ANDEEN-HAGERLING

AH 2700A

50 Hz-20 kHz
Ultra-precision
Capacitance Bridge

World's Most Accurate 50Hz-20kHz Capacitance/Loss* Bridge

The AH 2700A offers unparalleled stability, resolution, linearity and accuracy in a multi-frequency capacitance/loss* bridge (whether manual or automatic). Its numerous state-of-the-art features make it an exceptionally user-friendly instrument. The precision of the AH 2700A is creating new applications in calibration, science, and production in a wide range of fields.

Outstanding Features

- **Frequencies:** 50, 60, 70, 80, 100, 120, 140, 160, 200, 240, 300, 400, 500, 600, 700, 800 Hz and 1.0, 1.2, 1.4, 1.6, 2.0, 2.4, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10, 12, 14, 16 and 20 kHz
- **Selected Performance Specifications**

Frequency	Accuracy	Stability	Temperature Coefficient	Resolution	
kHz	ppm	ppm/year	ppm/°C	aF	ppm
0.1	±9	±<1.9	±0.07	16	0.8
1	±5	±<1.0	±0.035	0.8	0.16
10	±11	±<1.9	±0.07	2.4	0.5

- **Measures extremely low loss** down to a dissipation factor of 1.5×10^{-8} tan δ, a conductance of 3×10^{-7} nanosiemens or a resistance up to 1.7×10^{6} gigohms
- **As little as 0.4 second** required for full precision measurements and **as little as 30 ms** required for repeated measurements on the same DUT
- **NIST traceable** calibration
- **IEEE-488 GPIB and IEEE-1174 serial** interfaces included; remote device can act as controller or logger
- **Automatic internal calibration**
- **LabView Driver**
- **Monitoring of calibration due date** and temperature status
- **Deviation Mode with Fast Analog Output** has a frequency response of 4.2 kHz at 3 dB down
- **Continuous Frequency (Option C)** is now available
- **Synchronous Rejection (Patent No. 6,987,391)** eliminates virtually all power line related interference working in conjunction with conventional commutation (test signal reversal)
- **Negative capacitance and loss ranges** measure negative values to allow for unusual DUT's or three terminal networks
- **Three terminal BNC connections** minimize connector costs and number of cables
- **Programmability** can eliminate need for external controller
- **Large, variable-brightness displays** have 8 digits for capacitance and loss and 5 digits for frequency
- **Zero mode compensates for test fixture** capacitance and loss
- **External DC bias** may be applied up to ±100 volts
- **External trigger** capability
- **Self-test diagnostics** on power-up and by command
- **Autoranging**
- **Three year warranty**

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*The term "loss" is used to refer to the component of the impedance which is 90° out of phase with respect to the capacitive component. The AH 2700A can report loss in units of conductance, dissipation factor, series or parallel resistance, or loss vector.

BASIC DESIGN

The AH2700A measures capacitance and loss in medium- and high-impedance ranges, and thus allows using three-terminal rather than five-terminal connections to the DUT (Device Under Test). Its unmatched precision is the result of a uniquely designed ratio transformer which is the culmination of over 40 years of bridge design and manufacture. Equally important is the unique temperature-controlled, fused-silica capacitance standard which allows extremely high measurement stability and immunity to mechanical shock. These elements combine to form a true bridge operating at 50 Hz - 20 kHz to give capacitance/loss results which are independent of the exact test frequency.

MEASUREMENT FEATURES

Units

Capacitance units are picofarads. Loss units are selectable among nanosiemens, dissipation factor, series resistance in kilohms, parallel resistance in gigohms or magnitude of the loss vector in jpF – the choice being indicated by the front panel LED's.

DC Bias

A connector is provided to which an external DC bias voltage may be applied. The AH2700A can switch this voltage to the DUT through user-selectable resistors located within the instrument.

Bridge Balancing Time

Measurement time on a previously unmeasured DUT is less than 0.4 second. However, measurements following the first can be made in less than 30 milliseconds if the averaging time is set to be short.

Speed versus Resolution

Available resolution is determined primarily by the amount of time spent averaging out noise. The trade-off between resolution and measurement speed is selectable in factors of about two from 28 milliseconds to 20 minutes.

Inductance Measurements

The AH2700A can measure negative capacitance values. One way to get a negative capacitance reading is to measure an inductor. The inductance corresponding to a negative capacitance is easily calculated using $L = -1/\omega^2C$. Any inductance above 420µH can be measured. The AH2700A makes extremely accurate inductance measurements since its internal fused-silica reference capacitor is much more perfect than any reference inductor.

Display Results

Results are displayed on large, variable-brightness front panel LED's to as many as eight digits. Results go to remote devices using as many as nine digits.

Synchronous Rejection

A new kind of selectable commutation has been developed and patented by Andeen-Hagerling. It has the ability to reject power line related noise by a factor of about 50 db. This allows the AH2700A to operate at or near the line frequency or its harmonics. Synchronous Rejection has made it possible to offer a continuous frequency version of the AH2700A. Synchronous rejection works in conjunction with the existing commutation feature which performs a periodic test signal reversal to improve rejection of other periodic signals.

Standards Oven

The oven (and hence the entire bridge) normally becomes stable within only 15 minutes after power-on. A blinking front panel LED indicates when the oven has not stabilized or when the ambient temperature is too extreme for stabilization.

Test Voltage

The maximum test voltage applied to the DUT is continuously selectable from 0.3 mV to 15 V r.m.s. The actual voltage applied by the AH2700A may be much smaller than the selected maximum.

Zero Correction

Stray capacitance and loss (typically associated with a test fixture) may occur in parallel with the capacitance and loss that is to be measured. The stray values can be obtained from the previous measurement or from a user-provided value and used to correct the reported results. The stray loss is corrected as if it is in parallel with the loss that is intended to be measured. This occurs no matter what loss units are being used. This is more involved than a deviation measurement which would just do a simple subtraction. (The AH2700A itself has no significant zero offset.)

Analog Output

Rapidly changing capacitances or losses may be studied using the capacitance and/or loss analog outputs. The upper and lower limits of the capacitance or loss that the analog outputs are to span must be specified. Once initiated, both outputs will follow the changing DUT. These outputs have a flat frequency response up to 4.2kHz at 3dB down.

Deviation Measurements

Results may be provided in the form of a difference or offset from a set point value for capacitance or loss or both. The set point value can be the result of a previous measurement or a user-provided value.

Measurement Initiation

A single measurement is initiated by a front panel keystroke, an external trigger pulse, a single character from the IEEE-1174 serial or IEEE-488 ports, or a Group Execute Trigger from the IEEE-488 bus. Measurements can be taken continuously with a selectable delay time between the end of one reading and the start of the next. This delay time can range from zero to many hours in 0.01 second increments.

Cable Length Correction

The three-terminal connection method used by the AH2700A often makes the errors caused by the pair of cables that connect the instrument to the DUT small enough to be ignored. However, cable capacitance and inductance can reduce the accuracy of capacitance measurements made at higher frequencies or capacitances. Similarly, cable resistance can reduce the accuracy of loss measurements made at higher frequencies or capacitances. In these situations, the resistance, capacitance and inductance per meter of cable pair and the length of the cable pair can be entered into the instrument. The AH2700A then automatically reduces these errors.

Measurement Errors

Measurement troubles are easily pinpointed by one of over a dozen English language error messages (or, optionally, error codes). Additionally, many other command and status messages are reported.

Calibration

A unique calibration technique allows internal precision components to be compared against internal temperature-controlled standards with the appropriate corrections being made by a microprocessor. The AH2700A also provides for calibration against external standards. To prevent unauthorized calibrations, a passcode (which only the manager of the instrument can change) must be entered before any calibration can be performed.

Cal Due Date Monitoring

The user can enter a due date into the AH2700A for the internal and capacitance calibrations independently. If one of these dates passes, the CAL INVALID LED blinks and a warning message is reported with each measurement. The temperatures of the internal oven and DAC are similarly monitored.

Self Tests

Power-on or user-initiated self-tests check the microprocessor area, transformer ratio-arm switches, D/A switches and A/D converter. Special circuitry allows numerous internal self-consistency checks.

SYSTEM INTERFACES

IEEE-1174

An IEEE-1174 standard serial interface is included to allow simple operation with a computer, modem, printing terminal or video terminal. These devices can take control of the instrument interactively or can merely log the measured data passively.

IEEE-488

An IEEE-488 (GPIB) bus interface is provided. This implementation includes serial poll and extended talker/listener addressing. A bus controller can operate the bridge or it can work in "talk only" mode to send data to a passive printer or data logger. A front panel "remote" indicator is provided.

Setup of IEEE-488 & IEEE-1174

GPIB bus address and serial baud rate, parity, stop bits, and fill characters are all enterable from the front panel keypad and can be permanently stored from the keypad as well.

Sample Switch Interface

Some applications need to measure more than one sample or capacitor in quick succession. A device called a “sample switch” consisting mainly of very high isolation relays can be constructed to connect one sample at a time to the bridge. The AH2700A provides an interface that allows connection to such a sample switch. This interface has a simple design that allows customized connections to one-of-a-kind sample switches.

Data Formats

Measurement results consist of any combination of five fields: error message, frequency, capacitance, loss, and voltage. The number of decimal places and the width of the capacitance and loss fields are independently selectable. Field and unit labels are optional. Numeric results can be reported in floating point, scientific or engineering notations.

Friendly Commands

Both remote-device interfaces use the same English language commands that are found on the front panel. Commands can be abbreviated by supplying only enough letters to uniquely identify the desired command.

APPLICATION EXAMPLES

- Precision positioning in microscopy applications.
- Scanning capacitance microscopy
- Nanoelectronic characterization including devices composed of nanowires, nanotubes, quantum dots, etc.
- Monitor biophysical activity including capacitance cytometry and DNA detection.
- Magnetometry.
- Calibration work including use as a transfer standard in primary and secondary laboratories.
- Fuel gauge calibration.
- Measurement of very low cryogenic temperatures.
- Thermal expansion measurements for any type of matter, particularly metals, but also non-metals.
- Radiation measurements using crystalline structures and radiation-induced changes in non-metals.
- Rapid, accurate and direct humidity measurements.
- Measurement of the thickness of metals or dielectrics.
- AC resistance measurements to 1000 teraohms.
- Detection of contaminants in refrigerants.
- Displacement and strain. Tiny changes in dimensions are measurable, approaching the diameter of an atomic nucleus. (less than a millionth of the wavelength of visible light.)
- Research, development and production testing of capacitance- or loss-based sensors.
- Determination of quality and characteristics of any insulating medium (solid, liquid or gas). Contaminating water is very easy to detect. See ASTM D150 and D924.
- Monitoring chemical reactions.
- Exceptional at measuring tiny changes in capacitance or loss due to AH2700A’s very high resolution and stability.
- Substitution of electronics in manufactured capacitance-based sensors to obtain greatly improved precision.
- Pressure measurement by reading gas dielectric constant.
- Very high pressure gauge using a solid dielectric capacitor. (Patent No. 3,787,764)
- Liquid and vapor level measurements.

THE AH2700A HAS MANY POSSIBLE USES BEYOND CALIBRATION

The reaction of many technical persons upon first learning of the AH2700A is: "That's a very impressive instrument, but we don't see a need for such precision in our work. Furthermore, such measurements must be more difficult to make." Until the introduction of the original AH2500A, this attitude toward high precision capacitance measurements was justified. Previously, the only commercially available instruments were manually operated, required a skilled operator to spend several minutes balancing the bridge, were prone to reliability problems due to the large number of open switching contacts used, and were still far less stable than the AH2700A. It is not surprising that these bridges have not seen significant use outside of calibration or research laboratories.

