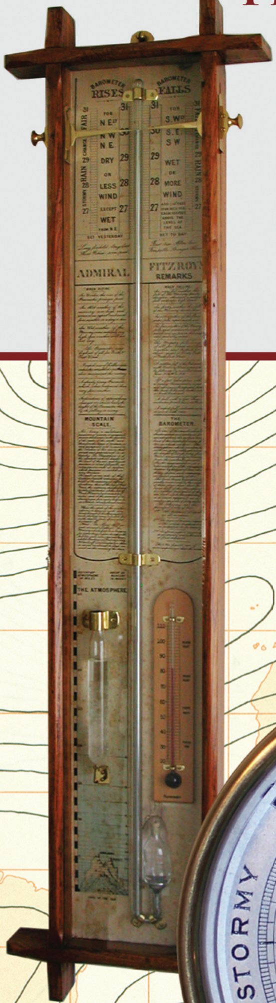
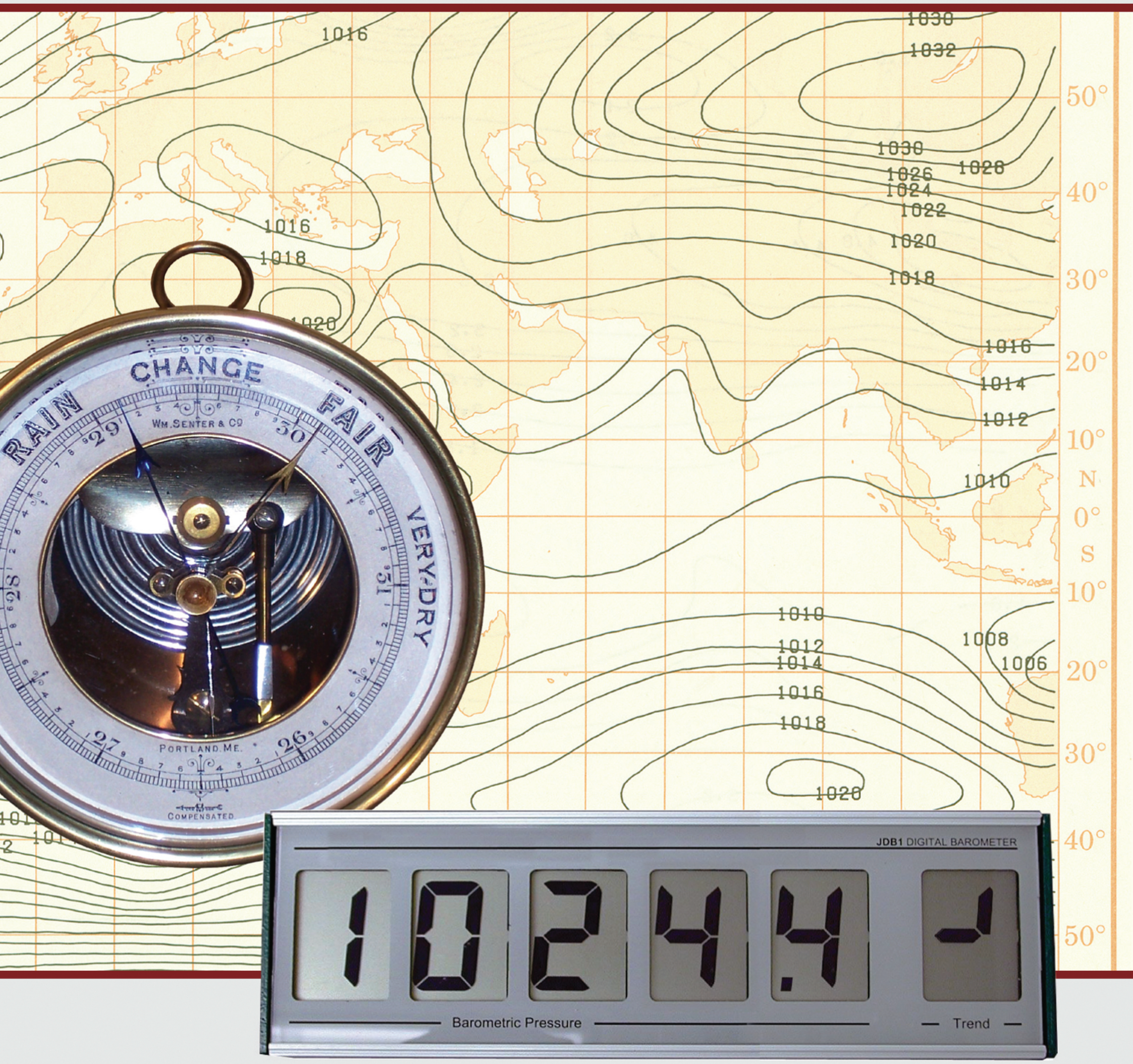
The Barometer Handbook



A MODERN LOOK AT BAROMETERS AND APPLICATIONS OF BAROMETRIC PRESSURE



DAVID BURCH
Author of *Modern Marine Weather*

The
BAROMETER HANDBOOK

A Modern Look at Barometers and Applications of Barometric Pressure

By

David Burch

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The mercury barometer is traditional FitzRoy Barometer in oak frame manufactured by Mason of Dublin in about 1880. Photo compliments of Patrick Marney (www.partick-marney.co.uk).

The 5-inch antique aneroid barometer was made by Short & Mason of London, and re-tailed by W. Senter & Co of Portland, Maine in about 1900. Photo compliments of John Forster (www.barometerfair.com).

The electronic barometer shown is a 2009 prototype for a new model II of the JDB-1 barometer from Conex Electro-Systems in Bellingham WA.

The background image is a seasonal pressure pattern reproduced from the *U.S. Navy Marine Climatic Atlas of the World*. The full pressure data from this publication are included in Chapter 10.

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Preface

Since the first public appearance of barometers some three hundred years ago, the barometer has traveled through history along two separate, parallel paths.

There has been the lineage of instrument makers and engineering scientists who focus on how barometers work, how to make and repair them, how to calibrate them, and how to tell a good one from not so good; and along the other path is the lineage of barometer users whose focus is on the meaning of atmospheric pressure and how to use that information to analyze and forecast the weather.

