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Environmental Instrumentation

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With 66 Figures

Springer-Verlag
New York Heidelberg Berlin

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Library of Congress Cataloging in Publication Data

Fritschen, Leo.
Environmental instrumentation.
(Springer advanced texts in life sciences)
Bibliography: p.
Includes index.
1. Environmental monitoring—Instruments. 2. Physical instruments. I. Gay, Lloyd Wesley, 1933–
II. Title.
TD170.2.F73 550′.28 79-10437

Printed in the United States of America.

9 8 7 6 5 4 3 2 1

ISBN 0-387-90411-5 Springer-Verlag New York
ISBN 3-540-90411-5 Springer-Verlag Berlin Heidelberg

Preface

The rapid increase in environmental measurements during the past few decades is associated with (1) increasing awareness of the complex relations linking biological responses to atmospheric variables, (2) development of improved data acquisition and handling equipment, (3) the application of modeling to environmental problems, and (4) the implementation of large, cooperative studies of international scope.

The consequences of man's possible alteration of the environment have increased our interest in the complex nature of biological responses to meteorological variables. This has generated activity in both measurements and in the application of modeling techniques. The virtual explosion of modeling activity is also associated with the development of large computers. The testing of these models has demonstrated the need for more, different, and better environmental data. In addition, technological developments, such as integrated circuits, have reduced the cost, power consumption, and complexity of data acquisition systems, thus promoting more environmental measurements.

The emergence of scientific cooperation on a global scale has increased measurement activities markedly. The International Geophysical Year (1958) has been followed by the International Hydrologic Decade, the International Biological Program, the Global Atmospheric Research Program, and a host of environmental studies of a regional nature that have all emphasized field data collection.

With few exceptions, space-age technology has led to improved methods for data recording and handling, rather than changes in instruments used to sense the environment. Thus, while recording methods have progressed from mechanically driven pens to data systems coupled with on-line computers, the same basic sensors have remained in use.

These developments have made it easier to collect large quantities of data, but all too frequently sensors are not properly exposed, electrically isolated, or even compatible with the recording instruments. Vast quantities of recorded data have often turned out to be invalid.

Courses on environmental instrumentation are not common on university campuses, despite the need for training on this topic. Earlier books on the subject, such as *Meteorological Instruments* by Middleton and Spilhaus, are out of date and out of print. This book is designed to be used as a text for advanced students and a guide or manual for researchers in the field. Our purpose is to present the basic theory of environmental variables and transducers, report our experiences on methodology and use, and provide certain essential tables. The user is expected to have a basic physics and mathematics background and to be knowledgeable in the area of his speciality.

We will concentrate on the principles that govern the use of sensors and the operation of recorder systems as these are less rapidly affected by technological process. The applications will use currently available equipment.

September, 1979

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List of Symbols

Symbol	*Unit*	*Definition*
a		constant, low temperature, absorption coefficient, ratio
A		constant, aspect ratio, intercept, variable metal, analog domain
A	$^{\circ}C^{-1}$	thermodynamic psychrometric constant
A	m^2	area
A_c	m^2	convective area
A_r	m^2	radiational area
A_0		Ferrel psychrometric constant
b		constant, midrange temperature
B		amplitude, constant, slope, variable, metal
B	$W(m^2\ sr)^{-1}$	steradiancy
c	$J(kg\ K)^{-1}$	specific heat
c		speed of light, constant
c	$m\ s^{-1}$	speed of sound in still air
c		high temperature
c_p	$J(kg\ K)^{-1}$	specific heat at constant pressure
C		constant, slope, variable, metal, correction factor
C	$J(m^3\ K)^{-1}$	heat capacity
d	m	diameter, delay distance
D	$W\ m^{-2}$	diffuse radiation flux density

D	V	thermoelectric potential
D	m	distance constant
D		variable, digital domain
e		natural logarithm
e	Pa	vapor pressure
E	V	applied voltage, thermal emf
E		edge correction, combined value, error
E	$W\ m^{-2}$	irradiance
E_i		Einstein (mole of photons)
E_i	$lm\ m^{-2}$	illumance
E_v		velocity error
f	Hz	sound wave frequency
F	$kg(ms^2)^{-1}$	force
F		variable
F	lm	luminous flux
F	°F	Fahrenheit degree
g	$m\ s^{-2}$	acceleration due to gravity
g	$V\ m^2\ W^{-1}$	calibration coefficient
Gr		Grashof number
G	$W\ m^{-2}$	heat flow through a medium
G		variable
h	m	height
h	$W(m^2\ K)^{-1}$	convective heat transfer coefficient
h		Plank's constant
h		damping ratio
H	$W\ m^{-2}$	sensible heat flux density
H		constant
i	A	current, electrical
I	$kg^2\ m^{-1}$	moment of inertia
I	$W\ sr^{-1}$	radiant intensity
I	$W\ m^{-2}$	direct-beam solar radiation perpendicular to sun's rays
I_i	$lm\ sr^{-1}$	luminous intensity
J		mechanical equivalent of thermal energy
J		constant
k		Boltzmann's constant, coefficient
k		wavelength dependent coefficient
k	$m^2\ s^{-1}$	thermal diffusivity