Today, the incredible ease with which high precision capacitance and loss measurements can be made with the AH2700A requires a reassessment of previous attitudes. The AH2700A allows totally automated operation with no human intervention. Its ability to maintain its precision over a wide temperature range and its immunity to mechanical shock make it ideally suited for factory floor or portable field use.

To apply the AH2700A to a productive task requires obtaining a suitable sensor. This is where the possibilities become exciting, because capacitive sensors are theoretically the most precise of all electrical sensors. The reasons are:

- A perfect capacitor dissipates no power. Thus relatively high voltages can be applied to the sensor without generating any heat in it. The higher the voltage, the better the signal-to-noise ratio. In contrast, all resistive sensors dissipate heat while being measured.
- A perfect capacitor generates no noise. Resistors are always limited by thermal noise and are susceptible to other kinds of noise as well.
- A perfect capacitor is linear with applied voltage. Most resistive elements are at least slightly non-linear and inductive elements are usually extremely non-linear.
- Real, practical capacitors can be made with a high degree of perfection.
- The variation with temperature of a small capacitor can be made very small and simultaneously very linear. Other elements, such as resistors, require compensation schemes which cause them to have low temperature coefficients over a narrow temperature range but much higher and very non-linear variations over a broader range.

These characteristics allow the creation of simple yet very precise capacitance sensors based on the change in area or the change in separation of a pair of plates, cylinders, etc. Such a sensor could also be based on the introduction of a conducting material of unknown thickness, size, shape, position, or whatever into the active field of a capacitor. If the material within the active field is a reasonably good insulating dielectric, then both the dielectric constant and the loss of the material are obtainable. This can be a very simple way to observe chemical changes, detect contaminants, etc., in a wide variety of non-metals.

INTRODUCTION TO THE SPECIFICATIONS

Bridge Balance Mode

In its conventional mode of operation, the AH2700A operates as a true bridge. It does this by balancing its calibrated, high-precision, internal bridge network against an external device under test (DUT). The balancing process requires making a series of adjustments to the bridge such that each adjustment brings the bridge closer to a state of balance. This process balances against the DUT well enough to allow computing the most significant six or seven digits of the capacitance result. However, due to the precision required, some of the switching is done with relays which slows down the rate at which measurements can be taken.

The degree of imbalance of the bridge is detected using a very high gain preamplifier (preamp) connected across the bridge. The balancing process minimizes the output signal from the preamp but leaves a residual signal. This residual is digitized and matrix multiplied to obtain the two or three least significant digits of the capacitance and loss results.

This conventional mode of operation is called the Bridge Balance Mode (BMode). In this mode, *the user has no access* to the residual imbalance signal from the preamp.

Deviation Mode and the Analog Outputs

A new mode of operation has been added to the AH2700A called Deviation Mode. In this mode, *the user is given access* to the processed imbalance signal from the preamp.

At the beginning of Deviation Mode (DMode) measurements, the bridge is first set as in BMode to capacitance and loss values that are close to those of the DUT. The bridge can be used to accurately measure these values or they can be manually entered. This pair of values is called the Bridge Balanced Point (BBPoint). Once DMode measurements begin, the BBPoint remains fixed for the duration of the measurements.

The imbalance signal from the preamp now represents the deviation of the capacitance and loss of the DUT from the BBPoint. This signal is digitized at a rate of 50,098 samples/s and matrix multiplied by a DSP to convert it to two real-time data streams representing the capacitance and loss deviations.

From this point the two deviation data streams each split into two branches. One branch goes to a pair of digital to analog converters (DAC's) which produce two analog voltages at the rear panel of the instrument that correspond to the capacitance and loss deviation signals. The other branch is used to produce alphanumeric results which are sent to the front panel and may also be sent to the serial and/or GPIB ports.

BRIDGE BMODE SPECIFICATIONS

Notation:

The specifications are grouped according to whether the DUT is modeled as a resistor in parallel with a capacitor or in series with it.

Parallel:	"C"	is the value of the measured (parallel) capacitance in picofarads (pF= 10^{-12} F). Also used are attofarads (aF = 10^{-6}pF) and femtofarads (fF = 10^{-3}pF).
	"G"	is the value of the measured loss expressed as a conductance in nanosiemens (nS = 10^{-9} S).
	"D"	is the value of the measured loss expressed as a dissipation factor (tan δ). D has no units.
	"R_P"	is the value of the measured loss expressed as a parallel resistance in gigohms (GΩ = 10^9Ω).
	"G/ω"	is the value of the measured loss expressed as the loss component of a complex vector in units of (imaginary) capacitance (jpF= 10^{-12} jF).
Series:	"C_S"	is the value of the measured series capacitance in picofarads (pF = 10^{-12} F)
	"R_S"	is the value of the measured loss expressed as a series resistance in kilohms (kΩ = 10^3 Ω).
Misc:	"*f*"	is the frequency in kilohertz (kHz = 10^3 Hz).
	"ω"	equals 2π*f*.
	"t"	is the measurement time in seconds.
	"V"	is the AC test signal voltage in volts applied across the DUT. Its upper limit is selectable to have any value from 0.3 mV to 15 V.
	"ppm"	is Parts Per Million.

General:

The expressions which give the uncertainty for accuracy, linearity, stability, resolution, and temperature coefficient give absolute rather than statistical uncertainties. Absolute uncertainties are the most conservative of those in common use. Andeen-Hagerling guarantees repair within the warranty period of any AH2700A whose measured errors repeatedly exceed these uncertainties. The expressions may be evaluated for particular values of capacitance (C or C_S), loss (G, D, Rp, R_S or G/ω), test voltage (V), and measurement time (t). Except for absolute resolution, G/ω shares the same equations as G. Only the resolution expressions contain the measurement time. However, the other uncertainty expressions assume that the measurement time is long enough so these other uncertainties are not limited by the resolution specification. In other words, specifications such as accuracy may be limited by the resolution rather than the accuracy expression if the measurement time is set too short.

Many of the expressions include an error contribution from cable effects. This cable is assumed to be an AH-DCOAX/TP cable that is one meter in length. Where these one or two cable error contribution terms exist, they may be identified by their enclosure within a pair of braces "{}". This pair will always be the inner of two pairs of braces.

Most of the uncertainty expressions can be evaluated by direct substitution of the values of capacitance, loss and voltage as if they were read directly from the AH2700A. The instrument reports these values in the units given in the notation section above. Some expressions also require the dissipation factor, D, which, if it is not directly available, can be calculated using one of the following relations:

$$D = G/(\omega C), \quad D = 1/(\omega C R_P) \quad \text{or} \quad D = \omega C_S R_S \times 10^{-6}$$

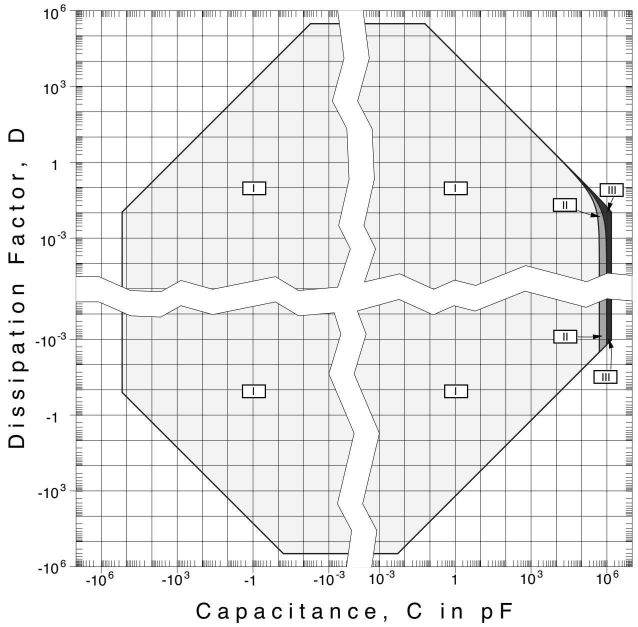


Figure 1. Measurable values of C and D are enclosed within shaded areas. II and III are examples of specific frequencies.

Region I applies to all frequencies
Regions I & II apply to frequencies below 10kHz
Regions I, II & III apply to frequencies below about 3 kHz

For low values of capacitance and loss, the maximum allowable test voltage set by the user (usually 15 volts at ≥1 kHz) can be substituted for every occurrence of V in the uncertainty expressions. For larger values of capacitance and loss, if the voltage value is not taken from a measurement result, then the value of V automatically chosen by the AH2700A must be determined from Table 1. The following equations may be used to convert to the units of C and G used in the table from units other than those used in the table.

Given units of:	*D:*	use	$G = \omega C D$
	R_P:		$G = 1/R_P$
	R_S:		$G = \omega C_S D/(1+D^2)$
	C_S:		$C = C_S/(1+D^2)$

Accuracy, stability, linearity and resolution specifications assume a recent internal calibration at the operating temperature. All specifications are valid for positive values of capacitance and loss. Specifications for negative values of capacitance and/or loss may be computed by entering their absolute values into the expressions and then multiplying the final results by three.

Range:*

Parallel: *C:* -0.00165/D μF to +10/(*f*+D/0.0019) μF
for $3\times10^5 \geq D \geq 0.01$
-0.165 μF to the lesser of +1.65 μF
or +10/(*f*+D/0.0019) μF for $-0.001 \leq D < 0.01$
-0.165 μF to +0.00165/|D| μF for $-0.1 \leq D < -0.001$
-0.0165/|D|μF to +0.00165/|D|μF for $-3\times10^5 \leq D < -0.1$
The capacitance range is also graphed in Figure 1.
G: See Table 1.
D: See Figure 1 and the equations for C above.

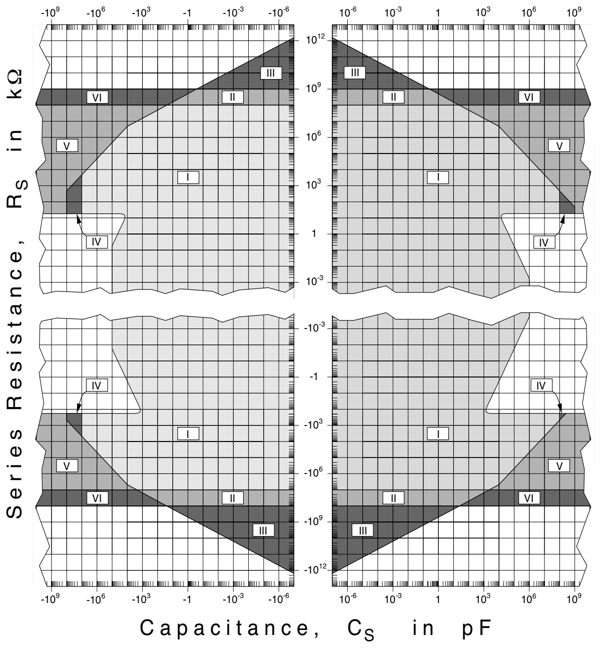


Figure 2. The values of C_S and R_S are measurable in the six shaded regions. In five of these regions, one or both of the measured values are too large to report on the AH2700A's display. In three of these five regions, one or both values are also too large to send to any remote devices. The table below shows what can be reported in each region. A "Display" entry means that the result can be shown on the instrument's display. A "Remotes" entry means that the result can be reported to an IEEE-1174 or IEEE-488 device.

