

B.F.Gray

Measurements, instrumentation, and data transmission

A text for the OND in Technology (Engineering)

B. F. Gray
Dean of Engineering, The Hatfield Polytechnic



London and New York

Longman Group Limited London

Associated companies, branches and representatives throughout the world

Published in the United States of America by Longman Inc., New York

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First published 1977

Library of Congress Cataloging in Publication Data

Gray, Bernard Francis, 1924—
Measurements, instrumentation, and data transmission.

1. Mensuration. 2. Measuring instruments. 3. Data transmission systems. I. Title.
T50.G69 620'.004'4 76-49922
ISBN 0 582 41065 7
ISBN 0 582 41066 5 pbk.

Set in IBM Journal 10 on 11pt and printed in Great Britain by Richard Clay (The Chaucer Press) Ltd, Bungay

Preface

This is the second book written specifically for a subject in the OND in Technology (Engineering). It follows very closely the syllabus of Measurements, Instrumentation and Data Transmission published by the Joint Committee responsible for the course.

Inevitably it has some overlapping features with other subjects in the OND scheme, logic circuits and electrical measurements being two examples.

The level of mathematics assumed is minimal although it is expected that students have at least met complex numbers and are aware of certain relationships in the field of probability and statistics.

Although the book is written for a well-defined market it is hoped that it will appeal as an introductory text at first-year level for many students reading for a degree in any branch of engineering. Technician students in certain City and Guilds courses involving Instrumentation and Control topics should find much of the text useful. The small number of students in the Higher National Diploma courses in Measurement and Control will also find the book of some use.

Once again it is necessary to thank colleagues who have made helpful comments on the book which have resulted in improvements in the way a number of topics have been presented. It is also necessary to thank the authorities in the colleges providing the OND (Tech.) for their permission in allowing certain examination questions to be published. The source of these questions has been noted. It is also necessary to acknowledge the source of some of the excellent mechanical engineering diagrams — mainly from R. L. Timings' books, Mechanical Engineering and Basic Engineering.

Finally I must once again thank Marion Dance who typed the manuscript so well.

B.F.G. Harpenden, 1976

Acknowledgements

We are grateful to Thomas Nelson & Sons Ltd for permission to reproduce copyright material from *Electrical Engineering Principles* by B. F. Gray, published by Thomas Nelson & Sons Ltd, 1970, and Hodder & Stoughton Ltd for permission to include some figures which are based on diagrams from Engineering Measurements and Instrumentation by L. F. Adams.

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General principles of measurement

1.1 Standards and fundamental units

Before we can make any measurement it is necessary to have an acceptable standard unit on which to base the measurement. This standard unit has to be recognised both nationally and internationally and has to be measured to a high degree of precision. If, for example, we wish to measure the distance between two points in London, we use as our standard of length the Metre (or its subdivision the millimetre) and we know that our measurement will be accepted both in Manchester and Melbourne. At one time in Great Britain we used the yard as our standard of length, this being based on some fairly arbitrary units evolved from medieval times. The original standard was set up in Greenwich in 1855 and was the distance between marks on a bronze bar (Fig. 1.1).

Apart from the fact that we have now adopted a metric system the increasing precision often required nowadays in the measurement of length

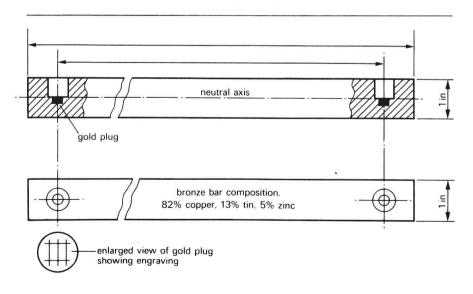


Fig. 1.1 The original British standard of length.

makes the bronze bar an insufficiently accurate primary standard. The bar is subject to variation of length with changes of temperature; but what is perhaps more unacceptable is its shrinkage — it has been contracting at a fairly uniform rate of a millionth of an inch per year. Today we require a standard which does not change, which is as precise as possible, and which can be fairly readily set up. We have turned to the physical phenomena of light radiation as our primary standard of length. Each electron contained within a single atom has been found to possess a certain very well defined amount of energy. When the energy of an electron is made to change from one precise level to a lower one, the change of energy is given up in the form of an electromagnetic radiation of an extremely well defined wavelength. Sometimes the radiation falls in the visible spectrum. This is an inherent property of the atom itself and is therefore of a fundamental nature. This provides the basis of our standard of length.

