Eruption column from Guagua Pichincha Volcano as seen from Quito, the capital city of Ecuador, on 7 October 1999. The column, which rose to a height of \(\sim 12 \text{ km} \ (\sim 7.5 \text{ miles})\), exhibits many of the features described by Pliny the Younger in his eyewitness account of the 79 CE (Common Era; substitute for AD, Anno Domini) eruption of Vesuvius (Preface), including a narrow ‘trunk’, spreading ‘branches’, white areas caused by condensation of water vapor as a result of rapid expansion of humid air, and dark areas laden with tephra. Such columns are characteristic of *plinian* eruptions, so called in recognition of Pliny the Younger’s early contribution to descriptive volcanology. Photograph by Daniel Andrade Varela, Departamento de Geofísica de la Escuela Politécnica Nacional, Quito, Ecuador.
USGS scientist Jack Kleinman, typically attired in shorts and a smile, sets up EDM reflectors on Novarupta lava dome in the Valley of Ten Thousand Smokes, Alaska, with Baked Mountain in the distance. The rhyolite dome was emplaced during the waning phase of the largest volcanic eruption of the 20th century, which produced about 20 km$^3$ of air-fall tephra and 11–15 km$^3$ of ash-flow tuff within about 60 hours in June 1912. Jack helped to establish a geodetic network near Novarupta in 1989 and served as crew chief for follow-up surveys in 1990 and 1993. His energy and zest for life inspired all those who knew him. Jack died in a kayaking accident on the White Salmon River, Washington, in 1994. Photograph by John Eichelberger, University of Alaska Fairbanks.
What separates the gifted from those who do is the doing of it. I’ve come across a lot of people who can write better than I can and do everything I do better than I can. The difference is I can keep my bottom to the chair.

Jim Lehrer, anchor, PBS’ The NewsHour with Jim Lehrer and author of 15 novels, 2 memoirs, and 3 plays.
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Volcanoes and eruptions are dramatic surface manifestations of dynamic processes within the Earth, mostly but not exclusively localized along the boundaries of Earth’s relentlessly shifting tectonic plates. Anyone who has witnessed volcanic activity has to be impressed by the variety and complexity of visible eruptive phenomena. Equally complex, however, if not even more so, are the geophysical, geochemical, and hydrothermal processes that occur underground – commonly undetectable by the human senses – before, during, and after eruptions. Experience at volcanoes worldwide has shown that, at volcanoes with adequate instrumental monitoring, nearly all eruptions are preceded and accompanied by measurable changes in the physical and (or) chemical state of the volcanic system. While geochemical methodologies of volcano monitoring have shown increasing sophistication and promise in recent decades, seismic and geodetic (ground-deformation) techniques remain the most widely used tools in volcanic surveillance. These two geophysical workhorses have proven to be robust and, generally, the most diagnostic and reliable techniques for volcanologists.

In the early 20th century, systematic measurements of ground deformation were initiated at a few active volcanoes in Japan and the USA. Since then, as this book illustrates, volcano geodesy – a specialized field of the still-young science of volcanology – has come a long way, not only in terms of greatly increased diversity and precision of measurements, but also in the number of volcanic systems being monitored worldwide. Having had some hands-on experience myself with ‘classical’ techniques of geodetic monitoring (e.g., tilt measurements, leveling, and laser electronic distance measurements), while a staff member at the USGS Hawaiian Volcano Observatory in the mid-1970s, I am overwhelmed by the tremendous advances in instrumentation, new techniques, data-acquisition telemetry and processing, and volcano-deformation source models over the past three decades. There has been a virtual explosion of volcano-geodesy studies and in the modeling and interpretation of ground-deformation data. Nonetheless, other than selective, brief summaries in journal articles and general works on volcano-monitoring and hazards mitigation (e.g., UNESCO, 1972; Agnew, 1986; Scarpa and Tilling, 1996), a modern, comprehensive treatment of volcano geodesy and its applications was non-existent, until now.