K	$W\ m^{-2}$	solar radiation flux density, constant
K_m		constant
K_r		view factor
K_v		vane quality factor
$K\uparrow$	$W\ m^{-2}$	reflected solar radiation
$K\downarrow$	$W\ m^{-2}$	global solar radiation
K^*	$W\ m^{-2}$	net solar radiation
K	K	Kelvin degree
l	m	length
L	$J\ kg^{-1}$	latent heat of vaporization
L		lead
L	$W(m^2\ sr)^{-1}$	radiance (radiant intensity per unit area)
$L\downarrow$	$W\ m^{-2}$	longwave atmospheric radiation
$L\uparrow$	$W\ m^{-2}$	longwave terrestrial radiation
L^*	$W\ m^{-2}$	net longwave radiation
m	kg	mass
M		aerodynamic damping, measured value
M	kg	molecular weight
M	$W\ m^{-2}$	radiant emittance
M_l	$cd\ sr\ m^{-2}$	luminous emittance
n		number, number of moles, eddy shedding frequency
n	m^{-1}	wave number
Nu		Nusselt number
N	$V\ {}^{\circ}C^{-1}$	thermoelectric power
o		vertex
P	W	electrical power
P	Pa	pressure
Pr		Prandtl number
P		coil, physical domain, potential
q	$kg\ kg^{-1}$	specific humidity
Q		quantum of radiation, entity, quantity of heat
Q	$W\ m^{-2}$	all wave radiation
Q^*	$W\ m^{-2}$	net radiation flux density
r		recovery factor
r	$kg\ kg^{-1}$	mixing ratio
r	m	radius
r_w	m	radius of counter weight

R		universal gas constant
R	Ω	electrical resistance
Re		Reynolds number
s		extinction coefficient
s	m	vertical span of air foil
S	$W\ m^{-2}$	direct-beam radiation
S		Strouhal number, cubical expansion coefficient, coil
S	m^2	area of air foil
t	s or min	time
T	°C or K	temperature
T	$kg\ m^2\ s^{-2}$	torque
T_a	°C	air temperature
T_d	°C	dew-point temperature
T_s	°C	surface temperature
T_w	°C	wet-bulb temperature, wall
u		unknown
U	$m\ s^{-1}$	wind speed
U		relative humidity
v		true value
V	m^3	volume
V_λ		relative luminous efficiency
$\bar{X}$		mean of sample population,
X		Wien's constant, volume fraction
$\bar{Y}$		mean of infinite population
y		variable
z	m	depth or height
α		first order coefficient, absorption coefficient, attenuation factor
β		second order coefficient, thermistor constant, thermal expansion coefficient
γ		reflection coefficient
γ	Pa $°C^{-1}$	psychrometric constant

Δ	Pa °C^{-1}	slope of saturation vapor pressure curve
Δf		Doppler shift
ε		emissivity, ratio of mole weight of water vapor to dry air (0.622), ratio of transducer conductivity to medium conductivity
θ		angle
θ	°K	temperature
λ	s	time constant
λ	W(m K)$^{-1}$	thermal conductivity
λ_d	m	damped wavelength
λ_n	m	natural wavelength
λ	μm	wavelength
μ		dynamic viscosity
Ω		angle
ω	sr	solid angle
ω	s^{-1}	angular frequency
ν	Hz	frequency
ν		kinematic viscosity
ν	m^3 kg^{-1}	specific volume
ρ	kg m^{-3}	density
ρ_v	kg m^{-3}	absolute humidity
σ	W m^{-2} K^{-4}	Stefan–Boltzmann constant
σ	g s^{-1}	surface tension
τ		transmission coefficient, time constant
Φ	W	radiant flux
ϕ		latitude
ψ		optical thickness

Subscript	*Definition*
a	air
b	bottom, bridge
c	conduction, convection, capillary
d	dew point, dry, damped

f	fluid
g	galvanometer
G	ground
Hg	mercury
i	ice, in
L	load
m	meter, mineral, mount, manometer
n	number, natural
o	out, organic matter, observed, surface level
p	parallel, plane
r	radiation, reference
s	shunt, surface
t	true, transient, top
T	temperature, transducer, thermistor
u	unknown
v	velocity, water vapor, vane
w	wall, weight, water, wet bulb
x	unknown
λ	wavelength
0	at zero °C, value at time zero

Contents

Chapter 1

Measurement Fundamentals

1.1 Introduction and Scope

Measurement programs should be planned with carefully defined objectives. Valid objectives include the verification of a hypothesis, the testing of a hypothesis, or explanation of phenomena. There is no place for measurement for the sake of measurement in a planned program. We hope that the techniques in this book will find their greatest usefulness in evaluating processes, such as growth, development, photosynthesis, or transpiration, rather than inventory or description of environmental factors.