The standard unit of time is also based on a radiation measurement.

In all there are seven standard units, although outside chemistry only six are normally employed. They form the basis of the Système Internationale employed in Europe and many countries outside Europe. The term Système Internationale has been abbreviated to SI and we now refer to the SI units.

1.2 Basic SI units employed in engineering

(a) Length

The primary unit of length is the Metre and is based on the radiation wavelength of the gas krypton 86 (an isotope of krypton) in a vacuum. Under certain conditions the gas emits orange light of a very precise wavelength.

The metre is defined as 1,650,763.73 wavelengths of this particular radiation (Fig. 1.2).

The fact that nine significant figures are quoted suggests the degree of precision on which we now base the metre. It is closer to 1,650,763.73 wavelengths than 1,650,763.72 wavelengths, for example.

Originally the distance from the North Pole to the equator along the meridian through Paris was intended to be 10,000,000 metres. The present-day standard is fractionally longer.

(b) Mass

The primary unit of mass is the Kilogramme and is the mass of a platinum-iridium alloy cylinder held in the International Bureau of Weights and Measures at Sèvres near Paris. It has not been possible to obtain a more fundamental measurement of mass.

(c) Time

The primary unit of time is the Second. Originally it was defined in terms of the mean solar day (1/86400 part of a day) but present demands of

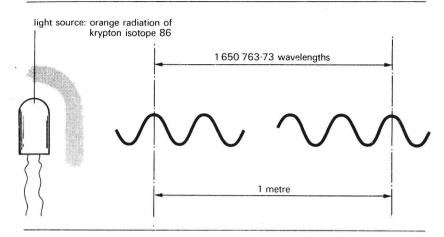


Fig. 1.2 The light standard of length.

accuracy have forced us into a more precise definition. Again we turn to the radiation phenomena for our standard.

The second is now defined as the time for 9,192,631,770 cycles of the radiation from vaporised caesium under resonant conditions. There are ten figures in this definition and once again there is an implied very high degree of precision.

(d) Other units

There are three other primary units employed in engineering — units of electric current, temperature and luminous intensity. The unit of electric current is the Ampere and is defined as follows:

The ampere is that unvarying electric current which, when flowing through two, infinitely long, straight, parallel conductors of negligible cross section and placed 1 metre apart in a vacuum produces a force of 2×10^{-7} newtons per metre length of conductor (Fig. 1.3).

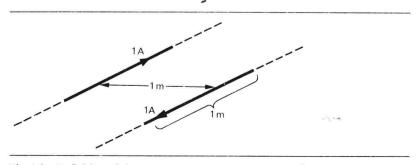


Fig. 1.3 Definition of the ampere.

The metre has already been defined and since the newton can be measured in terms of length, mass and time it follows that the definition of the ampere is dependent upon other SI units.

The SI unit of thermodynamic temperature is the Degree Kelvin (K). This is directly related to the Celsius (or Centigrade) scale. The scale is such that the temperature difference between absolute zero (0 K) and the triple point of water (0.01°C), where water can be simultaneously in the solid (ice), liquid and gaseous (vapour) state, is 273.16 K.

On this basis

Zero degrees Kelvin 0 K = -273.15°C

The unit of luminous intensity is the Candela and is defined in terms of the light output from a unit surface area of molten platinum.

The final SI unit is the Mol, seldom employed by engineers but used extensively by chemists.