More often than not, neither group has had a compelling interest in the activities of the other group. Those who know about the instruments care most about the instruments. They have confidence their instruments will be used well and properly if they make a good one, without a particular interest in what that use will be.

Barometer users, on the other hand, do not often care about the ingenuity or craftsmanship that might distinguish one instrument from another. They have confidence that the makers will provide quality instruments so they can do their job of weather analysis. Often they do not question the accuracy of the instrument, or even realize that this is a question that might be asked.

That is not to imply anything is wrong—at least so far. We have today phenomenally accurate barometers in science labs and weather stations on the one path, and on the other path our knowledge of the global atmosphere—which is ultimately dependent upon individual barometer measurements around the world—has also improved phenomenally, considering the immense complexity of the science.

Science labs and professional meteorology are well in tune barometrically, but the broader field of barometer users have not kept up as well. And there are changes on the near horizon that will be best met if we know as much as possible about the more common types of barometers now in use. In short, there is some virtue now in bringing these two paths closer together, which is one of the main goals of this book.

To give an important example, you will hear it said that the reason the typical mariner is not using a barometer so much these days is because they have so many wonderful new weather resources at their finger tips. With a satellite phone and a PC you can be in any ocean in the world and with the push of a button have all the winds and pressures immediately plotted out in front of you. Push another button and you see what they will look like tomorrow, and the next day, and so on.

This very convenient type of data, presented in what is called the GRIB format, are direct outputs from the super computers of the weather services. It is part of the data mentioned above that is getting better all the time. But it is not fully dependable yet. These are *not* the official forecasts. In fact, this type of computerized forecast has not been vetted at all by a professional meteorologist. Nevertheless, the use of this data grows very rapidly every year.

The idea that having that type of data means you do not need to use your barometer is as wrong as possible. It is one of the strongest reasons to use your barometer. With an accurate barometer, you have a way to test the weather map. Once you have tested the maps, then indeed these are wonderful new ways to do weather work at sea, or on land.

A key point in this comparison is having an accurate barometer. This is another new concept to mariners and others as well. Throughout maritime history, mariners relied almost exclusively on pressure trends: up or down, fast or slow. They did not concern themselves with the actual value of the pressure. This has been the teaching since the earliest days. Now we have a new reason to know accurate pressures, and to that end this book covers the process of barometer calibration using natural pressures, which we have access to through online resources. This Internet procedure itself was not possible five years ago, so there is much new to modern barometer usage. There are of course other ways to calibrate without the use of the Internet.

Once we know accurate pressure from our barometer, there are other applications, one of which is the forecasting of tropical storms using deviations from the known mean pressures. To facilitate that procedure and for other applications, we reproduce in Chapter 10 the monthly mean sea level pressures and their standard deviations worldwide. The more you use your barometer, the more interesting this data becomes, as does its applications.

Besides all of that, the crucial role of a barometer in weather forecasting has not diminished, but it is slipping out of the textbooks way before its time, and we hope, here, to belay that trend as best we can.

Finally, an important new development in the past ten years or so is the advent of inexpensive electronic barometers. These can be very accurate and easy to use, but like all others, they must be tested. It is another goal of this book to introduce these new devices to those who have not used them before, and to present ways to evaluate them.

As the book proceeds, we inevitably end up addressing the two most common issues that barometer repair departments ever receive: (1) My barometer does not read the same as the weather reports, and (2) My barometer does not change.

The typical short answers are: (1) Weather reports are for sea level, but your barometer is at a higher elevation, and (2) Watch more carefully, the changes are small and slow. But these answers do not really convey much information. If we want more productive use of our barometers, we need more in-depth answers to these questions—from each of the two paths mentioned earlier.

Examples and weather maps are from the Northern Hemisphere, unless otherwise noted.

Acknowledgements

Of the several book projects I have worked on over the years, none has been more rewarding and filled with discoveries than this one. Helping me along this venture were a number of people who care about this science and were kind enough to share their knowledge, expert opinions, and insights with me.

There are quite a few who deserve specific mention, but I must start with Merrill Kennedy, "The Barometer Man" (www.barometerman.com), who has earned that title through 38 years of study and experience as repairman, restorer, and calibrator of high-quality aneroids. We have spent countless hours discussing these instruments, and with each talk I learned more. This would have been a much more difficult task, if doable at all, without his help. So I will say again, what I have said many times before. Thank you Merrill.

My full list is long, but each person here has made a significant contribution to this book and I am very grateful to each of you. Early conversations with Robert Luke, Program Manager of the NWS Voluntary Observing Ship program, were influential on my decision to take up this project, and his specific reminder to heed the importance of temperature in barometry was confirmed at each step of the work. Several subsequent discussions with Pat Brandow, Port Meteorological Officer for the Pacific Northwest area, were always enlightening, and gave me invaluable insights into the practical use of barometers in ship reports. He also confirmed our in-house barometer calibrations.

Vacuum technology expert Steve Hansen of DiverseArts, LLC, designed and built our excellent barometer test chamber. We had many long discussions on this technology and applications of precision microbarographs. David Hale of Airflo Instruments, manufacturer of precision aneroids, provided unique insights into barometer production and gave several useful comments on the book. Dr. Jay Hendricks of the National Institute of Standards and Technology provided valuable comments on a related section of the text, which were much appreciated. I am also grateful to Roger F. Allen, President of Alti-2 Inc., who informed me, from a first-hand account, of the history and practical application of altimeters in skydiving.

George Huxtable, FRIN, provided information about Hooke's unique first marine barometer directly from an original in the Oxford Museum of the History of Science. He also figured out how it worked, which was not obvious from other accounts. Navigation historian Bruce Stark shared his insights and resources on the history of marine weather, just as he has done so often on the history of navigation. It is a pleasure to thank both of these gentlemen for the education and support they have given me over many years, on many aspects of navigation science.

Graham Bartlett and Steve Jebson, Library Information Managers at the U.K. MetOffice, very kindly and efficiently provided several unique documents and datasets, and answered other questions as well. Their hospitality was exceptional. Nearer home, Elizabeth Walsh and her associates at the Magazine and Newspaper Desk and Interlibrary Loan program of the Seattle Public Library did an absolutely wonderful job of tracking down and providing dozens of rare papers and books over the past year. The Internet has revolutionized how we can research a topic, but it is still a distant competitor to educated and dedicated librarians and the resources a good library has available.