	C_S	R_S
I	Display & Remotes	Display & Remotes
II	Display & Remotes	Remotes only
III	Display & Remotes	Neither
IV	Remotes only	Display & Remotes
V	Neither	Display & Remotes
VI	Neither	Remotes only

*Regions V and VI extend to infinity to the right and left because the resistance associated with an infinite C_S is measurable even though C_S itself is not reportable.

R_P: -8×10^{-5} GΩ to -1.7×10^{6} GΩ
and $+8\times10^{-6}$ GΩ to $+1.7\times10^{6}$ GΩ @ 1 kHz
Series: *C_S:* See Figure 2 for the range at 1kHz.
R_S: See Figure 2 for the range at 1kHz.

*The ranges of all measurable variables except R_P cover a region defined by negative numbers for the lower limit and positive numbers for the upper limit. This is due to the AH2700A's ability to measure both positive and negative values of capacitance and loss. Other instruments typically measure only positive values and have ranges which cover a region defined by small positive numbers for the lower limits to large positive numbers for the upper limits. For the AH2700A, the small numbers corresponding to the lower limits of other instruments are given by the AH2700A's resolution specifications in absolute units.

Front Panel Display Limitations:

(The front panel display may further limit the range and resolution of the capacitance and loss.)

Capacitance: 0.1 aF is best display resolution for C and C_S.
Loss: *G:* 10^{-7} nS is best conductance display resolution.
D: 10^{-7} is best dissipation display resolution.
R_S: 10^{-7} kΩ is best series resistance display resolution.
R_P: 10^{-7} GΩ is best parallel resistance display resolution.

Remote Device Reporting Limitations:

Capacitance: 0.01 aF is best resolution for C and C_S.
Loss: *G:* 10^{-8} nS is best conductance resolution.
D: 10^{-8} is best dissipation resolution.
R_S: 10^{-7} kΩ is best series resistance resolution.
R_P: 10^{-8} GΩ is best parallel resistance resolution.

Frequencies: 50, 60, 70, 80, 100, 120, 140, 160, 200, 240, 300, 400, 500, 600, 700, 800 Hz and 1.0, 1.2, 1.4, 1.6, 2.0, 2.4, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10, 12, 14, 16 and 20 kHz ± 0.0025%.

Sensitivity to changes in power line voltage:

Capacitance: ± 0.002 ppm per 1% change in line voltage.
Loss: Not measurable.

DC Bias: Up to ±100 volts may be applied to the DUT through the external DC bias input.

AC Test Signal Voltages: Any voltage from 0.0003 to 15 V may be entered to a resolution of 0.1%. The available ranges for a given entered voltage are on the line in Table 1 having the next highest voltage. The AH2700A will automatically use the lesser of the user's selected voltage or the highest voltage listed in the table which provides sufficient range to be able to measure the capacitance and loss of the DUT. The voltages listed have tolerances of ±5%.

Temperature range: 0° to 45°C while operating
-40° to +75°C while in storage

Humidity: 0 to 85% operating relative humidity, non-condensing.
0 to 60% storage relative humidity, non-condensing.

Power requirements: 25 watts, 48 to 440 Hz, 85 to 115, 102 to 138, 187 to 253 and 204 to 276 volts rms

Packaging: The instrument is 3.5 inches (8.9 cm) high and 15 inches (38.1 cm) deep behind the front panel. Hardware for rack mounting and a bail for bench top use are provided.

Weight: 18 pounds (8.2 kg)

Safety and EMC conformity: conforms to EN61326:1998 and EN 61010-1: 1993/A2: 1995

Patents: The AH2700A is currently protected by U.S. Patent No. 6,204,673 and 6,987,391

Warranty: The AH2700A is covered by a three year warranty. Forward and return shipping is covered during the first three months of the warranty.

Note: Specifications are subject to change without notice.

Table 1. Capacitance and conductance ranges for the preferred limiting voltages with $f \geq 1$ kHz. For $f < 1$ kHz, multiply Limit by f in kHz. A_T and A_C are used by the specification equations.

Limit	Capacitance range	Range of G; f is in kHz	A_T	A_C
15.00 V	-11 to +110 pF	-0.8f to +8f nS	0	0
7.50 V	-22 to +220 pF	-1.6f to +16f nS	0	0
3.00 V	-55 to +550 pF	-4f to +40f nS	0	0
1.50 V	-110 to +1100 pF	-8f to +80f nS	0	0
0.750 V	-220 to +2200 pF	-16f to +160f nS	0	0
0.250 V	-660 to +6600 pF	-48f to +480f nS	0	0
0.100 V	-1650 to +16,500 pF	-120f to +1200f nS	5	0.01
0.030 V	-5500 to +55,000 pF	-400f to +4000f nS	10	0.03
0.010 V	-16,500 to +165,000 pF	-1200f to +12,000f nS	15	0.1
0.003 V	-55,000 to +550,000 pF	-4000f to +40,000f nS	20	0.3
0.001 V	-165,000 to +1650,000 pF	-12,000f to +120,000f nS	30	1

Resolution in absolute units:*

Parallel:

$$C:\ \left\{\frac{C}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{V}\left[4+\frac{1}{f}+5n_c\right]+\frac{n_vC}{V}+\frac{50G}{\omega}+(1+10A_C)\frac{f^2C}{500}\left[1+\frac{1700}{200+CV}\right]\right\}\times 10^{-6}\ \text{pF}$$

$$G:\ \left\{50G+\omega\left[\frac{C}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{V}\left(4+\frac{1}{f}+5n_c\right)+\frac{n_vC}{V}+8\times10^{-6}fC^2+(3+50A_C)\,\frac{fC}{50}\left(1+\frac{1700}{200+CV}\right)\right]\right\}\times 10^{-6}\ \text{nS}$$

Divide result by ω to get absolute resolution for G/ω

$$D:\ \left\{(1+D^2)^{1/2}\left[50D+\frac{1}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{CV}\left(4+\frac{1}{f}+5n_c\right)+\frac{n_v}{V}+8\times10^{-6}fC+(3+50A_C)\frac{f}{50}\left(1+\frac{1700}{200+CV}\right)\right]\right\}\times 10^{-6}$$

$$R_P:\ \left\{50R_p+\omega R_p^2\left[\frac{C}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{V}\left(4+\frac{1}{f}+5n_c\right)+\frac{n_vC}{V}+8\times10^{-6}fC^2+(3+50A_C)\,\frac{fC}{50}\left(1+\frac{1700}{200+CV}\right)\right]\right\}\times 10^{-6}\ \text{G}\Omega$$

Series:

$$C_S:\ \left\{\frac{C_s}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{V}\left[4+\frac{1}{f}+5n_c\right](1+D^2)+\frac{n_vC_s}{V}+50DC_s+(1+10A_C)\frac{f^2C_s}{500}\left[1+\frac{1700}{200+CV}\right]\right\}\times 10^{-6}\ \text{pF}$$

$$R_S:\ \left\{50R_s+1.3+\frac{R_s}{D}\left[\frac{1}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{C_sV}\left(4+\frac{1}{f}+5n_c\right)(1+D^2)+\frac{n_v}{V}+(3+50A_C)\frac{f}{50}\left(1+\frac{1700}{200+CV}\right)\right]\right\}\times 10^{-6}\ \text{k}\Omega$$

where $n_c = 1.4t^{-1/2}$ and $n_v = 0.0l(1+0.1/f)(R_S+l0)^{1/2}(1+D^2)^{1/2}t^{-1/2}$. A_C is found in Table 1.
The series resistance R_S needed for n_v may be calculated using $R_S = D\times l0^6/(\omega C(l+D^2))$.

Resolution in ppm:*

Parallel:

$$C:\ \frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{CV}\left[4+\frac{1}{f}+5n_c\right]+\frac{n_v}{V}+50D+(1+10A_C)\frac{f^2}{500}\left[1+\frac{1700}{200+CV}\right]$$

$$G:\ 50+\frac{\omega}{G}\left\{\frac{C}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{V}\left[4+\frac{1}{f}+5n_c\right]+\frac{n_vC}{V}+8\times10^{-6}fC^2+(3+50A_C)\,\frac{fC}{50}\left[1+\frac{1700}{200+CV}\right]\right\}$$

$$D:\ \frac{(1+D^2)^{1/2}}{D}\left\{50D+\frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{CV}\left[4+\frac{1}{f}+5n_c\right]+\frac{n_v}{V}+8\times10^{-6}fC+(3+50A_C)\frac{f}{50}\left[1+\frac{1700}{200+CV}\right]\right\}$$

$$R_P:\ 50+\omega R_p\left\{\frac{C}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{V}\left[4+\frac{1}{f}+5n_c\right]+\frac{n_vC}{V}+8\times10^{-6}fC^2+(3+50A_C)\,\frac{fC}{50}\left[1+\frac{1700}{200+CV}\right]\right\}$$

Series:

$$C_S:\ \frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{C_sV}\left[4+\frac{1}{f}+5n_c\right](1+D^2)+\frac{n_v}{V}+50D+(1+10A_C)\frac{f^2}{500}\left[1+\frac{1700}{200+CV}\right]$$

$$R_S:\ 50+\frac{1.3}{R_s}+\frac{1}{D}\left\{\frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{C_sV}\left[4+\frac{1}{f}+5n_c\right](1+D^2)+\frac{n_v}{V}+(3+50A_C)\frac{f}{50}\left[1+\frac{1700}{200+CV}\right]\right\}$$

*Resolution is the smallest *repeatable* difference in readings that is *guaranteed* to be measurable at *every* capacitance or loss value. Useful resolution is typically a factor of ten better.

Non-linearity in ppm:

Parallel:

$$C\text{:}\quad \pm\left\{\frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{CV}\left[4+\frac{1}{f}\right]+50D+\frac{f^{2}}{200}\left[1+\frac{1700}{200+CV}\right]+\{1.5\times10^{-6}f^{2.5}C\}\right\}$$

$$G\text{:}\quad \pm\left\{50+\frac{\omega}{G}\left[\frac{C}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{V}\left(4+\frac{1}{f}\right)+8\times10^{-6}fC^{2}+\frac{fC}{6}\left(1+\frac{1700}{200+CV}\right)\right]+\left\{\frac{1.2\times10^{-4}\omega fC^{2}}{G}\right\}\right\}$$

$$D\text{:}\quad \pm\left\{\frac{(1+D^{2})^{1/2}}{D}\left[50D+\frac{1}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{CV}\left(4+\frac{1}{f}\right)+8\times10^{-6}fC+\frac{f}{6}\left(1+\frac{1700}{200+CV}\right)\right]+\left\{\frac{(1+D^{2})^{1/2}}{D}[1.2\times10^{-4}fC]\right\}\right\}$$

$$R_{P}\text{:}\quad \pm\left\{50+\omega R_{p}\left[\frac{C}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{V}\left(4+\frac{1}{f}\right)+8\times10^{-6}fC^{2}+\frac{fC}{6}\left(1+\frac{1700}{200+CV}\right)\right]+\{1.2\times10^{-4}\omega fR_{p}C^{2}\}\right\}$$

Series:

$$C_{S}\text{:}\quad \pm\left\{\frac{1}{20}\left[2+\frac{1}{f}\right]+\frac{1.5}{C_{s}V}\left[4+\frac{1}{f}\right](1+D^{2})+50D+\frac{f^{2}}{200}\left[1+\frac{1700}{200+CV}\right]+\{1.5\times10^{-6}f^{2.5}C\}\right\}$$

$$R_{S}\text{:}\quad \pm\left\{50+\frac{1.3}{R_{s}}+\frac{1}{D}\left[\frac{1}{20}\left(2+\frac{1}{f}\right)+\frac{1.5}{C_{s}V}\left(4+\frac{1}{f}\right)(1+D^{2})+\frac{f}{6}\left(1+\frac{1700}{200+CV}\right)\right]+\left\{\frac{20}{R_{s}}\right\}\right\}$$

Non-linearity is the deviation from a best fit straight line through a plot of the measured quantity versus the actual quantity. The test signal voltage is assumed to be constant.