Tab	le 1	1.1	SI	units

Quantity	Unit	Symbol
length	metre	m
mass	kilogramme	kg
time	second	s
electric current	ampere	Α
temperature	kelvin	K
luminous intensity	candela	cd

Two other units must also be mentioned. Both are non-dimensional and both are used in angular measurement. The first is the Radian. An angle in radians is defined as follows:

Angle in radians =
$$\frac{\text{Arc length at radius } r \text{ subtended by the angle}}{\text{radius } r}$$

Hence the angle in radians of a circle is

$$\frac{2\pi r}{r} = 2\pi \text{ radians}$$

The other is the Steradian or solid angle. This is the three-dimensional equivalent of the radian. The angle at the top of a cone is an example of a solid angle. It is defined by

Solid angle in steradians =
$$\frac{\text{Area at radius } r \text{ subtended by the angle}}{(\text{radius } r)^2}$$

Hence the angle in steradians of a sphere is

$$\frac{4\pi r^2}{r^2} = 4\pi \text{ steradians}$$

1.3 Sub-standards or secondary standards

The custodian of standards in this country is the National Physical Laboratory (N.P.L.), Teddington (now supplemented by the British Calibration Service), but it would be highly inconvenient if we had to check every measurement against the primary standards held there. It is much more usual for various organisations which require standards to produce their own standards or equipment which may then be checked against the primary standards periodically. These sub-standard or secondary standards as they are called are usually in a rather more convenient form than the N.P.L. standards, e.g. a sub-standard ammeter which has been calibrated against the standard ampere is much easier to use in subsequent measurements. Likewise a metrology department in industry would hold a number of 'slip gauges' which are essentially length standards and these would be used to check the accuracy of working gauges or micrometers which are in daily use. A slip gauge is made to very precise limits and depending upon its size might be accurate to 1 micron (1μ) (a micron is 10⁻⁶ m). (See Fig. 1.4.)

It is necessary to monitor the accuracy of working standards employed in production in a factory since the quality of the final product is dependent upon them. Whenever there is a significant fall in the accuracy or quality of a component coming off the production line one of the checks which must be made is the working standard. The frequency at which



Fig. 1.4 Metric slip gauges.

standards are checked is a matter for debate and depends to a large extent on the particular standard. It is more likely that the calibration of a deflection type ammeter may change over a period of 6 months than, say, the dimensions of a slip gauge. It is yital that if the quality of a product is to be maintained then not only should a factory check its standards regularly but full records should be kept of such calibration so that long-term changes in working standards are apparent. The 'traceability' of standards calibration is vital.

1.4 Calibration errors

The calibration of an instrument or gauge is normally carried out in a standards laboratory where there is some control over the environment, e.g. temperature and humidity which might affect the calibration. The instrument to be calibrated is compared against the standard and a graph is drawn of 'error' against 'indication'.

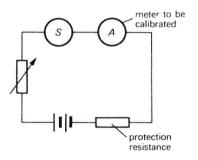


Fig. 1.5 Calibration of an ammeter.

For example, the calibration of an ammeter involves a simple circuit (Fig. 1.5) consisting of a sub-standard ammeter S in series with the meter to be calibrated A. The current through both meters (which is the same) is adjusted by means of the variable resistor. The current is set to perhaps one-fifth of the full-scale deflection on A and the sub-standard indication is noted on S. A typical graph is shown in Fig. 1.6. Occasionally readings are taken for both ascending and descending values of current. There will normally be allowable limits of error laid down for the instrument and if the calibration curve lies within these limits over the entire range (5 A in this case) then the instrument is passed as an 'industrial grade' meter or 'precision grade' meter. It should be noted that although the calibration points lie within the acceptable limits (see Fig. 1.6), the meter is only accurate at zero indication and 2.4 A (and then only as accurate as the sub-standard). When the meter indicates 1.0 A there is an error of +0.05 A, i.e. the correct indication should be 0.95 A. Such errors are referred to as