Discussions with international airline Captain (and sailor) Jay Towne on all matters of aviation were always useful and always enjoyable. Dr. Kenneth Mukamal, MD of Harvard University kindly reviewed the presentation of his research on headaches and barometric pressure and offered several useful suggestions. Dr. Richard Langley, Geodesy Department, University of New Brunswick, shared his insights on several matters relating to GPS and the elusive concept of sea level.

Regina Moore at NWS's National Data Buoy Center explained barometer procedures and instruments used in their measurements and also provided a copy of Gerald Gill's classic research paper on his original design of the Gill pressure port. Laura Cook at NWS's Office of Climate, Water, and Weather Services kindly provided information about the reduction to sea level process used in the ASOS program. And a special thanks to Christopher Hampel, Calibration Scientist in Barometry at Environment Canada for several discussions of the Plateau Correction as used in Canada, and for his review of the related section in this book. And thanks to Bob McDavitt ("The Weather Ambassador") of the New Zealand MetService for providing special NZ station data for our barometer calibration service and for giving us permission to reproduce his Southern Hemisphere barometer rules, and for his checking the Northern Hemisphere ones we presented here.

John Lewis read the entire manuscript and offered valuable suggestions at several points. His job was made much easier by the preceding detailed review by Larry Brandt, friend and Starpath instructor. Larry went though each section of the book, found most of our errors, and offered many good suggestions for improvements—not just in matters of expression, but also in content as well in some cases. Thank you Larry. Your work remains very much appreciated.

Toby Burch produced the illustrations for the book and did the cover design and page layout. There is not a single drawing in the book that he has not conceptually improved in the process of creating it. I am very fortunate to have his collaboration on this project and on others.

Table of Contents

*He who watches his barometer, watches his ship.**

* This saying appears to have originated with Henry Piddington in one of his books on Indian Ocean storms from the 1840s, probably *The Horn-Book of Storms for the Indian and China Seas*, 1844. He is thus credited with it by Jane Taylor in her *Hand-Book to the Local Marine Board Examination* of 1853. By 1865, this saying is referred to as a "maxim" without authorship in *Chambers's Journal of Popular Literature, Science, and Art*. In 1881 it was used by S. T. S. Lecky in the first edition of his famous *Wrinkles in Practical Navigation* (also without reference to its origin), which continued in print as a standard reference until its final (23rd) edition in 1956.

CHAPTER ONE
INTRODUCTION

A barometer is an instrument designed specifically to measure atmospheric pressure, but this one measurement has diverse applications. So diverse, in fact, that the name of this instrument has come to mean a way to measure anything. It was recently explained to seventy million TV viewers in the first sentence of a U.S. vice presidential debate that the "barometer of the economy" is a soccer mom. But despite exposure to such figures of speech, it is the very image of the instrument as dependable and durable over several hundred years that has led to this etymology.

1.1 Overview

The main goal of this book is to explain what a barometer is and how we might use one to our best advantage in several applications. It is not intended as just a description of the instruments and an outline of their history, which we do only briefly, but more of a working manual on the "nuts and bolts" of practical applications, with an emphasis on the latest technology of both the devices and their applications.

The application we consider in most detail is the use of a barometer for the analysis and forecast of weather, using specific examples from marine weather. Pilots, farmers, fire fighters, sportsmen, and many other landsmen count on knowledge of the weather, but the mariner isolated on a ship at sea, a thousand miles from land, has as close a tie as possible to the barometer and the insights it can offer on prospective weather. This has been true since its very inception and remains true today, as reflected in the history of the instrument and its applications.

The barometer is nearly as venerable an instrument as is the mariner's compass, and coincidentally pioneering research on both instruments was carried out on the same, first-ever, worldwide voyage dedicated to scientific study. Capt Edmond Halley in 1696 to 1698 sailed throughout the North and South Atlantic mapping the earth's magnetic variation as well as recording daily barometric pressures, which he correlated with observed weather patterns. Both sets of data were keystone steps to the productive use of each instrument.

Throughout the three-hundred-year history of the barometer, there have been numerous well-circulated reference texts that appeared with each new stage of its development. The modern bible from a practical point of view is the *Manual of Barometry*, from the U.S. Weather Bureau in 1963. From a mariner's perspective, the most famous is the *Barometer Manual* published in 1866 by Robert FitzRoy, known as the father of marine weather. He invented the concept (and the name) of a "weather forecast," and was a champion of the use of barometers on both land and sea. He was also the sea captain of the *Beagle* who took Darwin around the world on his great voyage of discovery (1831 to 1836) that served as the foundation of his theory of evolution. FitzRoy was later appointed head of the newly established Bureau of Meteorology, which evolved into the modern British Met Office, counterpart of the U.S. National Weather Service. A severe storm during the Darwin voyage that nearly sank the *Beagle* was later recalled by FitzRoy as one he might have avoided had he paid more attention to his barometer—an incident that certainly contributed to his conversion to the cause and lifelong devotion to its promotion.

Another goal of this book is to "introduce" the modern electronic barometer to new users and to those who have used more traditional designs for many years. This transition is actually a big step, especially for maritime applications. It is suggesting a transition from instruments that have been used and tested for 100 years to a completely new style that has been on the market for only a dozen or so years, with effectively no discussions of their properties or function in the popular literature. Furthermore, traditional aneroid barometers in use for the past 150 years or so are easily identified at first sight as scientific instruments, not to mention that the appearance of these devices has not even changed during this period. (Can we think of any other instrument, of any kind, that has not changed appearance in 150 years?) Many aneroid barometers even have open front panels to expose the inside workings of the instrument. On the other hand, many of the new electronic barometers look more like a gadget than a scientific instrument. And the fact that we are surrounded in our daily lives by essentially disposable electronic clocks and calculators and cell phones, does not help build the image of another electronic device, made quite possibly in the same factories where these other devices are made.

So the task at hand is to try to help establish guidelines for evaluating these new instruments—and the older styles as well—so that prudent users can separate out what are in fact instruments from what are more like gadgets. The electronic devices, just like the traditional aneroid devices, are not all the same, but very rarely can you tell this difference by just looking at them. The fact that a traditional aneroid device might look quite venerable is no guarantee of its quality.

