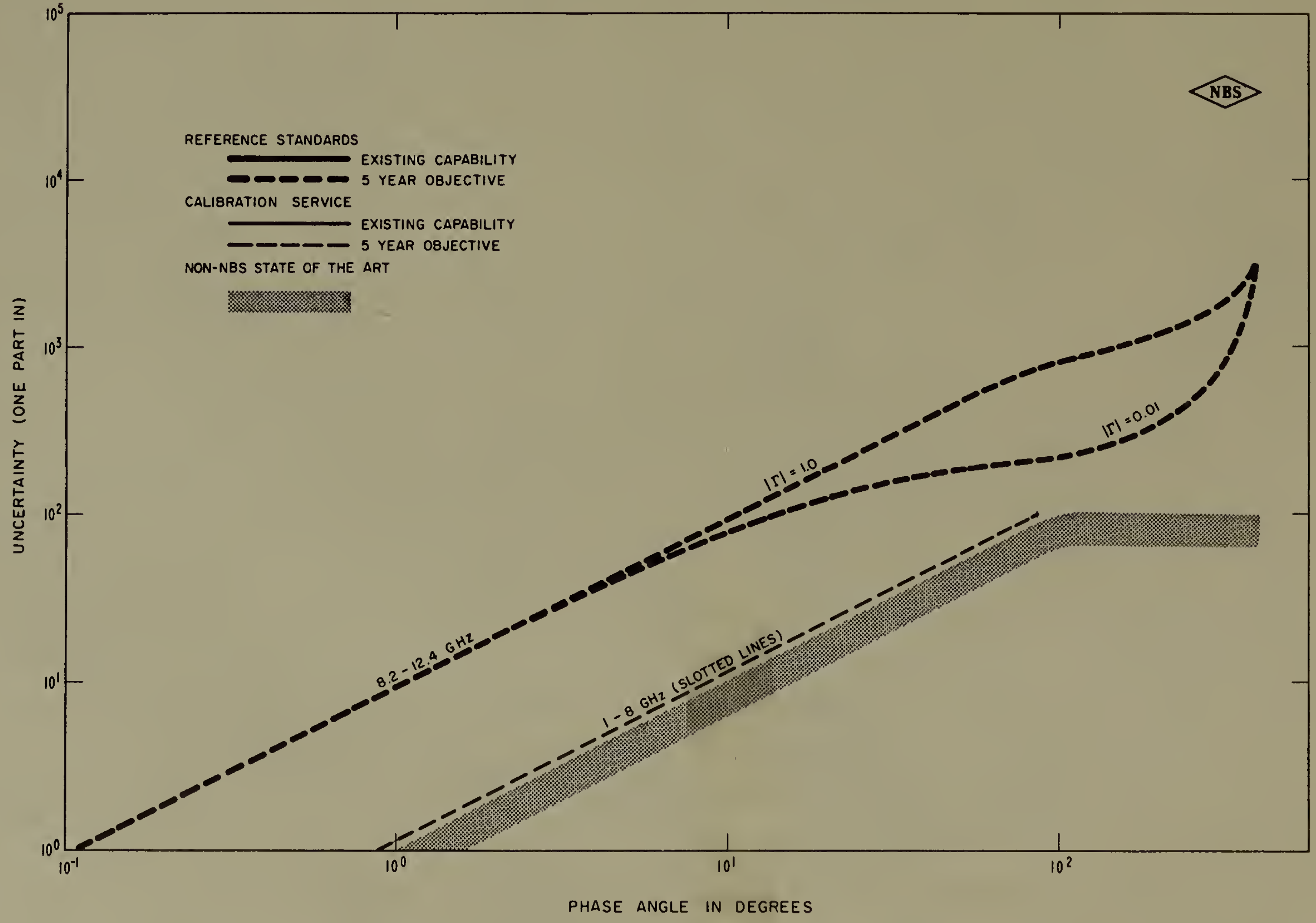
MICROWAVE REFLECTION COEFFICIENT
(PHASE ANGLE OF REFLECTION COEFFICIENT)



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