In the mid-1990s, when Daniel Dzurisin (DZ to friends and colleagues) was serving as the Scientist-in-Charge of the USGS Cascades Volcano Observatory (CVO), I first learned of his dream to write a book on volcano geodesy. DZ asked me whether he should undertake this book project in addition to his CVO managerial duties and research commitments. As his immediate supervisor at the time, my answer to him was a no-brainer: Absolutely! With the advent of ‘space geodesy’ (e.g., GPS and InSAR), such a book would be timely and fill a long-existing need. Most importantly, however, DZ, with his expertise and experience in both classical and emerging geodetic techniques, was clearly the right guy for the job. With the passing years, his dream gradually assumed tangible form, with decisions on content and format, identification of possible collaborators, obtaining a suitable and interested publisher, and the actual writing and technical reviews of each individual chapter. DZ was able to assemble a stellar team of knowledgeable experts to author several of the chapters (6, 8, 9, and 10) covering related topics beyond his own areas of specialization. With the reawakening of Mount St. Helens Volcano in October 2004 and its ongoing eruption, the book required some last-minute additions and updating. The rest, as they say, is history. However, completion of the book took somewhat longer than DZ and I had anticipated; Praxis and its editors and
production staff have been patient and cooperative throughout a sporadic and lengthy process.

In the Preface, DZ states that the book’s intended audience is primarily undergraduate and graduate students interested in volcanology. Doubtless this book will admirably fulfill the academic needs of professors and students in the geosciences, but *Volcano Deformation* has much more to offer. Not only is it a content-rich, clearly written and profusely illustrated textbook, but it also provides useful contextual information for the general volcanologist, like myself, who is not involved full time with geodetic studies. Moreover, because volcano geodesy is a multidisciplinary pursuit, this book should be valuable to volcano-deformation specialists wanting to know more about technique(s) apart from those they themselves employ. This volume is not a how-to compendium for making and interpreting ground-deformation measurements, but it contains pertinent references to classical surveying manuals and other works containing the theoretical basis, instrumentation and specifications, equations, and data-processing procedures related to measurement of the Earth. The book is organized and written in an easily approachable manner, even for the non-specialist reader, in that any discussion heavily laden with technical detail or mathematics can be skimmed, or even skipped, with minimal loss of the chapter’s principal theme and message.

For me, the major strength of the book is its focus on how volcano geodesy complements other volcano-monitoring approaches and tools. As emphasized throughout, optimum monitoring of a restless or an erupting volcano is achieved by a combination of techniques, rather than by uncritical reliance on any single one. An even greater strength of *Volcano Deformation* is its extensive treatment (Chapter 7) of the key lessons volcanologists have learned at well-monitored deforming volcanoes. These lessons amply demonstrate that geodetic and other volcano-monitoring data not only contribute to advancing our scientific understanding of how volcanoes work, but that they also can benefit society in reducing the risks from hazardous eruptions. The results of volcano geodesy provide basic research data on our dynamic planet and, at the same time, have practical, at times life-saving, applications. Yet, as the book cautions, despite the impressive strides made in volcano geodesy and other monitoring techniques in recent decades, volcanologists still lack the capability to reliably forecast the outcome of sustained or escalating volcanic unrest. Lamentably, at present we cannot provide definitive answers to vital questions invariably asked of us by emergency management officials and populations at potential risk: Will the volcanic unrest culminate in eruption? If so, how large will the eruption be? Will the eruption be explosive or non-explosive? How long will it last? Chapter 11 addresses how we might better answer these and related questions in the 21st century.

Finally, the readers of this book cannot help but notice a sense of adventure and excitement – above and beyond scientific curiosity – that pervades the pages of the book, especially the chapters solely authored or co-authored by DZ. For me at least, this excitement is palpable. Clearly, the author has been fascinated by how and why volcanoes deform throughout his career, and in this book DZ and his co-authors convey that fascination and wonderment to the readers. *Volcano Deformation* is hardly a dry, information-packed scientific treatise; instead, it provides vibrant testimony that doing good, important science can also be a lot of fun. It is sure to inspire some readers to become volcanologists, if not volcano geodesists, and to pick up where this book leaves off.