No matter what your application is, be it predicting the wind and weather, or fixing the elevation of your hike across a mountain, or tuning the fuel injectors of a race car on the starting line, all applications are better served by an understanding of how the instrument works, and most important, how you can test that it is working properly.

1.2 What is a Barometer?

By the early1700's, barometers were known to most educated people as instruments that measure something related to the weather—and perhaps, in some individuals, to some level of well being. It was also discovered very early on that they have great utility in determining the elevation of terrain, and thus they became as much a practical tool for explorers wishing to document their finds as to seamen and landsmen wishing to anticipate the weather. This level of public understanding of these devices remains pretty much the same today, three hundred years later.

The instruments themselves, on the other hand, have evolved through three completely different designs during this period: mercury, aneroid, and electronic. It started with the simple design of an inverted glass tube filled with mercury, invented in 1643 by Torricelli, an associate of Galileo. This concept quickly found its way across Europe and into England, and by 1700 became standardized to the point they could be readily manufactured. Thus they moved out of "science labs" and into private homes, public buildings, and ships of the sea. Designs for maritime use continued to improve until the late 1800s, but it was a losing race. By that time mercury barometers were replaced almost entirely by the new aneroid design. Aneroid means "without liquid," because the new design was purely mechanical, with no mercury or other liquids.

The "Torricellian Experiment"

Torricelli and Galileo had in essence set about to measure how long a straw could be that you could still suck water through, primarily in response to more practical questions of how high water could be pumped in various applications. We know from the soda fountain that a foot or so works just fine, but is there a limit to how tall it could be? They got all the way to 33 feet, but it would go no higher.

The long straw behaved just like a short one, namely as long as you kept suction on the top, the column of water did not fall. But no matter how hard you tried, you could not pull water up a glass tube higher than about 33 ft.

Torricelli reasoned that when he removed the air from the top of the straw by sucking on it (pumping it out to be more precise), it was the weight of the air pushing down on the water in the basin at the base that forced the water up the straw. The 33-foot limit was reached when the weight of the water in the straw balanced the weight of the air pressing down on the basin of water. And if that interpretation was right, he supposed—which Galileo, by the way, did not think was true—that if he changed the liquid to be mercury, some 13.7 times heavier than water, then the column would only reach to (33/13.7) feet, which is about 29 inches.

And sure enough that was right. Though many of his contemporaries remained more interested in pumping water into tall decorative fountains, or over the tops of hills for irrigation, he realized his device could measure the weight of the air. It was not long till he noticed that the column height changed from day to day, and he rightfully suspected (for slightly the wrong reasons) that the weight of the air was changing. As we would say it now, when the local atmospheric pressure was low, the column of mercury was low, and when high pressure passed by, the mercury column was taller.

Unfortunately he was not able to make any useful correlation between his mercury height and the weather, because the height of the mercury expanded and contracted with air temperature and he was not aware of that. Nor was he able to prove that the air weighed less at higher elevations, which is also something he believed to be true. These discoveries using his device emerged only slowly over the next 50 years or so.

Torricelli's experiment itself, however, fairly quickly evolved into a simple operation that could be carried out by anyone, using the most basic equipment. This remains until today the epitome of a scientist's ideal experiment—easy to do, with simple, inexpensive equipment, and with rigorously reproducible results.

Here is how his experiment is described, but this is not a recommendation that you do this. On the contrary, you should not do this. Mercury can be toxic if not handled properly, and the glass tubes, open bowls, etc, make this in fact a hazardous way to handle it. This is something early researchers were not aware of, to the detriment of many. Even as late as the 1990s, dangerous levels of mercury vapor were being discovered in old science laboratories in England. Mercury spilled onto the floor and through the floor boards had collected for many decades in some cases, contaminating both air and surfaces.

Think of starting with a bowl of mercury and a clear glass tube about a quarter of an inch in diameter and 36 inches long that is sealed at one end. Then fill up that tube with mercury (Figure 1.2-1). Place your finger over the open end of the tube to seal it, and carefully turn in over, and place the finger covering the bottom of the tube into the bowl, under the surface of the mercury, and very slowly remove your finger keeping the tube held upright in the vertical position. The mercury in the tube will run out somewhat, adding to what is in the bowl, but it won't all run out. It will leave a vacuum at the top of the tube about 6 inches long, and a column of mercury standing about 30 inches high in the tube.

The weight of the air on the surface of the mercury in the basin is forcing it up the tube, telling us exactly what we want to know from such a device, the atmospheric pressure, in a unit of atmospheric pressure that has come to be called "inches of mercury." The worldwide, season-wide average pressure is 29.92″ and it varies with the weather usually not more than about ±1″.

If we wanted to know the actual weight of the air from this apparatus, we could figure the weight of

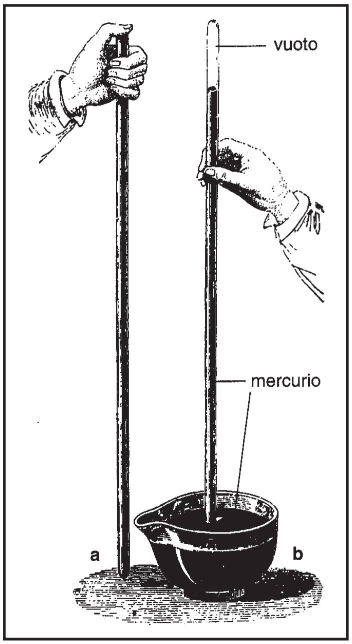
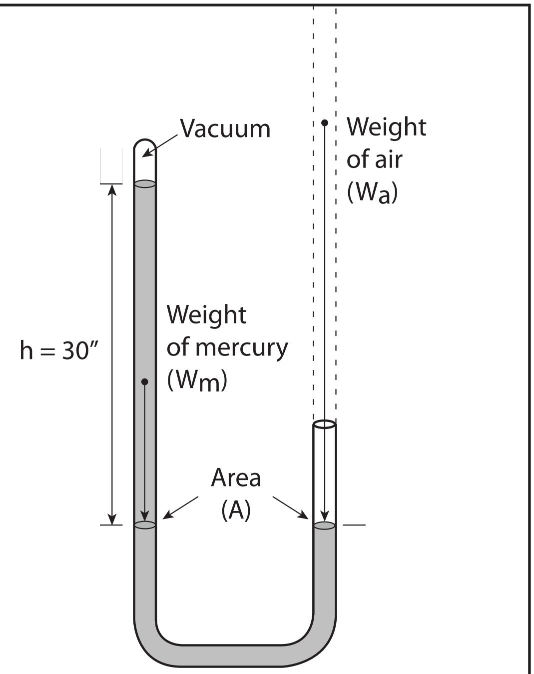