Accuracy in ppm following calibration:

Parallel:

$$C\text{:}\quad \pm\left\{\frac{1}{2}\left[8+\frac{1}{f}+f\right]+\frac{1.5}{CV}\left[4+\frac{1}{f}\right]+200D+\frac{f^{2}}{100}\left[1+\frac{1700}{200+CV}\right]+A_{T}\left[f+\frac{1}{f}\right]+\left\{3\times10^{-6}f^{2.5}C+\frac{f^{2}}{4C}\right\}\right\}$$

A_T is found in Table 1.

$$G\text{:}\quad \pm\left\{200+\frac{\omega}{G}\left[\frac{C}{2}\left(2+\frac{1}{f}+f\right)+\frac{1.5}{V}\left(4+\frac{1}{f}\right)+\frac{fC^{2}}{3300}+\frac{fC}{3}\left(1+\frac{1700}{200+CV}\right)+A_{T}C\left(f+\frac{1}{f}\right)\right]+\left\{\frac{\omega f}{G}\left[2\times10^{-4}C^{2}+\frac{f}{4}\right]\right\}\right\}$$

$$D\text{:}\quad \pm\left\{\frac{(1+D^{2})^{1/2}}{D}\left[200D+\frac{1}{2}\left(2+\frac{1}{f}+f\right)+\frac{1.5}{CV}\left(4+\frac{1}{f}\right)+\frac{fC}{3300}+\frac{f}{3}\left(1+\frac{1700}{200+CV}\right)+A_{T}\left(f+\frac{1}{f}\right)\right]+\left\{\frac{(1+D^{2})^{1/2}f}{D}\left[2\times10^{-4}C+\frac{f}{4C}\right]\right\}\right\}$$

$$R_{P}\text{:}\quad \pm\left\{200+\omega R_{p}\left[\frac{C}{2}\left(2+\frac{1}{f}+f\right)+\frac{1.5}{V}\left(4+\frac{1}{f}\right)+\frac{fC^{2}}{3300}+\frac{fC}{3}\left(1+\frac{1700}{200+CV}\right)+A_{T}C\left(f+\frac{1}{f}\right)\right]+\left\{\omega R_{p}f\left[2\times10^{-4}C^{2}+\frac{f}{4}\right]\right\}\right\}$$

Series:

$$C_{S}\text{:}\quad \pm\left\{\frac{1}{2}\left[8+\frac{1}{f}+f\right]+\frac{1.5}{C_{s}V}\left[4+\frac{1}{f}\right](1+D^{2})+200D+\frac{f^{2}}{100}\left[1+\frac{1700}{200+CV}\right]+A_{T}\left[f+\frac{1}{f}\right]+\left\{3\times10^{-6}f^{2.5}C+\frac{f^{2}(1+D^{2})}{4C_{s}}\right\}\right\}$$

$$R_{S}\text{:}\quad \pm\left\{200+\frac{50}{R_{s}}+\frac{1}{D}\left[\frac{1}{2}\left(2+\frac{1}{f}+f\right)+\frac{1.5}{C_{s}V}\left(4+\frac{1}{f}\right)(1+D^{2})+\frac{f}{3}\left(1+\frac{1700}{200+CV}\right)+A_{T}\left(f+\frac{1}{f}\right)\right]+\left\{\frac{30}{R_{s}}+\frac{f^{2}(1+D^{2})}{4DC_{s}}\right\}\right\}$$

The length of the cables connecting the 2700A to the DUT has a negligible effect on the accuracy for *small* capacitances. This assumes that the coaxial shield on these cables has 100% coverage. If uncorrected by the CABLE command, cables similar to RG-58 will increase the capacitance readings at 1 kHz by about 40 ppm per meter of cable pair and per µF of capacitance being measured.

The accuracy Y years following calibration may be calculated from the expression A + YS where A is the desired accuracy expression from above and S is the corresponding stability per year below.

Stability in ppm per year:

Parallel:

$$C\text{:}\quad \pm\left\{\frac{1}{10}\left[8+\frac{1}{f}+f\right]+\frac{1}{2CV}\left[4+\frac{1}{f}\right]+30D+\left\{10^{-6}f^{2.5}C+\frac{f^{2}}{20C}\right\}\right\}$$

$$G\text{:}\quad \pm\left\{30+\frac{\omega}{G}\left[\frac{C}{10}\left(2+\frac{1}{f}+f\right)+\frac{1}{2V}\left(4+\frac{1}{f}\right)+5\times10^{-5}fC^{2}\right]+\left\{\frac{\omega f}{G}\left[3\times10^{-5}C^{2}+\frac{f}{20}\right]\right\}\right\}$$

$$D\text{:}\quad \pm\left\{\frac{(1+D^{2})^{1/2}}{D}\left[30D+\frac{1}{10}\left(2+\frac{1}{f}+f\right)+\frac{1}{2CV}\left(4+\frac{1}{f}\right)+5\times10^{-5}fC\right]+\left\{\frac{(1+D^{2})^{1/2}f}{D}\left[3\times10^{-5}C+\frac{f}{20C}\right]\right\}\right\}$$

$$R_{P}\text{:}\quad \pm\left\{30+\omega R_{p}\left[\frac{C}{10}\left(2+\frac{1}{f}+f\right)+\frac{1}{2V}\left(4+\frac{1}{f}\right)+5\times10^{-5}fC^{2}\right]+\left\{\omega R_{p}f\left[3\times10^{-5}C^{2}+\frac{f}{20}\right]\right\}\right\}$$

Series:

$$C_{S}\text{:}\quad \pm\left\{\frac{1}{10}\left[8+\frac{1}{f}+f\right]+\frac{1}{2C_{s}V}\left[4+\frac{1}{f}\right](1+D^{2})+30D+\left\{10^{-6}f^{2.5}C+\frac{f^{2}(1+D^{2})}{20C_{s}}\right\}\right\}$$

$$R_{S}\text{:}\quad \pm\left\{30+\frac{8}{R_{s}}+\frac{1}{D}\left[\frac{1}{10}\left(2+\frac{1}{f}+f\right)+\frac{1}{2C_{s}V}\left(4+\frac{1}{f}\right)(1+D^{2})\right]+\left\{\frac{5}{R_{s}}+\frac{f^{2}(1+D^{2})}{20DC_{s}}\right\}\right\}$$

Temperature coefficient relative to change in ambient temperature in ppm per °C:

Parallel:

$$C:\ \pm\left\{\frac{1}{400}\left[8+\frac{1}{f}+f\right]+20D+\frac{A_T}{33}\left[f+\frac{1}{f}\right]+\frac{200}{2+6CV(2+1/f)}+\left\{10^{-7}f^{2.5}C+\frac{f^2}{100C}\right\}\right\}$$

$$G:\ \pm\left\{20+\frac{\omega C}{G}\left[\frac{3}{400}\left(2+\frac{1}{f}+f\right)+3\times10^{-6}fC+\frac{A_T}{33}\left(f+\frac{1}{f}\right)\right]+\frac{400}{4+VG(2+1/f)/\omega}+\left\{\frac{\omega f}{G}\left[2\times10^{-6}C^2+\frac{f}{100}\right]\right\}\right\}$$

$$D:\ \pm\left\{\frac{(1+D^2)^{1/2}}{D}\left[20D+\frac{3}{400}\left(2+\frac{1}{f}+f\right)+3\times10^{-6}fC+\frac{A_T}{33}\left(f+\frac{1}{f}\right)\right]+\frac{200}{2+6CV(2+1/f)}+\frac{400}{4+CVD(2+1/f)}+\left\{\frac{(1+D^2)^{1/2}f}{D}\left[2\times10^{-6}C+\frac{f}{100C}\right]\right\}\right\}$$

$$R_P:\ \pm\left\{20+\omega CR_p\left[\frac{3}{400}\left(2+\frac{1}{f}+f\right)+3\times10^{-6}fC+\frac{A_T}{33}\left(f+\frac{1}{f}\right)\right]+\frac{400}{4+V(2+1/f)/\omega R_p}+\left\{\omega R_p f\left[2\times10^{-6}C^2+\frac{f}{100}\right]\right\}\right\}$$

Series:

$$C_S:\ \pm\left\{\frac{1}{400}\left[8+\frac{1}{f}+f\right]+20D+\frac{A_T}{33}\left[f+\frac{1}{f}\right]+\frac{200}{2+6C_sV(2+1/f)/(1+D^2)}+\left\{10^{-7}f^{2.5}C+\frac{f^2(1+D^2)}{100C_s}\right\}\right\}$$

$$R_S:\ \pm\left\{20+\frac{0.5}{R_s}+\frac{1}{D}\left[\frac{3}{400}\left(2+\frac{1}{f}+f\right)+\frac{A_T}{33}\left(f+\frac{1}{f}\right)\right]+\frac{400}{4+C_sVD(2+1/f)/(1+D^2)}+\left\{\frac{0.3}{R_s}+\frac{f^2(1+D^2)}{100DC_s}\right\}\right\}$$

where A_T is found in Table 1.

SELECTED BRIDGE BALANCING MODE SPECIFICATIONS IN GRAPHICAL FORM

Specifications versus frequency:

There are ten graphs on pages 10-12 of plots versus frequency of the accuracy, resolution in ppm, non-linearity, stability and temperature coefficient specifications. These plots were generated by using the specification equations presented on the previous three pages except that the dissipation equations were multiplied by D. Each graph contains a set of curves for various values of capacitance. These capacitance values range from one femtofarad up to one microfarad. The graphs show that the specifications tend to be best for capacitance values in the region of 10 pF to 1 nF and worst at either extreme of capacitance. These graphs assume that the capacitance of the DUT is of good quality implying a small dissipation factor (D<~0.001). Each curve was plotted using the maximum possible voltage.

Accuracy specifications versus C and loss:

There are six contour plots on this and the next page. The three graphs in the left columns are contour plots of the accuracy of capacitance(C) versus C and conductance(G). The first of these graphs applies at 100 Hz, the second one at 1 kHz and the third one at 10 kHz. The accuracy in the area within or below each contour is equal to or better than the labeled accuracy (in percent) for that contour. These graphs show that the accuracy of C depends not only on the value of C but also on the value of the loss. Each contour was plotted using the maximum possible voltage.