Robert I. Tilling
Menlo Park, California
October 2005
He [Pliny the Elder] was at Misenum in his capacity as commander of the fleet on the 24th of August, when between 2 and 3 in the afternoon my mother drew his attention to a cloud of unusual size and appearance. He had had a sunbath, then a cold bath, and was reclining after dinner with his books. He called for his shoes and climbed up to where he could get the best view of the phenomenon. The cloud was rising from a mountain – at such a distance we couldn’t tell which, but afterwards learned that it was Vesuvius. I can best describe its shape by likening it to a pine tree. It rose into the sky on a very long ‘trunk’ from which spread some ‘branches’. I imagine it had been raised by a sudden blast, which then weakened, leaving the cloud unsupported so that its own weight caused it to spread sideways. Some of the cloud was white, in other parts there were dark patches of dirt and ash. The sight of it made the scientist in my uncle determined to see it from closer at hand.

From Pliny the Younger’s eyewitness account of the 79 CE (Common Era; substitute for AD, Anno Domini) eruption of Vesuvius, translated from his Letter 6.16 to the historian Tacitus by Prof. Cynthia Damon (2000), Amherst College, Massachusetts.

Almost two millennia after Pliny the Younger’s insightful description of the Vesuvius eruption that resulted in the death of his uncle and entombed the residents of Pompeii and Herculaneum, modern volcanology is still in its infancy. Like a child with boundless enthusiasm and seemingly endless opportunities, volcano science has yet to develop fully an identity of its own. Instead, it freely draws upon such diverse disciplines as geology, seismology, hydrology, geochemistry, and geophysics. Fewer than half of the scientists who study volcanoes would call themselves volcanologists, and therein lies a great strength. Volcanology is inherently a multidisciplinary pursuit with ample room for specialists and generalists alike – physicists, chemists, biologists, hydrologists, limnologists, dendrochronologists, ecologists, remote-sensing specialists, and many others. Scientists who study volcanoes often find themselves looking beyond their own expertise for answers, surrounded by others doing the same. For novices and experts alike, volcanoes are humbling but very exciting subjects to explore.

In spite of the best efforts of countless volcano watchers dating back at least to Pliny the Younger, no unifying theory yet exists to explain the diversity and complexity of magmatic and volcanic systems. This may be due in part to the tremendous breadth of volcanic phenomena (e.g., bubbling mudpots and lava lakes; steaming hot springs and jetting lava fountains; lavas that flow freely, others seemingly too stiff to move, and others still that explode into towering ash columns and swift pyroclastic flows; geysers that entertain onlookers by erupting on schedule and rare, caldera-forming cataclysms that threaten entire civilizations). To make matters worse, all of this diversity is served up with a heavy dose of complexity. Earth’s deep interior is not only hidden from direct view, but it is also heterogeneous in virtually every way imaginable. Before it explodes or oozes onto the surface, magma forms deep within the Earth, rises through extreme conditions of pressure and temperature, interacts physically and chemically with diverse crustal rocks, cools, partially crystallizes and degases, sometimes mixes with other magmas of similar complexity, responds to regional tectonic influences, and interacts to varying degrees with groundwater. Each of these processes leaves an imprint on the eruptive or intrusive end products, so the complete sequence of events can be exceedingly difficult to decipher.
All of this says nothing about the additional complexity that arises when magma finally reaches the surface, where it interacts with the atmosphere, hydrosphere, and biosphere. During the past two centuries, more people have died as a result of tsunamis, lahars (volcanic mudflows), and post-eruption starvation and disease associated with eruptions than as a direct result of eruptive processes. On the island of Hawai‘i, many residents’ complaints of unusual respiratory problems have been attributed to ‘vog’ (volcanic fog) or ‘laze’ (lava haze), a product of previously undocumented interactions between seawater and basaltic lava flows as they pour into the Pacific Ocean from a long-lived eruption of Kīlauea Volcano (Montothersky, 1995). Atmospheric scientists still debate the relative contributions of anthropogenic and volcanic sources of several gases that play an important role in sustaining life on Earth. Because they reflect our planet’s inherent complexity from mantle to stratosphere, volcanoes present an immense challenge to those who strive to understand them.