Figure 1.2-1 *Torricellian experiment that started it all... the science of barometers and atmospheric pressure, as well as the philosophical quest to understand the concept of a vacuum. Figure 1.2-2 illustrates the principle.*

the mercury column being supported. The quarter-inch-diameter tube has a cross-sectional area of $\pi r^2 = \pi(0.25/2)^2 = 0.049$ square inches. The weight of the mercury is the volume times its density (0.4889 lbs per cubic inch) and if the column balanced out at 30 inches, it would weigh (length x area x density) = 30 x 0.049 x 0.4889 = 0.72 lbs. This then would be the force exerted on the area of the tube at the base, so the actual pressure would be 0.72 lbs/0.049 square inches, which equals 14.7 lbs per square inch. This is illustrated in Figure 1.2-2, which shows a variation of the Torricellian tube called a mercury manometer. Notice that the actual diameter of the tube in use will always cancel out of this computation, so it is not crucial to the conclusion.

Many of the greatest scientists and philosophers of the time devoted some of their energy and intellect to the development, understanding, or application of this "Torricellian Experiment."



$$\text{Pressure} = \frac{W_a}{A} = \frac{W_m}{A} = \frac{h \times A \times \rho}{A} = h \times \rho$$

i.e. Pressure = height x density

Figure 1.2-2 *A mercury manometer.*

Galileo Galilei (1564-1642), Italian scientific giant, was the father of the scientific method. Among what are typically considered more profound discoveries, in the 1630s he confirmed the observations of others that water could not be pumped higher than 33 feet by suction and proposed a reason why, though it was not correct. Shortly before he died, he passed on this pump mystery to his new associate Torricelli, who made his mercury tube discoveries about a year later.

Evangelista Torricelli (1608–1647), Italian physicist and mathematician, is the central figure of this story. His main claim to fame is his work in 1643 on the original mercury tube. He has been forever honored with a unit of pressure called the Torr, equal to 1 mm of mercury as it stands in a mercury barometer. In 1644, he wrote: "We live submerged at the bottom of an ocean of air." He appreciated the fact that his device measured the weight of the air, but he was not able to fine tune the observations enough to associate actual weather changes with mercury heights. Though less known to the public, he made other important contributions to science and mathematics and succeeded Galileo as Professor of Mathematics and Science at Pisa.

Rene Descartes (1596–1650), French philosopher and scientist, was the first to put numerical scales on a "Torricelli tube," at which time he also sent a duplicate scale to an associate in 1647 so they could compare results. In this sense he deserves some credit for inventing "the barometer." There is even evidence that Descartes knew how they worked, having proposed a way to measure atmospheric pressure in 1631. On philosophical grounds, however, he would not accept the idea that there was a vacuum at the top of the mercury column, which could not help but lead him astray—which does not distract the slightest from his many profound contributions to mathematics and philosophy.

Blaise Pascal (1623-1662), French giant in science, mathematics, and philosophy, proposed that air became thinner as you ascend in the atmosphere and proved it in 1648 with a scaled mercury tube measured at two elevations, 3000 feet apart. Thus he established the use of barometers as altimeters, which spread rapidly around Europe and England.

He also defended his conclusion that it was indeed a vacuum over the top of the mercury, and in discussing this position and his barometer measurements he formulated a principle of scientific philosophy that remains today a cornerstone of modern science. "In order to show that a hypothesis is evident, it does not suffice that all the phenomena follow from it; instead, if it leads to something contrary to a single one of the phenomena, that suffices to establish its falsity." We can on some level thank the barometer for that insight.

He also derived Pascal's Principle, which states that pressure applied to an enclosed fluid is transmitted undiminished to every part of the fluid, as well as to the walls of the container. This is not only a key to the function of a barometer, but he could use it immediately to build the first hydraulic pump. He too has been rewarded with a unit of pressure called a Pascal, which is equal to 1 Newton of force per 1 square meter of area. It leads directly to the common unit of atmospheric pressure called a millibar, which is the same as a hecto Pascal.

Pascal was also a fountain of well-made aphorisms in his later writings. "Chance favors those who are best prepared" is a good one for ocean navigators and backgammon players to keep in mind.

Robert Boyle (1627-1691) was a wealthy Englishman, considered the founder of modern chemistry. He is most famous for Boyle's Law (1669), which states that the pressure of an enclosed gas is inversely proportional to its volume so long as the temperature remains the same. Thus if you have gas in a cylinder, its pressure will rise as the piston lowers to reduce the volume. Cut the volume in half and the pressure will increase by a factor of two. See Figure 1.2-3. Boyle described this process by thinking of a "spring in the air." When you compress the gas, the pressure builds, which acts like a spring resisting the compression. Recall these were days before the knowledge of atoms and molecules, so this was quite an abstract concept for the time.

He made this discovery while defending his belief that air pressure can in fact exert strong forces, which had come under attack in the ongoing arguments about the nature of air, and more importantly, the nature of a vacuum.

To carry out these experiments he and his assistant Robert Hooke also made significant contributions to air pump design and related technologies, and they were the first to use a mercury tube manometer as a pressure gauge for scientific studies of more basic matters, such as the proprieties of gases.

In a letter of 1665 and later in a published paper in 1666, Boyle was the first person to describe the mercury tube used to measure pressure as a *barometer*, thus establishing the name we still use today.

Robert Hooke (1635-1703), British, is often described as the single greatest experimental scientist of the seventeenth century. He has been called England's Leonardo. He made pioneering contributions in many areas of science and engineering, including the escapement and balance spring that ultimately led to accurate clocks, the discovery of plant cells (a word he invented for this use), as well as proposing a theory of evolution based on microscope work with fossils.

He also worked on astronomy and proposed a theory of gravity, which made him a rival of the great and powerful Newton, who shamefully succeeded in dampening the acclaim Hooke deserved at the time.