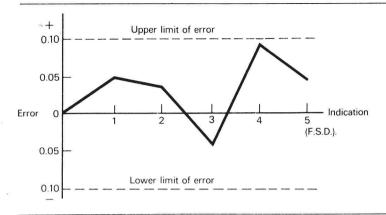
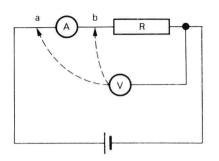


Fig. 1.6 Error graph.

calibration errors. In the example given the allowable error is ±0.10 A at all points of the scale. As a percentage error on the indication the allowable error at 1.0 A is ±10 per cent of the indication. At full scale deflection (5 A) the allowable error is still ±0.1 A, which is now ±2 per cent of the indication. It follows that as far as indicating pointer instruments are concerned it is advantageous to arrange matters so that readings are taken as near full scale deflection as possible. Whatever instruments are used, whether electrical or mechanical, they are always subject to a calibration error. The allowable error is usually stipulated in a British Standard specification (BS) and these errors should be known before a measuring instrument is used. The allowable error for certain types of industrial grade pointer ammeters is given by BS 89 and is ±2 per cent of full scale deflection. If when a meter or instrument is checked its calibration is found to be outside the standard specification then it should be either recalibrated or returned to its manufacturer. Often the reason for the error being outside allowable limits is due to some malfunction of the instrument so that when this happens a careful check should be made of its operation.

1.5 Systematic errors

Systematic errors may be attributable to the method of measurement employed. When measurements are made the system which is being measured is disturbed by the instruments which are used. The amount of disturbance should normally be made as small as possible or at least allowed for. Take for example the measurement of a resistance by the voltmeter—ammeter method (Fig. 1.7). If the voltmeter is connected to point 'a' the voltmeter reading \div ammeter reading gives the resistance of the resistor + the resistance of the ammeter in series. If the voltmeter is connected to point 'b' the current flowing through the ammeter is that



Ammeter 0–5 A, Industrial grade (2%). Resistance 1.7 Ω . Voltmeter 0–100 V, Industrial grade (2%). Resistance 100 k Ω .

Fig. 1.7 Measurement of resistance.

through the resistor + the current flowing through the voltmeter. The ratio of the voltmeter and ammeter readings will not give the true value of the resistance for either method of connection. In either case it is possible to calculate the systematic error. The calibration errors of the two instruments will result in further sources of error.

Example 1.1

A resistor of about 20Ω is to be measured as shown in Fig. 1.7 by the ammeter-voltmeter method. Details of the two meters are given. A reads 3.0 A, V reads 60 V. What are the probable limits in the measurement of the resistance?

The voltmeter has an error of ± 2 per cent of full scale deflection (F.S.D.). The voltage recorded would therefore be between 60 + 2 per cent of 100 and 60 - 2 per cent of 100, i.e. between 62 V and 58 V. Similarly the ammeter would have calibration errors lying between ± 2 per cent of 5 A, i.e. ± 0.1 A. The ammeter indicates a value between 3.1 A and 2.9 A. Taking the worst cases, the observed value of resistance lies between

$$\frac{62}{2.9} = 21.3 \Omega$$
 and $\frac{58}{3.1} = 18.7 \Omega$

The voltmeter is, however reading the voltage across the resistor and the ammeter and this introduces a systematic error. The resistance given by the ratio of voltage and current includes the ammeter resistance (1.7 Ω). This value must be subtracted from the above values so that the probable value of R lies between 19.6 Ω and 17.0 Ω . Note that in this measurement the systematic error could have been reduced by connecting the voltmeter to point b. The high value of the voltmeter resistance would increase the current flow through the ammeter only fractionally. No higher degree of precision would have been achieved because the systematic error has already been taken into account.

Systematic errors may be due to environmental conditions. A steel cylindrical gauge being used to measure a diameter in a low temperature cabinet has contracted and its calibration is slightly different to that at room temperature. If the temperature of the cabinet and the temperature at which the gauge was calibrated are known then with the further knowledge of the coefficient of expansion of steel the systematic error can be calculated and allowed for.