Responding to crises that threaten the lives and livelihoods of thousands of people, volcano scientists at the beginning of the 21st century still rely to a great extent on collective experience and intuition to anticipate the outcome of volcanic unrest. In the words of two scientists who played key roles in the mitigation effort surrounding the historic 1991 eruption of Mount Pinatubo, Philippines, ‘Successful mitigation of volcanic risks requires correct forecasts, effective warnings, and a willingness of public officials and citizens to take necessary precautions. Volcanologists should be prepared for obstacles and delays at each step and should be aware that, even when progress is being made toward such forecasts, warnings, and precautionary actions, the margin of safety can be alarmingly narrow.’ (Newhall and Punongbayan, 1996, p. 807). Happily, this situation is improving rapidly. The past 25 years have witnessed several important advances in our understanding of volcanic processes, products, and attendant hazards. Progress has been spurred both by technological improvements and by inexorable encroachment of cities onto the flanks of dangerous volcanoes. Tragically, a major impetus for this change was the highest death toll from a single eruption since the beginning of the 20th century. In 1985, more than 23,000 people died as a result of lahars triggered by an eruption of Nevado del Río Volcano in Colombia – the deadliest eruption since 1902, when pyroclastic flows from Mont Peleé claimed nearly 30,000 lives in the town of St. Pierre on the island of Martinique, West Indies (Fisher et al., 1980; Fisher and Heiken, 1982).

In response, volcanologists focused their efforts on eruption prediction and volcano-hazards mitigation, with encouraging results. Volcano seismology has evolved from a descriptive science based on cataloging events toward a deterministic theory of the mechanisms of several distinctive types of earthquakes that commonly occur beneath volcanoes. Volcano geochemistry has taken its place with seismology and geodesy as a mainstream of modern volcanology, in part by providing some of the earliest and most definitive indicators that fresh magma was involved in several recent episodes of volcanic unrest that culminated in eruptions. Remote-sensing techniques have been applied to volcanoes with increasing frequency and success, promising a future of global volcano surveillance by spaceborne sensors.

The global telecommunications revolution, especially the Internet and World Wide Web, has profoundly changed the way in which scientists monitor volcanoes and share information. Although the presence of trained scientists at volcano crises will continue to be essential for effective hazards mitigation, in most places it is now possible to establish a virtual volcano observatory to share information globally in near-real time. Scientists monitoring a remote volcano can draw upon the expertise of colleagues around the world, even as hazardous events are unfolding. At the same time, advances in volcano geodesy have brought powerful new tools to bear on problems of volcano monitoring and hazards assessment. At the start of a new millennium, volcanology seems to be passing from infancy to adolescence, anxious to establish a unique identity among its more mature siblings in the Earth sciences.

This book focuses on one aspect of volcanology’s recent advances that I have been fortunate to experience firsthand – a revolution in volcano geodesy. During my career, not one but two breakthroughs...
techniques for measuring surface deformation from space have burst on the scene: the Global Positioning System (GPS) and interferometric synthetic-aperture radar (InSAR). Earth scientists have coined the phrase ‘space geodesy’ and put the concept to good use studying geodynamic processes, including volcanism. Other technological advances have made it possible to measure crustal strain in situ with amazing precision over a very wide range in frequency, blurring the distinction between seismology and geodesy. Although traditional techniques are still the best choice for many tasks, a growing collection of new tools has greatly extended the reach and capability of classical geodesy.