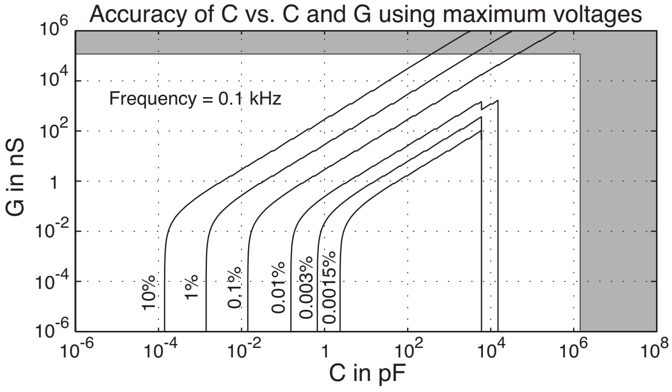
The graph below at the right is a contour plot of the accuracy of the dissipation factor(D) versus C and D. The accuracy in the area within each contour is equal to or better than the labeled accuracy (in percent) for that contour. This graph shows that the accuracy of D depends not only on the value of D but also on the value of C.

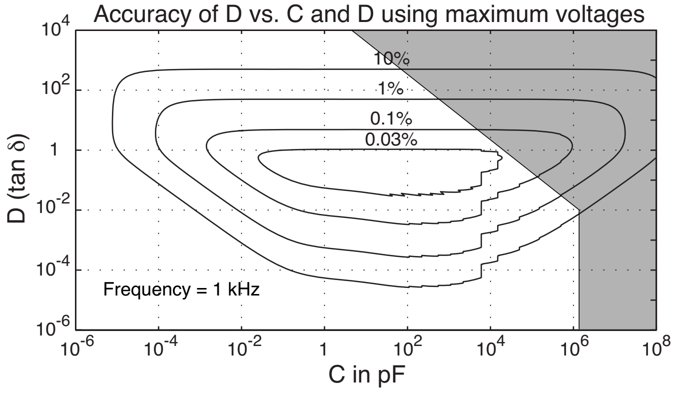
Accuracy specifications at selected voltages:

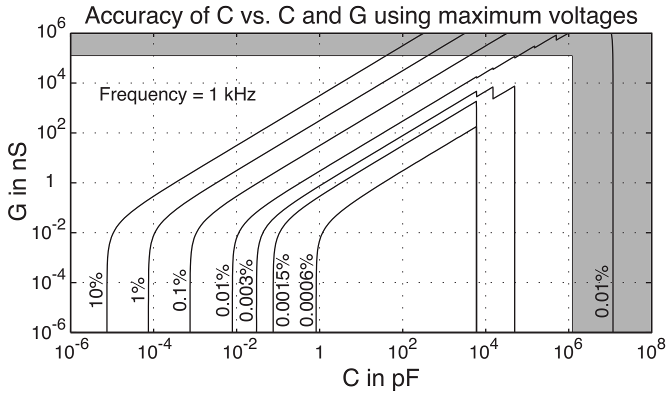
The first graph in the right column on the next page is a contour plot of the accuracy of C versus C and G. The accuracy in the area within or below each contour is equal to or better than 0.001%.

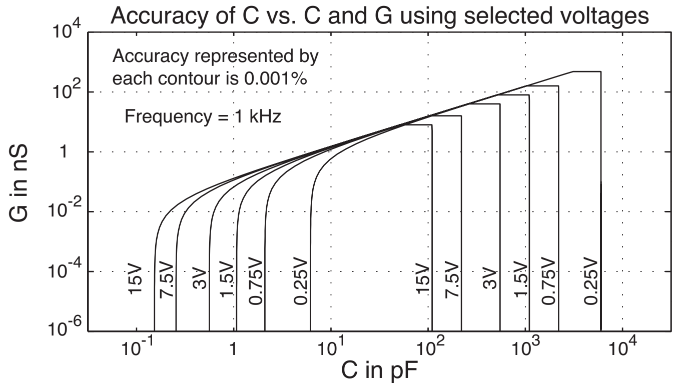
The second graph in the right column on the next page is a contour plot of the accuracy of D versus C and D. The accuracy in the area within each contour is equal to or better than 0.03%.

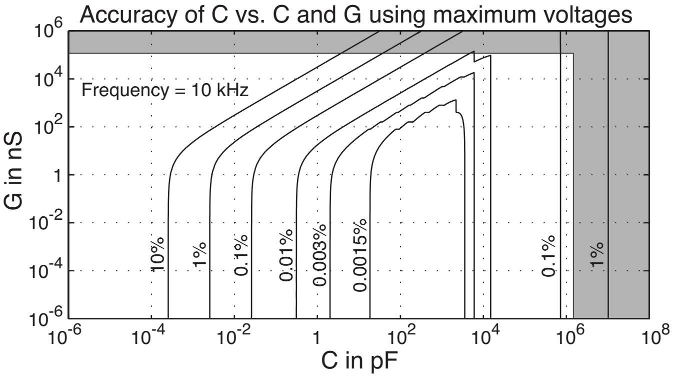
These graphs show how the accuracy of C and D depends on the measurement voltage. Each contour represents operation at the labeled voltage which is one of the voltages in Table 1 on page 7. The gray regions are out of range.