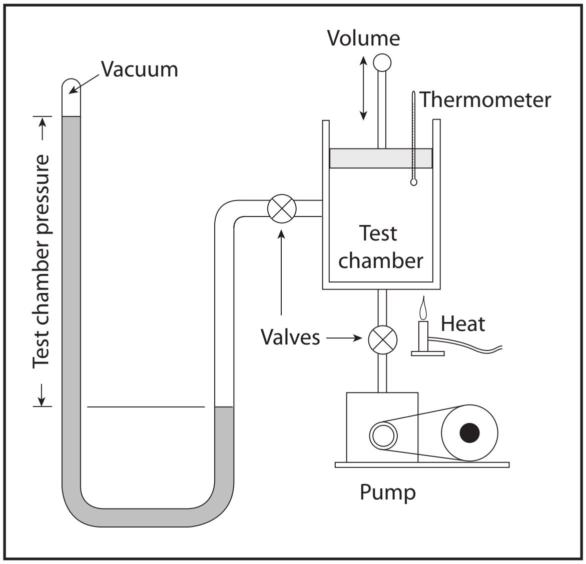


Figure 1.2-3 *A mercury manometer pressure gauge. Students around the world use this same type of apparatus that Boyle used to learn about the properties of gases. With such an arrangement, the temperature, volume, and pressure of the gas can all be varied to see how they are related.*

Hooke developed the theory of combustion, and he was a principal architect and surveyor in the rebuilding of London after the great fire. The list goes on into many fields, including the development of the first marine barometer used by Edmund Halley on the first-ever worldwide voyage of scientific discovery.

His namesake in the world of science these days, however, is Hooke's Law of Springs, which has a direct and lasting effect on the functioning of aneroid barometers, something he did not know about at the time.

Edmund Halley (1656-1742) was an English astronomer and sea captain. He is most famous for his prediction of what is now called Halley's Comet, but his contribution to the evolution of barometer usage is just as profound, though much less known. As mentioned earlier, he took a custom marine barometer (designed by Hooke) with him on his worldwide voyages of scientific discovery, during which he recorded pressures and correlated them with the weather observations in both hemispheres (1698-1700).

Other than noting the measurements, his actual logbooks do not include much detail about barometers, but the following year he published an article describing the Hooke barometer he used along with the declaration:

> "I had one of these Barometers with
> me in my late Southern Voyage, and it
> never failed to prognostick and give early
> notice of all bad weather we had, so that
> I depended thereon, and made provision
> accordingly; and from my own experience
> I conclude that a more useful contrivance
> hath not for this long time been offered
> for the benefit of Navigation."

John Locke (1632-1704), an English giant among philosophical thinkers, was also a weather buff, having known both Boyle and Hooke at Oxford. He measured and recorded what is considered the first systematic record of temperature, pressure, humidity, wind, and weather in England from 1666 to 1683. The data are cited in the article by Boyle where he first used the word barometer. So we can remember Locke not only for his profound influence on the thinking of the American Founding Fathers and the subsequent Declaration of Independence, but also for the key role he played in associating barometric pressure with the weather we experience. Thomas Jefferson bought his first barometer in 1776, about 100 years later—and chances are the instruments were very similar.

An example of a modern mercury barometer of the type found in many laboratories even today is shown in Figure 1.2-4.

Aneroid Barometers

Gottfried Wilhelm Leibniz (1646-1716) was a German giant in philosophy and mathematics, inventor of the binary number system that modern computers are based upon, and inventor of a me-

Figure 1.2-4 *A Fortin style mercury barometer originally from Princo. The first step in reading it is to adjust a pointer at the bottom to just touch the top of the mercury, then use the sliding vernier scale to read the height of the column. Corrections for temperature and latitude have then to be applied. This unit is at Starpath HQ in Seattle..*

chanical calculator, rival of Newton for the invention of calculus and other aspects of theoretical physics. Though not usually listed among his many brilliant achievements, he was the first person to propose the construction of a steel bellows aneroid barometer in several communications (with the famous Dutch scientist Daniel Bernoulli) from about 1700, but he did not have craftsmen available to build it. Thus the seeds of the future were at hand early in the history of barometers, but its realization had to wait for 140 years.

Nicolas Jacques Conte (1755-1805), French painter, engraver, and mechanical genius invented many practical devices and procedures and was a national leader in the birth of the French industrial revolution for which he received the first Legion of Honor award from Napoleon. He also created in essence the first aneroid barometer in 1798 to measure relative heights of hot-air balloons, but it was not pursued for use with atmospheric pressure measurements. He also was the inventor of what we now call the lead pencil.

Lucien Vidie (1805-1866), was a French engineer who designed, built, and patented the first successful aneroid barometer in 1844. He is described as a poor businessman who had legal troubles getting the instruments manufactured as well as defending his patent, and was in and out of court for decades to follow. He apparently did not prosper greatly from the invention. Unlike others mentioned here who took part in the evolution of the barometer, he was not distinguished for other achievements.

Figure 1.2-5 *Aneroid barometer. They look much the same today as they did in 1850. Diameters vary from 2” to 8”, but typically are 4” to 5“. They are about 2 to 4” deep.*

Besides those mentioned, Pascal, Boyle, and Bernouilli had each considered the concept of an aneroid device but none succeeded in building one.

Aneroid means “without liquid,” in that this is a barometer that does not use mercury as all precursors did. It relies on a vacuum sealed metal bellows (sometimes called a sylphon depending on how it is made) that expands and contracts in response to the atmospheric pressure outside of it. A clock-like mechanism then transfers this expansion and contraction into a dial setting that shows the pressure.