In one sense, volcano geodesy is a very specialized field with relatively few practitioners. On the other hand, the subject is sufficiently intuitive to have widespread appeal among many non-specialists who are fascinated by volcanoes and curious about how they work. This book is by no means a comprehensive treatment of modern geodetic techniques applied to volcanoes, nor is it a historical account of the development of volcano geodesy. For a more systematic treatment of geodetic principles and practices, the reader might want to consult a reference book on geodesy or surveying such as Bomford (1980), Davis et al. (1981), or Krumm et al. (2002). For an overview of geodetic techniques applied to volcanoes, the article on ground deformation methods and results by Van der Laat (1996) is a good choice. Readers interested in a more general treatment of volcanology or volcano hazards might want to consult excellent texts on those subjects by Williams and McBirney (1979), Latter (1989), Francis (1993), Scarpa and Tilling (1996), Fisher et al. (1997), or Decker and Decker (1998).

This is neither a how-to book nor a reference manual. Instead, it describes some widely used techniques for measuring ground movements at volcanoes and attempts to place volcano geodesy in the broader context of volcano monitoring and hazards assessment. It tries to make the point that useful geodetic information is where you find it, and sometimes an old-fashioned tape measure or leveling rod is a better tool than a state-of-the-art GPS receiver or remote-sensing satellite. Most of all, I have tried to convey a sense of the excitement that comes from knowing that the ground beneath your feet is moving, for reasons you can only guess – slowly at first, but inexorably, in response to forces that defy comprehension. This is the essence of volcano geodesy – the thrill of exploring unstable ground – that I have tried to capture on these pages.

Many of the examples cited in the book are from my personal experience, because these are the ones I know best. At the same time, I have tried to acknowledge others’ work wherever possible, as a guide to readers in search of other perspectives or more detailed information. Toward that end, I have included an extensive list of References in the hope that some readers will use the book as an entrée to the volcanological research literature. Also included is a Glossary of technical terms that should be helpful for non-specialists seeking to get beyond jargon to an understanding of volcanic processes and phenomena. The book’s intended audience is primarily undergraduate and graduate students interested in volcanology, but hopefully it will also be of interest to anyone else who wonders, as I do, how and why volcanoes deform.
Acknowledgements

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A DVD supplied with this book includes all of the figures in jpeg and pdf format. Photographs without annotation are supplied in tiff format. The reader is free to use the figures, with proper attribution, for presentations or reproduction. Also included on the DVD is a Mathematica notebook with an expanded version of Chapter 8, Analytical volcano deformation source models, by Michael Lisowski. Mathematica, by Wolfram Research Inc., is one of several mathematics software packages capable of symbolic mathematics. A free reader to access the notebook is included on the DVD. Those with a licensed version of Mathematica will have greater functionality, including the ability to specify parameter values, calculate surface displacement and its derivatives for several analytical models, and modify plots that appear in Chapter 8. Readers should direct questions or requests concerning the figures, including the availability of other file formats, to Daniel Dzurisin. Questions concerning Chapter 8 or the Mathematica notebook should be directed to Michael Lisowski.
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Common symbols used in the text are listed alphabetically, first in the Latin, then in the Greek alphabets. In a few cases, the same symbol is used differently in different chapters. All symbols are defined on first use in each chapter, and the meaning should be clear from context. Units are shown in square brackets, mostly in the International System of Units (SI). See also Abbreviations and Acronyms.