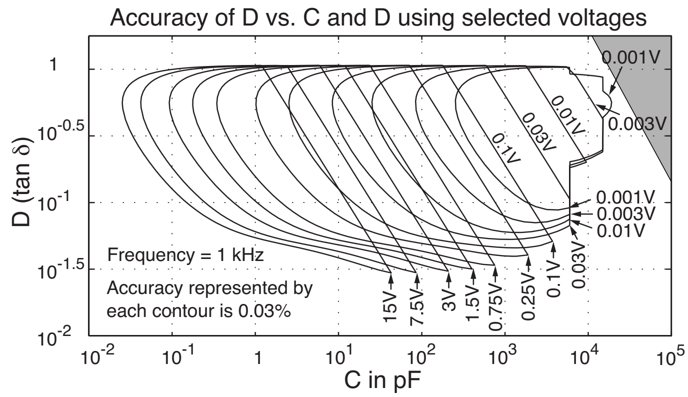


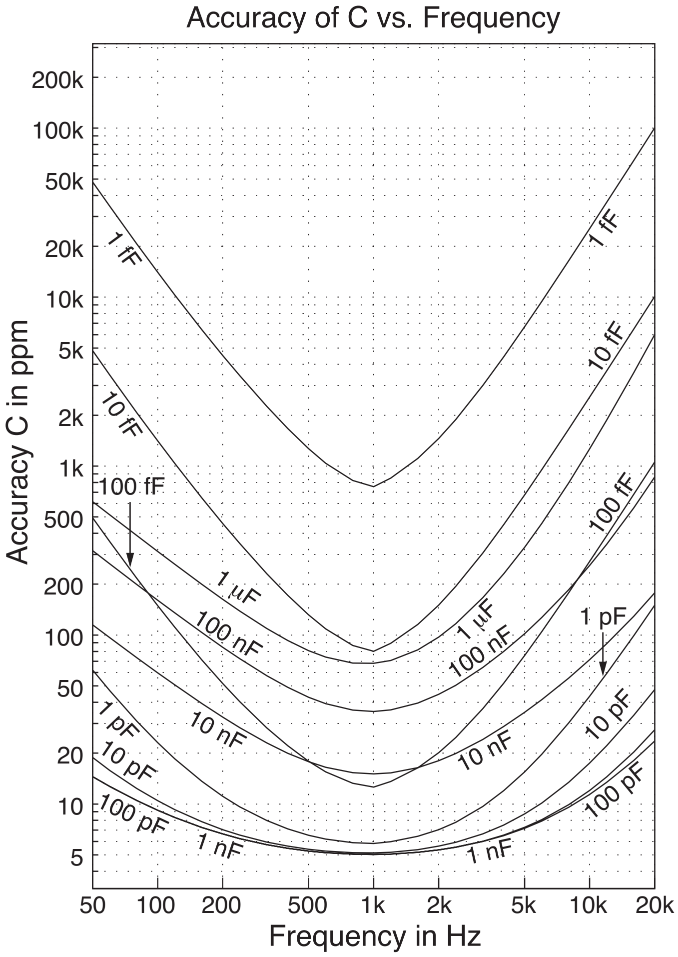


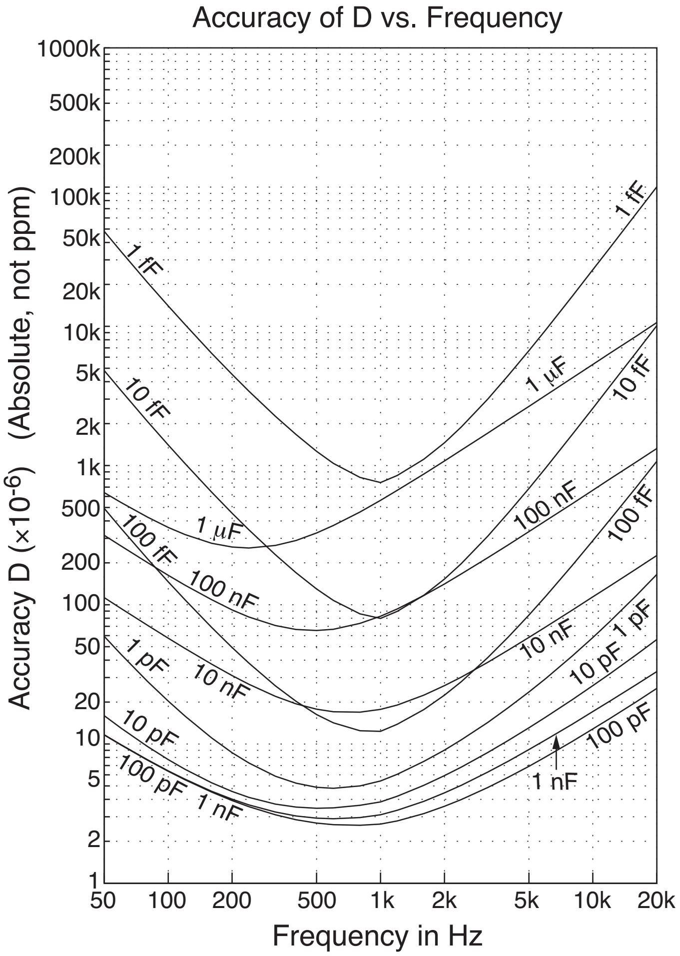

Accuracy of C vs. C and G using maximum voltages

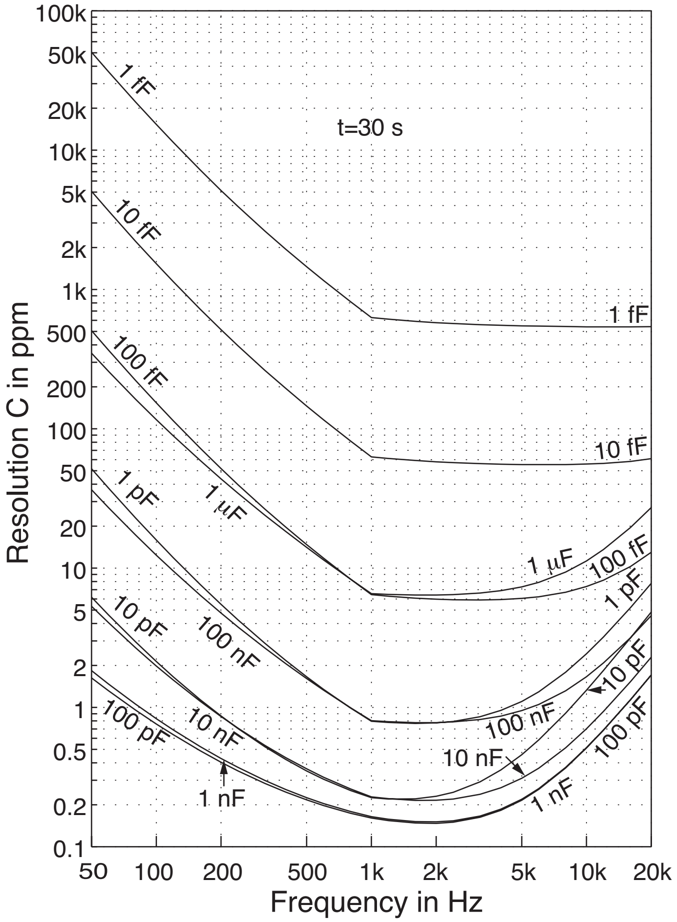

Accuracy of C vs. C and G using selected voltages


Accuracy of C vs. C and G using maximum voltages

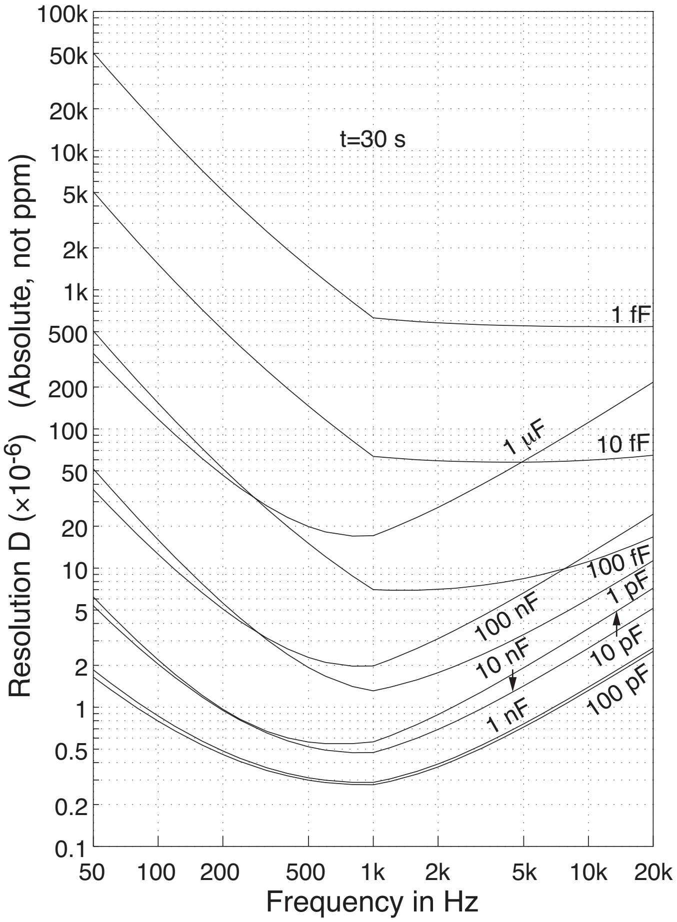

Accuracy of D vs. C and D using selected voltages


Accuracy of C vs. Frequency

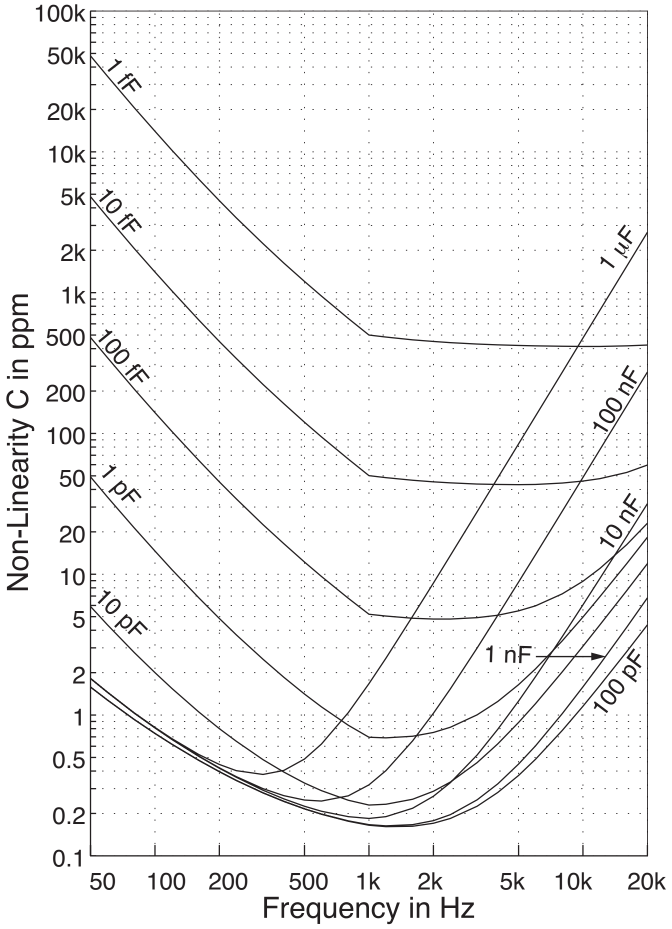

Accuracy of D vs. Frequency



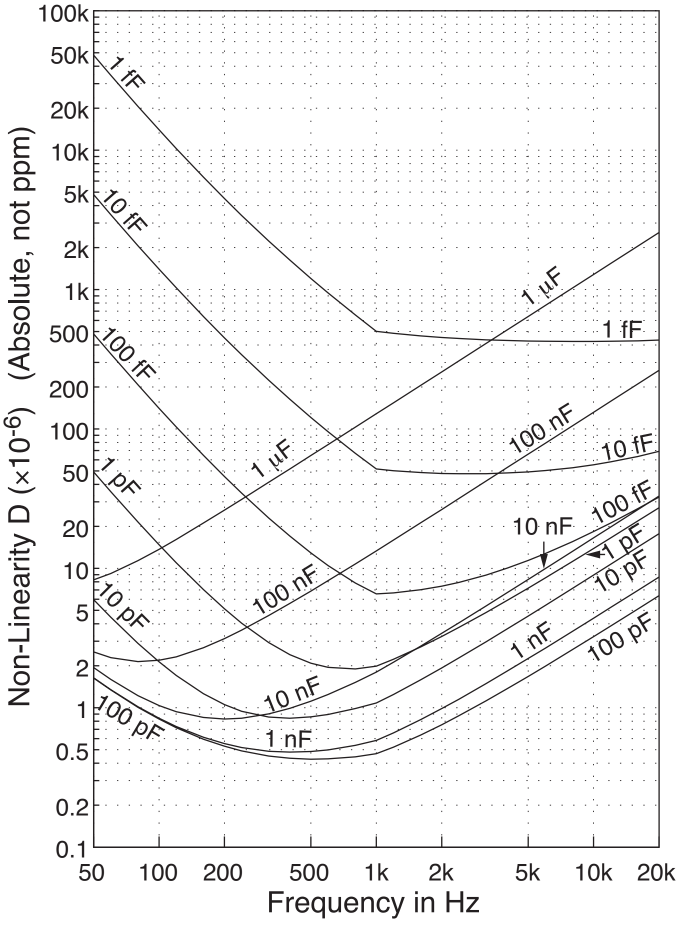
Resolution of C vs. Frequency



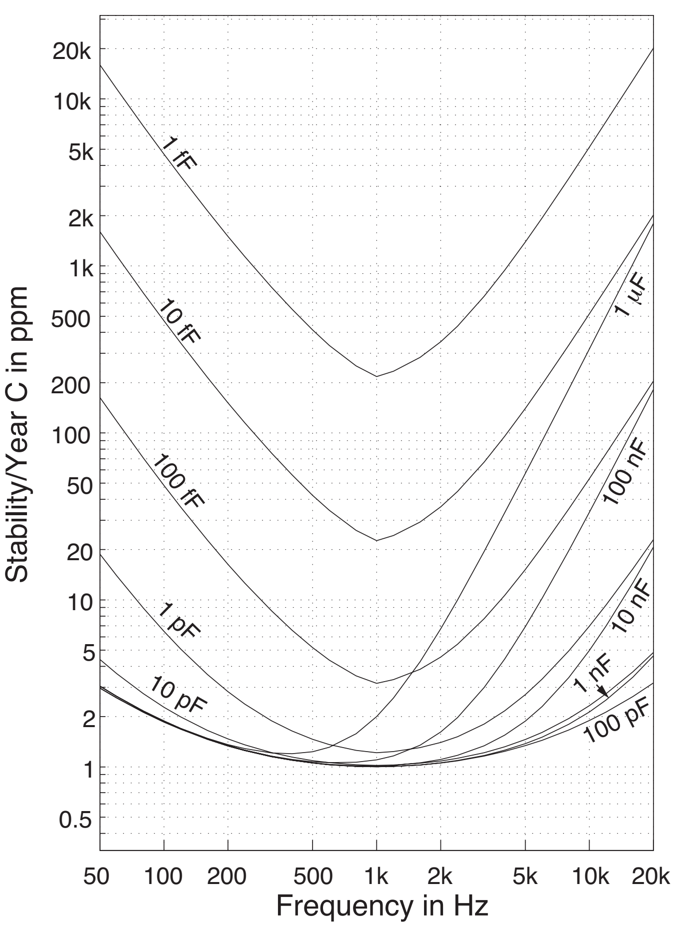
Resolution of D vs. Frequency

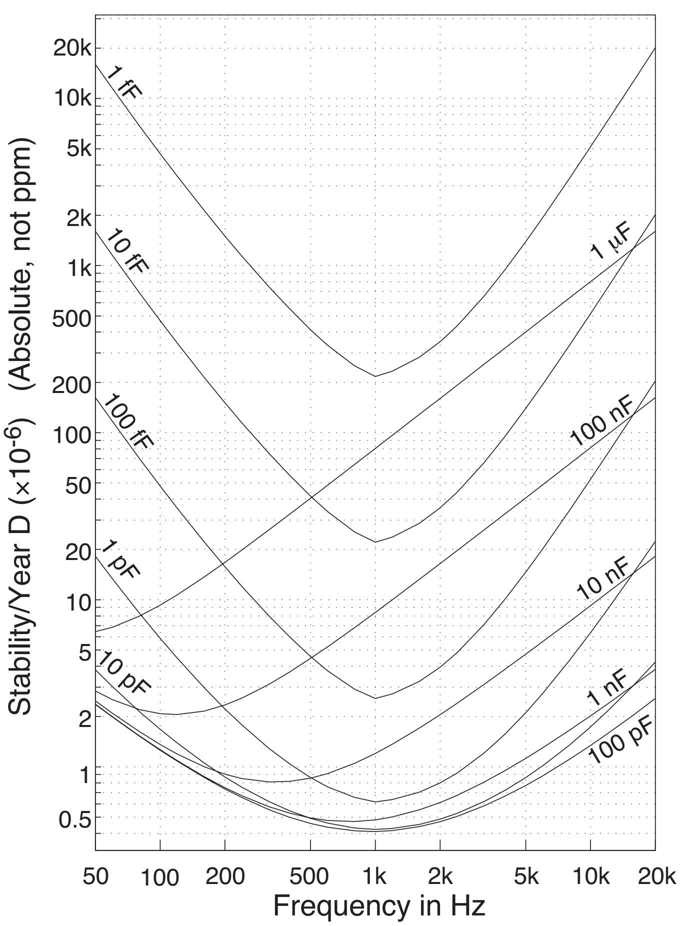


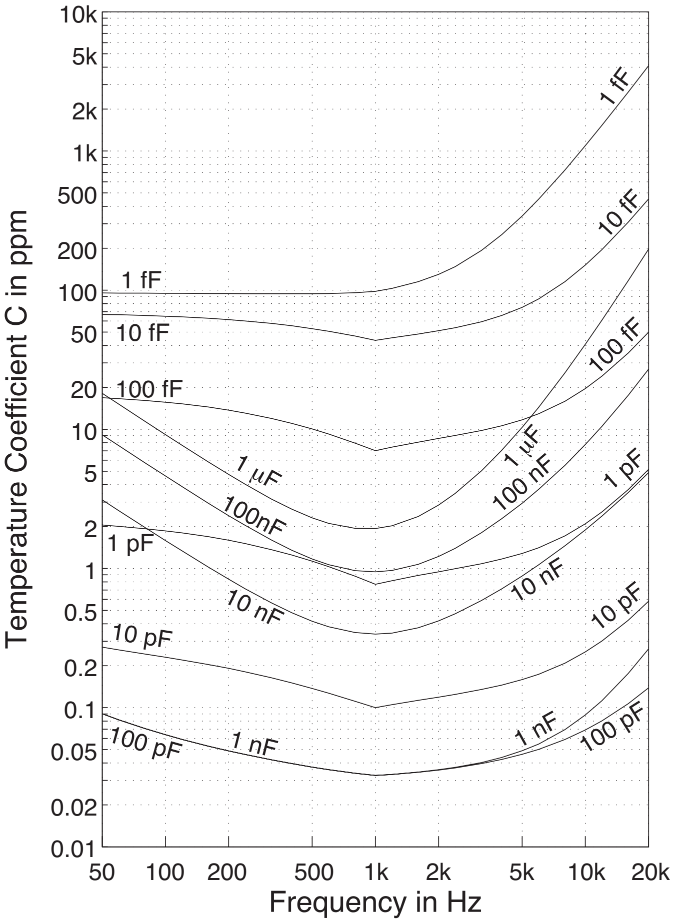
Non-Linearity of C vs. Frequency

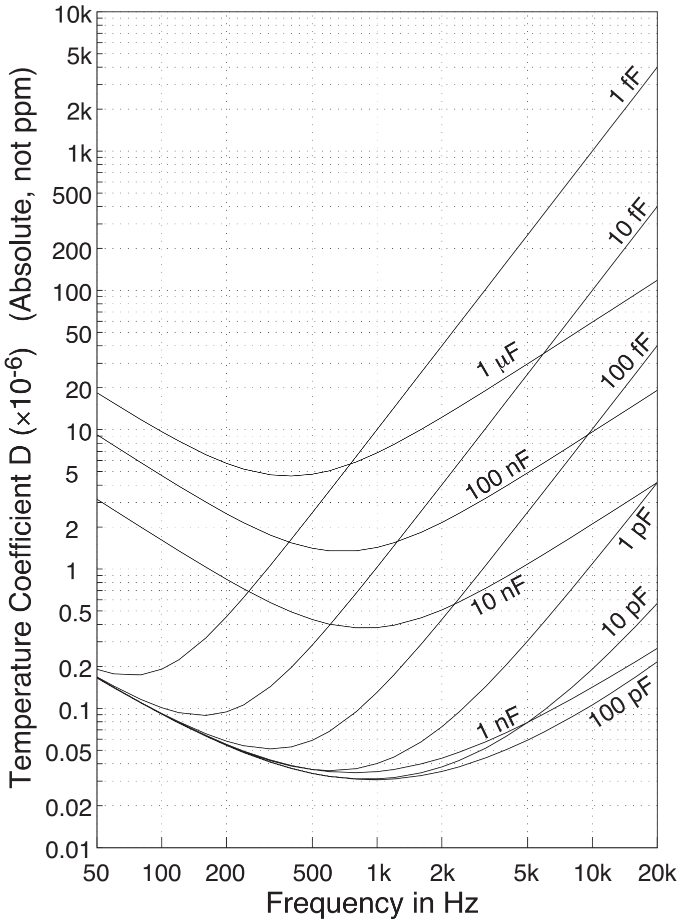


Non-Linearity of D vs. Frequency


Stability/Year of C vs. Frequency


Stability/Year of D vs. Frequency


Temperature Coefficient of C vs. Frequency


Temperature Coefficient of D vs. Frequency

DEVIATION MODE SPECIFICATIONS

Some symbols used are given in the table below.

Symbol	Variable
BMode	Bridge Balancing Mode
BBPoint	Bridge Balanced Point
DMode	Deviation Mode
DSPoint	Deviation Set Point
DReading	Deviation Reading
DSpan	Deviation Span
Freq	Bridge Frequency

This section describes the performance of the Deviation Mode (DMode) subsystem for both alphanumeric and analog output results. Specifications are common to both kinds of results unless noted otherwise. ***These specifications apply to both capacitance and loss channels.***

Units having equivalent magnitudes are used for both the capacitance and loss analog output channels. These units are pF and jpF. The jpF unit can be thought of as pF that are shifted in phase by 90 degrees. These units have the advantage of allowing direct comparisons between capacitance and loss analog outputs. Unlike BMode, there is no provision to set the loss to other units.

Static Performance

Accuracy

The magnitude of the overall error in (j)pF is typically less than the sum of the *GainError, TemperatureCoefficient*, *ParabolicError*, *Non-Linearity, Resolution, Noise* and *BridgeErrors*. These individual contributions are described in the following subsections.

The accuracy of DMode results depends upon how much the capacitance and loss deviate from the BBPoint. The greater the deviation, the lower the accuracy. There are several such sources of error, all of which contain this deviation.

Gain and Temperature Errors

The magnitudes of the *GainError* and *Temperature Coefficient* are:

$$GainError \le 0.003|DReading - BBPoint| \quad \text{(j)pF}$$

$$TemperatureCoefficient \le 0.0003|DReading - BBPoint| \quad \text{(j)pF}/°C$$

The analog output only, has an additional temperature dependence of less than 0.03% of the analog output voltage span per °C or 2 mV/°C, whichever is greater.

Non-Linearity

The magnitude of the *Non-Linearity* is given by:

$$Non–Linearity \le DSpan/2000 \quad \text{(j)pF}$$

Parabolic Error

A parabolic error occurs as a function of the DUT's total low to ground impedance, which includes the high to low capacitance and loss. The magnitude of the *ParabolicError* in the DMode output is approximated by:

$$ParabolicError \le \frac{-(|BBPoint| - |DReading|)^2}{|DReading + 10,000|} \quad \text{(j)pF}$$

This formula is always effective when *DSpan* is > 6pF. If *DSpan* is between 2 to 5 pF the formula applies if a linearizing preamp shunt capacitor is present. If *DSpan* is less than 2 pF the parabolic error is minimal.

Resolution

Resolution is limited by system noise and *DSpan*. The magnitude of the Resolution is given by:

$$Resolution \le DSpan/20000 \quad \text{(j)pF}$$

This specification includes a small repeatability error. As in BMode readings, resolution may also be reduced by noise.

Analog outputs only, have an additional limitation due to DAC resolutions of about 0.35 mV with unit to unit variations of up to ±10%.

Noise