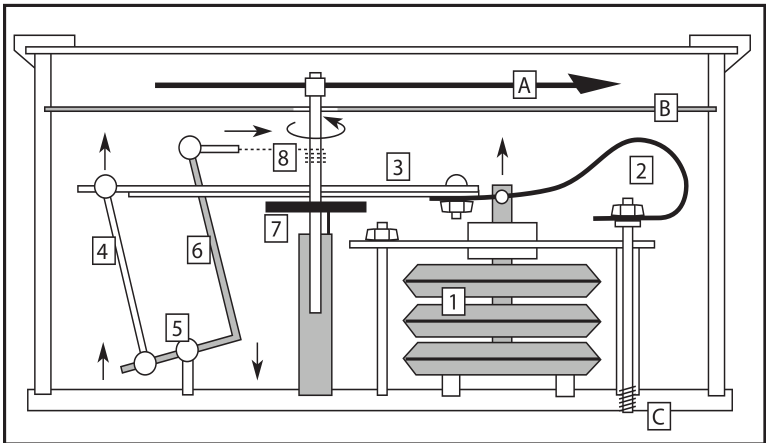
The generic aneroid barometer appearance is shown in Figure 1.2-5. Aneroids (shorthand for aneroid barometer) were introduced to the public shortly after their invention and many competing models were readily available worldwide by the 1860’s. They became popular because they were smaller (about 5 inches or less in diameter) and more portable than the mercury devices. They were also more durable (no glass tubes or mercury to spill), they cost less, and they were easier to read.

Aneroid barometers were also considered more accurate at the time by some, but this was largely a misunderstanding tied to the fact that they were easier to read, and could be read to a higher precision. The challenge of distinguishing between “precision” and “accuracy” is with us still today, and it is a mantra that will come up in multiple settings as this book proceeds. For now we just note that proper questions on their inherent accuracy or limitations were raised in the scientific and maritime literature almost immediately when the instruments appeared across Europe and the UK in the mid 1800’s. In any event, within 25 years or so, they had done away with their mercury-tube competitors as a popular barometer, though some mercury tubes remained on a few vessels till beyond 1900, and they remain in science laboratories even today.

It is only the fairly recent official declaration (in the U.S. and Common Market) that mercury can be toxic if mishandled, which has led to legal restrictions on the sale and transport of mercury (2007) that put mercury barometers to rest on still another level. A longtime popular source for laboratory grade mercury instruments in the U.S. (www.princoinstruments.com) discontinued selling them but keeps their earlier webpage and instruction manuals online. It's hard to give up something that has been such a good tool for so long, not to mention that there are likely hundreds in use around the world still. We have one in our classroom in Seattle.

There are still experienced antique dealers and barometer specialists that restore and sell antique mercury barometers. They have developed safe ways to transport them within the law. An Internet search on antique barometers will find many sources, worldwide. There are also companies such as Russell Scientific (www.russell-scientific.co.uk) and Barometer World (www.barometerspareparts.co.uk) in the U.K. that sell classic mercury barometer kits and parts to be self assembled. They leave it to the customer to acquire locally the needed mercury and to fill it. The latter company also offers an extensive source of aneroid barometer parts as well.

Laboratory grade mercury barometers are available from the Dr. Alfred Müller Meteoroglogical Instruments Company in Berlin (www.rfuess-mueller.de) who have carried on with the production of the renown R-Fuess instruments that date from the 1800s. We have been told by those who have used the instruments that their mercury instruments No. 2k and 20k are unsurpassed in quality. This company also produces the R-Fuess precision aneroid barometers, which are among the best available today.



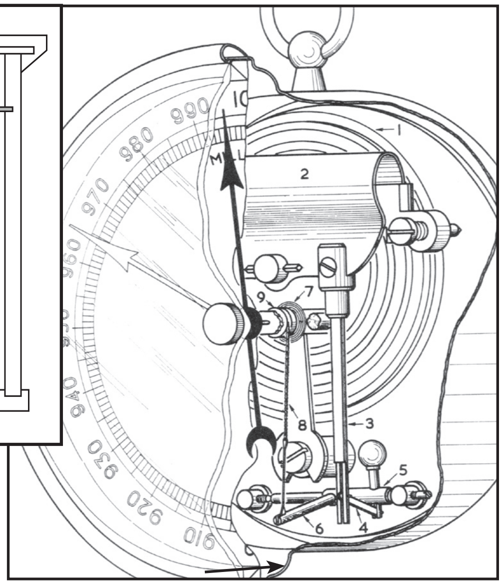


Figure 1.2-6 Left. *Side view of an aneroid barometer movement. There are two systems in balance. The evacuated bellows [1] are trying to collapse under the force of the atmospheric pressure and they are being held apart by a large flat spring [2]. The main pin axis that holds the needle [A] is being twisted clockwise by a spiral hairspring [7], which is being resisted by a counterclockwise twist from a thin chain [8] wrapped around it. When the pressure drops, the bellows have less force on them so the spring pulls them more apart, which in turn raises the arm [3] connected to rod [4]. As [4] is pulled up, the front side [6] rotates down on pivot [5]. This lets the thin chain [8] forward, so spring [7] wrap more chain on the pin, turning [A] counterclockwise showing a drop in pressure on the dial [B]. On the back of the device, there is a set screw [C] that makes small adjustments to the bellows height, so you can set the pressure right at a desired reading. Several adjustments are built into the movement so that the rotation of the needle can be made proportional to the change in pressure.*

Right. *A cutaway view of a similar movement. There are several movement designs in use today. Some aneroids have 1 bellows only, others have 2 to 5. The bellows are usually corrugated as shown, as this reduces distortion during expansion [hysteresis]. In better units, the bar [3] is usually a bimetal strip that bends with temperature to compensate for temperature changes in the bellows and main spring. Adapted from* Handbook of Meteorological Instruments, Vol. 1.

Aneroid barometers are the main type used at sea today. The heart of the instrument remains the partially evacuated, thin metal bellows, also called an aneroid capsule. As the external pressure varies, the bellows expand or contract, and this motion is used to indicate the pressure. Several bellows designs and movements have been invented over the years. One

Barographs

A "barograph" is usually thought to be an aneroid barometer with a strip chart that records the pressure as an ink trace on a drum, rotating in response to a wound spring (Figure 1.2-7). A sample barograph trace from a famous storm is shown in Figure 1.2-8.

Modern versions sometimes use battery-operated quartz clocks to rotate the drum. Barographs are very convenient on land or on large ships, but not practical on a small boat at sea. Often the trace you care about is in bad weather and then the trace ends up a broad smear as the instrument bounces around in the seas. Speaking from experience, it is difficult to avoid this. I have done an ocean passage on a 40-foot sailboat devoting half of a quarter berth to a conventional barograph, suspended into free space using bungee cords on four corners. The smear of the trace was still broad and erratic when the seas got rough. Larger deep-sea vessels, however, routinely use these at sea, especially those with extra dampening (Figure 1.2-7).