\begin{itemize}
  \item \( a \) = semi-major axis (ellipsoid) [m], radius [m], or acceleration [m s\(^{-2}\)]
  \item \( A \) = area [m\(^2\)]
  \item \( b \) = semi-minor axis (ellipsoid) [m] or perpendicular component of the baseline between two image-acquisition points for SAR images (Chapter 5)
  \item \( B \) = Skempton’s coefficient [dimensionless] or radar-pulse frequency bandwidth (Chapter 5) [s\(^{-1}\)]
  \item \( c \) = speed of light in a vacuum [299,792,458 m s\(^{-1}\)]
  \item \( d \) = distance or depth [m]
  \item \( f \) = ellipsoid flattening (Chapter 2) [dimensionless], frequency [s\(^{-1}\)], or focal length (Chapter 6) [m]
  \item \( g \) = local gravitational acceleration at Earth’s surface [m s\(^{-2}\)]
  \item \( G \), \( \mu \) = shear modulus (one of two Lamé constants; also called rigidity, modulus of rigidity, or torsional modulus) [Pascals, kg m\(^{-1}\) s\(^{-2}\)]. In Chapter 2, \( G \) = universal gravitation constant [6.6742±0.0010 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}] and \( \mu \) = shear modulus. Elsewhere, \( G \) = shear modulus.
  \item \( h \) = height [m], ellipsoidal height (Chapter 2) [m], or thickness [m]
  \item \( h_a \) = altitude of ambiguity (Chapter 5) [m]
  \item \( H \) = orthometric height (Chapter 2) [m] or altitude (Chapter 5) [m]
  \item \( K \) = bulk modulus (Chapters 8 and 9) [Pascals, kg m\(^{-1}\) s\(^{-2}\)]
  \item \( K_{\text{magma}} \) = effective bulk modulus of magma (Chapter 8) [Pascals, kg m\(^{-1}\) s\(^{-2}\)]
  \item \( K_u \) = undrained bulk modulus (Chapter 9) [Pascals, kg m\(^{-1}\) s\(^{-2}\)]
  \item \( K_s \) = bulk modulus of solid grains in porous medium (Chapter 9) [Pascals, kg m\(^{-1}\) s\(^{-2}\)]
  \item \( L \) = length [m]
  \item \( m \) = mass [kg]
  \item \( M \) = earthquake magnitude, assumed to be local magnitude, \( M_L \), unless specified otherwise [dimensionless]
  \item \( M_E \) = mass of the Earth [kg]
  \item \( M_L \) = local earthquake magnitude [dimensionless]
  \item \( M_b \) = earthquake body magnitude [dimensionless]
  \item \( M_s \) = earthquake surface-wave magnitude [dimensionless]
  \item \( M_w \) = earthquake moment magnitude [dimensionless]
  \item \( M_g \) = Mach number [dimensionless] (Chapter 3)
  \item \( M_0 \) = seismic moment [joules, kg m\(^2\) s\(^{-2}\)]
  \item \( M_0^{(g)} \) = geodetic moment [joules, kg m\(^2\) s\(^{-2}\)]
  \item \( N \) = Newton, Standard International (SI) unit of force: 1 N = 1 kg m s\(^{-2}\) (Chapter 2)
  \item \( N \) = ellipsoid-geoid separation (Chapter 2) [m] or initial ambiguity at first observation, cycle ambiguity, phase
\end{itemize}
ambiguity, or integer ambiguity (Chapter 4) [dimensionless]

$p, P$ = pressure [Pascals, kg m$^{-1}$s$^{-2}$]

$P_f$ = pore-fluid pressure (Chapter 10) [Pascals, kg m$^{-1}$s$^{-2}$]

$R, r$ = pseudorange (Chapter 4), slant range (Chapter 5), or radial distance [m]

$R$ = gas constant (Chapter 9) [8.314472 J mol$^{-1}$K$^{-1}$ (joules per mole per degree Kelvin)]

$R_E$ = mean radius of the Earth (Chapter 2) [6.371 $\times 10^6$ m]

$S$ = scale (Chapter 6) [dimensionless]

$S_Y$ = lithostatic load or vertical stress (Chapter 10) [Pascals, kg m$^{-1}$s$^{-2}$]

$t$ = time [s]

$T$ = period [s], torque (Chapter 3) [kg m$^2$ s$^{-2}$], or absolute temperature (Chapter 10) [degrees Kelvin]

$u, v, w$ = displacements along the x-, y-, and z-axes, respectively (Chapter 8) [m]

$v$ = velocity [m s$^{-1}$]

$V$ = volume [m$^3$]

$\Delta V_{surface}$ = integral of surficial vertical displacement (Chapter 8) [m$^3$]

$\Delta V_{chamber}$ = source-chamber volume change (cavity volume change) (Chapter 8) [m$^3$]