The successful scientist must be capable of a sequence of activities that begins with a measurement program. First and foremost, the investigator should be an expert in the chosen field, with a thorough knowledge of the organisms or processes to be studied. Second, the investigator should know the instruments, their method of operation, and basic techniques for exposure and recording. Third, a knowledge of data analysis is required if the data are to be interpreted in terms of the objective. Calculators or computers are usually brought in at this step in order to analyze the data in terms of statistics, theory, and/or physical models. Finally, the observations, results, and conclusions should be reported to colleagues to avoid useless duplication of time and effort.

Mastery of the entire process normally comes after intensive training and a long period of experience. We shall focus on the second area: principles of instrumentation, exposure of instruments, and the recording of valid data. We will emphasize the validity of measurement rather than accuracy, as it is possible to accurately measure a temperature that is completely unrelated to the true value. We will bring our experience to bear on the problem of measuring true values of the desired entity.

1.2 Measurement Errors

Every measurement can be described with respect to accuracy, precision, and error. The definition of these terms at the outset will be helpful.

Accuracy is often confused with precision. *Accuracy* refers to the relation between the measured and "true" value, or the closeness to an accepted standard such as those maintained by the National Bureau of Standards. The true value plus the error is equal to the indicated value. *Precision*, on the other hand, refers to the variability observed among numerous measurements of a quantity. As an example, consider a micrometer that was initially both accurate and precise. If the micrometer is dropped and the frame bent, the accuracy is altered, but the precision would be unaffected if the lead screw remained undamaged. Accuracy is generally specified in terms of "inaccuracy." The accuracy of a thermometer, for example, may be accurate to $\pm 0.1°C$ over a given range.

The error may be composed of systematic and random components. A *systematic* error is unchanged between repeated measurements. For example, if a meter is not set to zero before making a series of measurements, the resulting errors would be consistently high or low. *Random* errors, in contrast will vary between measurements. They may be caused by such factors as electrical "noise," fluctuating temperatures, operator error, or wind. Many variables may contribute to random errors.

Random and systematic errors are illustrated in Fig. 1.1. The systematic error is the difference between the true value, V, and the mean of an infinite population of measurements, $\bar{Y}$. Random error is the difference between $\bar{Y}$ and the mean of a sample population, $\bar{X}$. As the sample size increases, the difference, $\bar{Y} - \bar{X}$, will decrease.

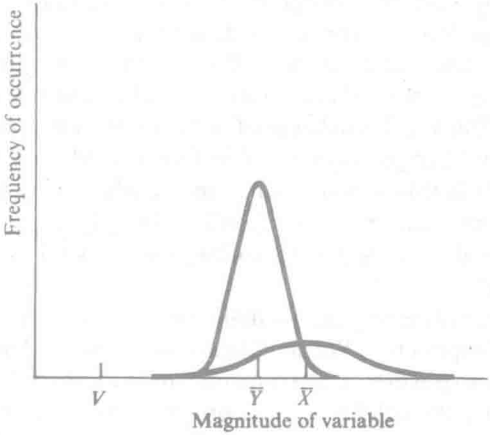

Figure 1.1 Illustration of systematic error ($V - \bar{Y}$) and random error ($\bar{Y} - \bar{X}$) where V is the true value, $\bar{Y}$ is the mean of an infinite number of measurements, and $\bar{X}$ is the mean of a sample population.

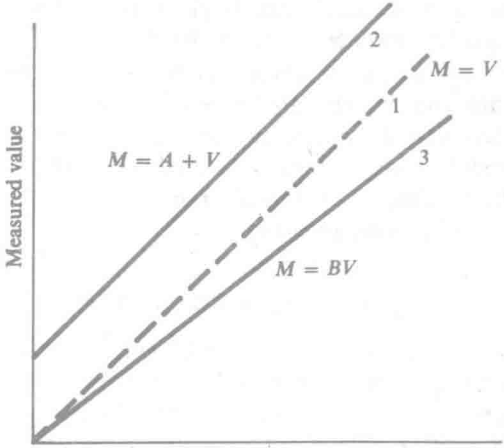

Figure 1.2. Various types of agreement between measured values, M, and true values, V, with intercept of A and slope of B.

Two types of systematic errors are illustrated in Fig. 1.2. Line 1 indicates perfect agreement between the measured and true values; line 2 differs from the true value by a constant amount; and line 3 differs by a constant slope, B. If there were additional data available for statistical analysis, the random error component could be illustrated by plotting confidence limits on either side of the lines.

The systematic and random error components can be added to indicate the range of error that may be expected in a specific reading. The error limits for a digital voltmeter, for example, may be given as $\pm(0.01\%$ of reading $+ 0.005\%$ of range $+ 1$ digit), indicating random components associated with the size of the measured value, the scale of the voltmeter, and the ambiguity of digital systems, respectively. The error limits will probably specify the conditions of measurement in order to exclude random errors associated with noise. If, for example, the voltmeter is reading a 60 mV signal with the range on 999.99 mV, the error limits would be

$$\pm(0.006 + 0.05 + 0.01) = \pm 0.066 \text{ mV}.$$

1.3 Estimating Error

Statistical techniques will yield the agreement between measured and predicted values when a number of observations are available, but it is often useful to estimate the error limits that may apply to a single measurement. The error is the difference between the measured value and the true value, and it may be expressed in units of measure, as a percentage, or as