Noise in deviation outputs and especially in analog outputs is greater for shorter signal sample times. Sample time is determined mainly by *Freq*. In the range of 6 to 20 kHz, the sample time is 20 µs whereas at 50 Hz the sample time is 2036 µs. This allows deviation signals to be averaged 100 times longer at 50 Hz than at or above 6 kHz. The complete noise specification is given at the bottom of the page.

Due to the real-time nature of DMode, the `COMMUTATE LINEREJ` noise rejection feature (Patent No. 6,987,391) is disabled during DMode. This reduces the rejection of low frequency noise and may require DMode measurements to be made in a lower noise environment. This will certainly be true if the `COMMUTATE LINEREJ` feature was necessary to make good measurements in BMode.

Bridge Errors

BridgeErrors includes all errors occurring in measurements made using the Bridge Balancing Mode. The specifications for these errors are on pages 5 through 12.

Dynamic Performance

Analog Output Frequency Response

By far the biggest advantage of DMode is speed. Capacitance and loss analog output results occur at rates typically over 100 times faster than those obtained in BMode.

$$Noise = \left(1 + \frac{1}{Freq}\right)\sqrt{\frac{DRolloff}{0.3Freq}}\left[1 + \frac{4(DReading - BBPoint)}{DSpan}\right][1 + 10^{-4}(DReading)^2 + 35DSpan]10^{-5} \quad \text{(j)pF}$$

The maximum frequency response of the analog outputs is 4.2 kHz at -3 db. It occurs at a *Freq* of 14 kHz, and decreases above and below this frequency.

A deviation rolloff parameter, *DRolloff* in kHz, is used to reduce the frequency response. *DRolloff* sets the value of the 3 db down frequency and can reduce it to as low as 0.00028 Hz. The highest possible rolloff frequency, *RolloffMax*, is:

$$RolloffMax = 0.3\,Minimum(Freq, 28 - Freq)\ \text{kHz}$$

The actual rolloff frequency used by the instrument is the lesser of *DRolloff* and *RolloffMax*.

Analog Output Update Rate

The deviation voltage present at the analog outputs is updated at a rate that depends upon *Freq*. This data rate can vary from 491 to 50,098 updates/s as *Freq* varies from 50 to 20,000 Hz.

Signal Averaging for Alphanumeric Results

The maximum rate at which alphanumeric DMode results can be generated depends on *Freq* and ranges from about 5 to 500 times slower than those from the analog outputs. The alphanumeric result rate is ≤100 Hz.

Like the *AverageTime* parameter used in BMode, a *DAvgTime* parameter is used in DMode to determine the minimum length of time during which deviation signal samples are averaged to produce an alphanumeric result. Increasing *DAvgTime* may further reduce the frequency response while also lowering the noise. *DAvgTime* is automatically increased at low *DRolloff* frequencies, so at least one sample is taken for each averaged result. If *DAvgTime* is set to be less than one tenth of the period of the DUT variation or *DRolloff* whichever is less, the response to a sinusoidal variation should not be affected.

Remote Device Result Rates

When *DAvgTime* is set ≥ 0.1 s, the alphanumeric result rate, *DResultRate,* is approximately:

$$DResultRate \approx \frac{1}{DAvgTime}\quad \text{results/s}$$

For *DAvgTime* < 0.1 s, *DResultRate* depends upon the number of characters in each measurement result message. For the serial channel, baud rate is also a factor. Ideally *DAvgTime* should be set so *DResultRate* equals the observed results/s.

Using optimum settings, the serial *DResultRate* will be about 40 results/s at 9600 baud and 100 results/s at 115,200 baud.

Using optimum settings and a fast controller, the GPIB *DResultRate* will be about 60 results/s.

Step Response

The digital processing of the preamp imbalance signal adds a 0.8ms delay to all results.

Fast step changes in capacitance and loss of the DUT produce the following results at the analog outputs:

With *Freq* set near 14 kHz and *DRolloff* set near 4000 Hz, a step voltage having a rise time of <100 µs is produced.

For lower values of *DRolloff* and with *Freq* several times higher than *DRolloff*, the response is that of a simple RC filter having a time constant of 1/(2π*DRolloff*).