1.6 Observational and random errors

Under this heading we can place all the other forms of measurement error. There is firstly the personal error of observation. Given a deflectional type instrument where it is necessary to interpolate between markings on a scale, different observers obtain slightly different readings for the same deflection. Sometimes there may be a gross observational error - a figure of 45.6 may be wrongly observed as 55.6 or we may be reading the wrong range on a multirange instrument. The increased use of digital meters reduces the possibility of observational errors. Even however when all the calibration systematic and observational errors have been taken into account a residual error remains which cannot be accounted for since there is a certain degree of randomness in all measurements. The random error should be small but becomes evident when measurements are repeated. Almost invariably slight changes in observed values occur. It is seldom possible to repeat the observed indications precisely. To take one example, a digital instrument will always be liable to a ±1 digit random error in any measurement.

1.7 The economics of measurement

Accurate measurement costs time and money and it would be quite wrong to use sophisticated and costly equipment making a precise measurement where an approximation would do. The speedometer in a car for instance need not be very accurate and no one would be unduly worried by a 5 per cent calibration error. The air speed indicator on a large passenger-carrying aircraft must be more precise since there may be danger of approaching stalling speed without the pilot knowing it and catastrophic results might occur with a 5 per cent uncertainty in air speed. There has to be an awareness of the degree of precision which the circumstances demand and it is wasteful to produce measurements to an unnecessary degree of accuracy.

1.8 Accuracy and sensitivity

The accuracy of an instrument is basically the limitations on its indication

within which we cannot place any reliability. The sensitivity or discrimination on the other hand controls the smallest change in its indication which can be discerned. Sensitivity can be expressed as

Change of indication (output)

Change of measured quantity (input)

e.g. in a pressure gauge the sensitivity might be twenty divisions per N/m². The sensitivity is normally required to be high so that small changes in the quantity being measured produce relatively large changes in indication. High sensitivity does not necessarily imply high accuracy but high accuracy usually requires high sensitivity.

For instance, an instrument may have a calibrated scale on which we can discern a change of 0.1 per cent of its full-scale deflection but the instrument may be only accurate to ±10 per cent of its full-scale deflection due to a fault.

In general the more sensitive an instrument is, the more likelihood there is of it also being more accurate, but there is no guarantee of this.

A Wheatstone bridge uses a 'null balance' to obtain a measurement (see p. 45). The sensitivity of the bridge depends upon the smallest change in resistance value of one of the four arms of the bridge which causes a discernible current to flow through the galvanometer. If the bridge balances with the variable arm set to 1759 Ω and we know that the accuracy of the resistance is ± 0.2 per cent then we might at first glance say that the value of the unknown resistance was between 1759 $\Omega \pm 0.2$ per cent, i.e. between 1762 Ω and 1756 Ω . However, if we require a change of 15 Ω in the setting of the resistance before we can detect a change of current the sensitivity of the bridge is such that we cannot say with any certainty where the balance point is between the limits 1759 \pm 15 Ω i.e. 1774 Ω and 1744 Ω .

Very often there is a lower limit placed on accuracy in the appreciation that there is a limit to the accuracy which an instrument or standard can be made.

A micrometer for example may be stated to have an accuracy of ± 0.02 per cent of the reading ± 0.01 mm error. If we measure a cylinder of diameter 100 mm with this instrument the accuracy would be

100 ± 0.02 per cent ± 0.01 mm

i.e. the upper limit would be 100.03 mm the lower limit would be 99.97 mm.

If the same micrometer were used to measure the diameter of a 1 mm cylinder the 0.02 per cent error (0.0002 mm) would be quite negligible in comparison with the ± 0.01 mm error (the lower limit).

For this measurement the limits of accuracy would be

 $1 \pm 0.01 \, \text{mm}$

i.e. 1.01 mm and 0.99 mm.

As a percentage of the nominal value (1 mm) this is ± 1 per cent and not