Barographs are a wonderful luxury, but if you record the pressure from a conventional barometer when you read it, you don't need the graph. Furthermore, we are likely to be more aware of what is going on with the pressure if we must read and record it, rather than having this all done for us.

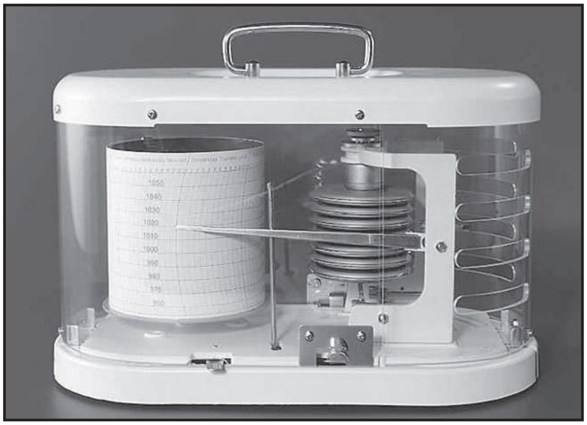


Figure 1.2-7 *A Fischer precision barograph with extra dampening for use at sea. They are also available in glass and wood frames. Drum rotation rates can be set to 26 hr or as high as 783 hr (32 days).*

It is true that if you record the pressure at each watch change, or simply routinely when on land, you get all the information the barograph provides (missing only the nice plot of the results), but that is not the whole story. When underway in the ocean we typically record the pressure all day *and* all night, but on coastal trips if we anchor out or tie up at night we typically do not have a watch on to record the pressure. A barograph feature can be quite nice in these circumstances to alert us to what took place over night.

The exceptions in ocean sailing are the single-handed and double-handed racing sailors who often have to keep irregular hours. They have discovered that a barograph trace is crucial because they do not always have time to keep systematic logbook records. A glance at the pressure trace over the past 2 hours or past 24 hours could alert them to something they might have missed otherwise. They often prefer an electronic trace (rather than conventional ink on paper) of the pressure, which brings up the next point.

To be more modern, we are better to think of the

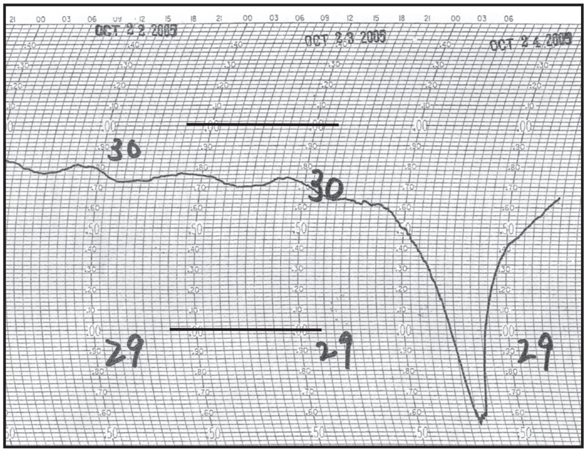


Figure 1.2-8 *A barograph trace of Hurricane Wilma as it crossed south Florida in October of 2005. The observed pressure dropped from about 29.60 to 28.54 (1002 to 966 mb) in 10 hours, but it had, 5 days earlier, set the Atlantic record Low of 882 mb (26.05") in the Caribbean.*

word "barograph" as meaning any barometer that records and displays past pressures. That makes many electronic barometers into electronic barographs, because these models store the data and display them graphically, or they allow users to push buttons to step back through past pressures. These offer nice histories underway without the smear of a printed record. Thus we might refer to "electronic barometers" as instruments that measure and display the pressure electronically, whereas "electronic barographs" are ones that can also display past pressures. One popular electronic barometer has a unique compromise of offering inkless printing onto heat sensitive paper so the user can get a smooth trace even underway in rough seas. On land, of course, all forms of barographs offer clean beautiful traces.

Typical aneroid barograph recording papers are for 7 days, but multiple traces can be recorded on one paper. Barographs are usually made with high quality aneroid movements. They are often works of art as well as dependable instruments. They are, however, often expensive instruments, varying from about eight hundred to several thousand dollars.

A "microbarograph" is a barograph with extra bellows and precision movements intended for more accurate measurements. The use of this name today is commonly intended to convey a quality instrument, though its origin can be traced to a significant expansion of the plotting scale that allowed for more accurate readings. Early Navy barographs had a 1-inch change in the pressure represented by a 1-inch range of the recording pen, but these were then updated to microbarographs that expanded this to 2.5 inches on the plot for each 1 inch of pressure change. Thus barographs can be characterized by the ratio of pressure change in inches to the corresponding sweep of the pen, as 1-1 barographs for the former and 2.5-1 microbarographs for the latter. This property can be used as a benchmark in comparing instruments.

Figure 1.2-9 shows samples of the electronic "barograph" display of a popular unit showing how you can change the scale to view the past 2 hours, or condense the scale to show the past 2 days.

Figure 1.2-9 *An electronic barograph display from Vion model 4002, imported in the U.S. from France by Weems and Plath. The time range of the display can be varied to show the past 2 hr to the past 48 hr, as shown. Once a history display is selected, the user can step back through the data to view actual times and pressures recorded.*

Electronic Barometers

An "electronic barometer" (sometimes called "digital barometer") is a small electronic device with internal sensors and electronic circuits that measure atmospheric pressure and then display the value digitally—as opposed to an aneroid display, which is a pointer on a dial. The crucial components are a small electronic sensor that measures the pressure and an electronic processor (essentially a tiny computer) that interprets the output of the sensor and then controls the numerical display. There are several sensor designs, some of which are just tiny aneroid cells, and there are several designs of how the expansion of the cell is measured. The units themselves can be anything from a sleek modernistic design the size of a card deck to a plain 10-inch wide metal box with 2-inch tall digits. Some have computer interfaces, others do not. Some show a graph of the pressure history, others do not. Some are simply the component of a large wrist watch. Some are included in hand-held GPS units. Electronic barometers vary in price from $25 to $2,500. Samples are shown in Figures 1.2-10

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This is the end of the sample.

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