Alphanumeric results are similar for lower *DRolloff* frequencies if the results are not affected by the lower data rate of the serial or GPIB channel. For the best alphanumeric response time, *DAvgTime* should equal 1/(2π*DRolloff*).

Set Point, Bound, Span and Other Settings

In addition to the frequency response and averaging settings described previously, the parameters described below may also be set. Unless stated otherwise, each of these parameters actually refers to two independent parameters, one for capacitance and one for loss. Note also that many of these parameters interact with others of the same capacitance or loss channel. A graphical representation of the deviation parameters is shown in Figure 3. This figure also shows the region in which measurements can be made.

Limits on Enterable Values	Largest or Most Positive	Smallest or Most Negative
DSPoint Cap	1650 nF	–165 nF
DSPoint Loss	19 jnF	–1.9 jnF
DSpan Cap	100 nF	–100 nF
DSpan Loss	1200 jpF	–1200 jpF
DBound Upper & Lower Cap	1650 nF	–165 nF
DBound Upper & Lower Loss	19 jnF	–1.9 jnF
Deviation Position	1	–1
Analog Output Voltage Limits	10.5 V	–10.5 V
Analog Output Bounds	160 V	–160 V
Analog Output Span	320 V	0.1 V
Conversion Factor Cap	$(10^{8}$-1)V/pF	–$(10^{8}$-1)V/pF
Conversion Factor Loss	$(10^{8}$-1)V/jpF	–$(10^{8}$-1)V/jpF
Deviation Margin	20	1

The BBPoint is always the center of the capacitance and loss spans that can be passed by the preamp. This point can be set by entering a Deviation Set Point (*DSPoint*) to which the BBPoint is equal to by default.

However, BBPoint need not coincide with *DSPoint. DSPoint* can be set anywhere within the measurable region, an example of which is shown in the Figure 3. *DSPoint* exists for the convenience of the user who, for example, can set it equal to the quiescent point of the DUT (which may not be in the center of the span).The table of limits above gives the most positive and most negative values that can be entered for *DSPoint* and other deviation parameters.

DSpan is settable. This is the capacitance and loss range that is passed by the preamp.

The Upper and Lower Deviation Bounds are settable. The values of the DUT that can be measured must lie between the

Upper Bound and the Lower Bound. Values outside these bounds will generate an error message. The *DSPoint*, *DSpan* and Upper and Lower Bounds all interact. Setting any two in the capacitance or loss channels will automatically set the other two in the same channel.

DSPoint can be offset from BBPoint by setting the Deviation Position parameter. A setting of zero causes *DSPoint* to equal BBPoint. Settings of ±1 cause *DSPoint* to be equal to one of the Deviation Bounds.

The Analog Output Voltage Limits are settable. These are limits placed on the voltages that can be generated by the analog outputs in Analog Output Mode.

The Upper and Lower Analog Output Bounds are settable. Their maximum values are ±160 V which are much higher than the Analog Output Limits. This allows an analog output to be magnified by as much as 15 times thereby allowing a correspondingly greater resolution over the Analog Output's 21 volt maximum span.

The voltage of the Analog Output Span may be set. This span is the difference in voltage between the Upper and Lower Analog Output Bounds.

The Conversion Factor (*CFactor*) is settable. This is the ratio (or gain) of the Analog Output Span to *DSpan*. *CFactor* is calculated automatically when DMode is started. It can be changed at any later time. Changing *CFactor* causes a rotation of its slope about *DSpoint*.

The Deviation Margin (*DMargin*) is a single parameter applying to both capacitance and loss. It is shown in Figure 3. Increasing *DMargin* decreases the sensitivity of the preamp so that noise spikes do not overload it causing error messages instead of measurement results. The trade-off is that the signal-to-noise ratio is reduced in the same proportion as the value of *DMargin*.

In DMode only, 13 different result formats may be chosen. These subtract *DSPoint* and/or a settable Reference value from the measurement result. Many of these also report percentages based on *DSPoint*, *DSpan* or the Reference value.

Pros and Cons of Deviation Mode

DMode, when used with the analog outputs, produces capacitance and loss results that are several orders of magnitude faster than by using BMode. The trade-off is that most of the specifications for DMode are significantly lower in performance than the corresponding BMode specs. Nevertheless, DMode still offers certain performance advantages not found in high speed capacitance meters.

- One of the greatest advantages of DMode is that the BBPoint is measured just as accurately as any other BMode measurement. This means that the values of

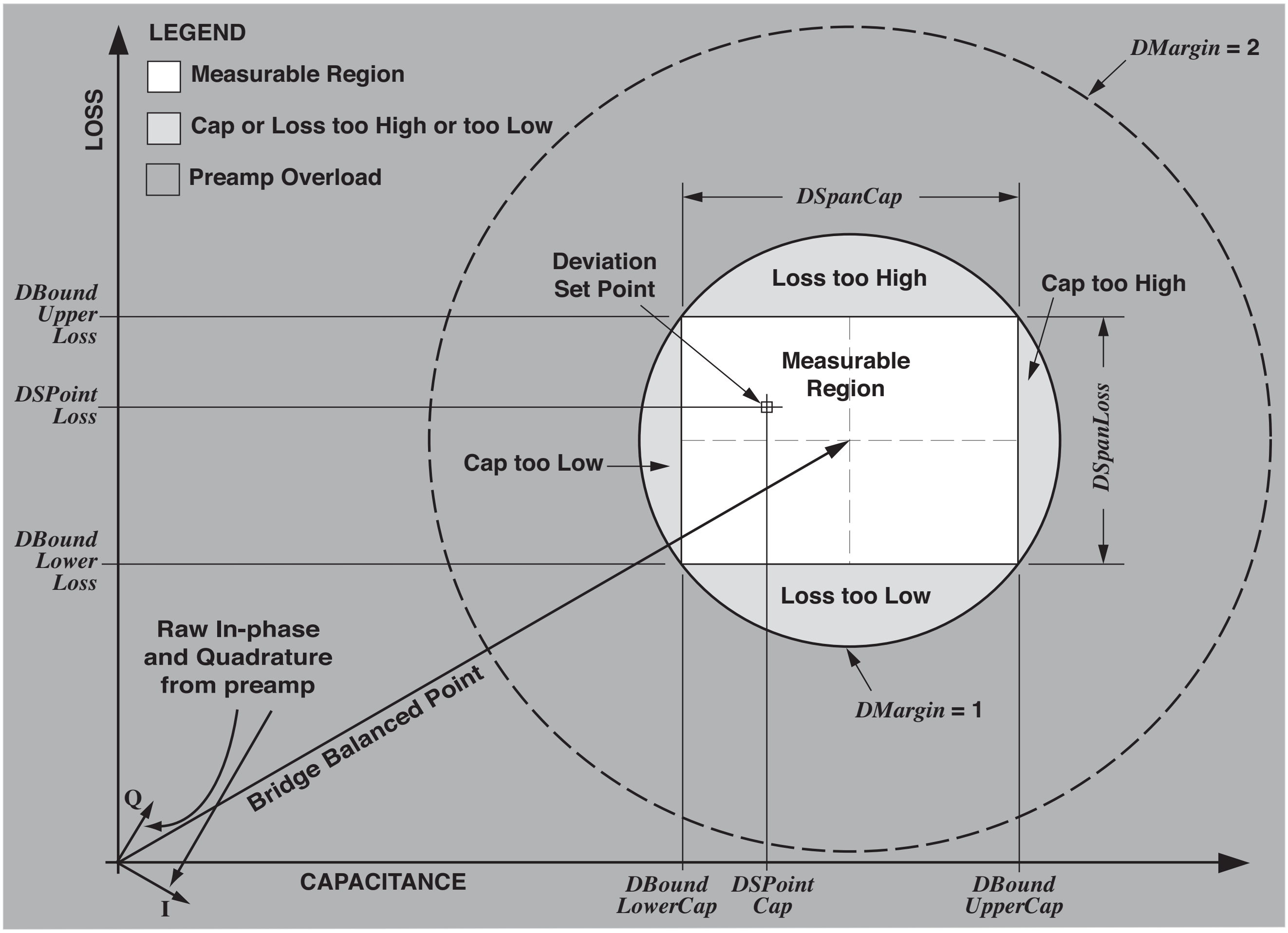


Figure 3. Deviation parameters and the measurable region on the cap/loss plane.

capacitance and loss around which deviation measurements are made are extremely accurately known. The result is that any measured deviations are due essentially entirely to changes relative to the BBPoint and *not* due to absolute changes of BBPoint. This is a big advantage since the measured BBPoint may be many thousands of times larger than the deviation that is desired to be measured relative to it.

- When used with the analog output, DMode can be part of a feedback loop to control a device or process.
- DMode can rapidly measure the difference between a stable capacitor and a DUT. The stable capacitor is first measured in BMode, then BBPoint is set equal to the measured value. The DUT can then replace the capacitor and be measured relative to the capacitor's value in DMode.

Bias Voltage Performance

The AH2700A can generate fixed voltages on the two analog output channels. These are called Bias Voltages and are settable with a command. Their performance is described in the following subsections. Bias Voltages are independent of the Deviation Subsystem but allow the same range of voltages.

Voltage Range

For both Bias and DModes the output range is ±10.5 V.

Accuracy

The magnitude of the capacitance or loss bias voltage errors is:

$$AoutBiasError \le 0.003|ABias| + 0.003 \quad \text{VDC}$$

where *ABias* is the output voltage setting in VDC.

Noise

The output voltage noise is less than 1 mV RMS.

Temperature Coefficient

The bias voltage temperature coefficient is $\le |\pm 2|$ mV/°C.

Resolution

DAC voltage resolution is about 0.35 mV with a unit to unit variation of ±10%.

Step and Delay Responses

The 10% to 90% rise time is approximately 30 µs.

The delay time from issuing a command within an AH2700A macro to change the bias voltage to the time when the voltage begins to change is about 12 ms.

The delay time from issuing a command within an AH2700A macro to enable or disable the bias voltage to the time when the voltage begins to change is about 8 ms.

The Continuous Frequency Option

The standard version of the AH2700A operates at any of 33 discrete frequencies from 50 Hz to 20 kHz. The AH2700A may be ordered with Option C to allow it to take capacitance/loss measurements at ***any*** frequency over this same range. This frequency may be set to a resolution of seven digits. Operation of the AH2700A with Option C is identical to that of the standard AH2700A in all other respects.

The most difficult aspect of developing the Option C was its requirement to operate at any frequency including those at or near the power line frequency or any of its harmonics (which can be troublesome even above 1 kHz). This happens to be a very demanding requirement especially if the power line frequency is not stable. Andeen-Hagerling solved this problem by inventing a novel and fundamentally new means for rejecting interference. We named it the method of Synchronous Rejection. It is described in U.S. Patent No. 6,987,391. Without using Synchronous Rejection, the performance of the AH2700A would be unacceptable at times at many frequencies.

Website: www.andeen-hagerling.com

Please look for a downloadable spreadsheet to make it easy to evaluate all of the specification equations.

Ordering Information:	**Model or Option No.**
Ultra-Precision 50 Hz-20 kHz Capacitance Bridge	AH2700A
Continuous Frequency Option for AH2700A	Option C

For questions regarding the AH2700A, possible applications, the location of your nearest sales representative, or ordering information:

Call: 440-349-0370 Fax: 440-349-0359 E-mail: info@andeen-hagerling.com

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