$\Delta V_{magma}$ = volume of intruded magma (Chapter 8) [m$^3$]

$\Delta V_{compression}$ = net volume change of stored magma due to pressure change in chamber ($\Delta V_{compression} = \Delta V_{magma} - \Delta V_{chamber}$) (Chapter 8) [m$^3$]

$V_p$ = seismic compressional velocity [m s$^{-1}$]

$V_s$ = seismic shear-wave velocity [m s$^{-1}$]

$W$ = weight [kg m s$^{-2}$]

$W_a, W_r$ = width of the radar antenna footprint in the azimuth and range directions, respectively (Chapter 5) [m]

$\alpha$ = radius (Chapter 8) [m]

$\beta_a, \beta_r$ = angular beam width in azimuth and range directions, respectively (Chapter 5) [degrees or radians]

$\gamma$ = gravitation constant (Chapter 8) [6.6742$\pm$0.0010$\times 10^{-11}$ N m$^2$ kg$^{-2}$ or m$^3$ kg$^{-1}$s$^{-2}$]

$\Delta$ = change or difference (e.g., $\Delta g$ = change in local gravitational acceleration, $\Delta h$ = height difference between bench marks)

$\varepsilon_{ij}$ = strain component [dimensionless]

$\varepsilon_{rr}$ = radial strain (Chapter 8) [dimensionless]

$\varepsilon_{\theta\theta}$ = tangential strain (Chapter 8) [dimensionless]

$\varepsilon_{\Delta V}$ = volumetric strain (Chapter 8) [dimensionless]

$\dot{\varepsilon}$ = strain rate (Chapter 10) [s$^{-1}$]

$\Theta$ = bearing (degrees) (Chapter 2)

$\lambda$ = wavelength [m], one of two Lamé constants [Pascals, kg m$^{-1}$s$^{-2}$], or coefficient of friction (Chapter 10) [dimensionless]

$\mu, G$ = shear modulus (one of two Lamé constants; also called rigidity, modulus of rigidity, or torsional modulus) [Pascals, kg m$^{-1}$s$^{-2}$]. In Chapter 2, $G$ = universal gravitation constant [6.6742$\pm$0.0010$\times 10^{-11}$ N m$^2$ kg$^{-2}$ or m$^3$ kg$^{-1}$s$^{-2}$] and $\mu$ = shear modulus. Elsewhere, $G$ = shear modulus.

$\nu$ = Poisson’s ratio [dimensionless]

$\pi$ = pi [dimensionless]

$\rho$ = density [kg m$^{-3}$]

$\rho_c$ = density of Earth’s crust (Chapter 8) [kg m$^{-3}$]

$\sigma$ = standard deviation

$\pi$ = tilt (Chapter 8) [microradians] or radar pulse duration (Chapter 5) [s]

$\sigma_{ij}$ = stress component [Pascals, kg m$^{-1}$s$^{-2}$]

$\sigma_1$ = maximum principal stress [Pascals, kg m$^{-1}$s$^{-2}$]

$\sigma_3$ = least principal stress [Pascals, kg m$^{-1}$s$^{-2}$]

$\varphi$ = longitude [degrees]

$\omega$ = tilt (Chapter 8) [microradians]
Abbreviations and acronyms

a annum or year (e.g., mm a\(^{-1}\), millimeters per year)
A/D analog-to-digital (e.g., A/D converter)
ADGGS State of Alaska Division of Geological and Geophysical Surveys
AKDA Alaska Deformation Array (continuous GPS network)
ALOS Advanced Land Observing Satellite (Japan)
ANSS Advanced National Seismic System (USGS)
AS anti-spoofing (GPS)
ASAR Advanced Synthetic-aperture Radar (Envisat, European Space Agency)
ASI Agenzia Spaziale Italiana (Italian Space Agency)
AKST Alaskan Standard Time. AKST = GMT – 9 hours
Auto GIPSY Automated online GPS data-processing service provided by the Jet Propulsion Laboratory: http://milhouse.jpl.nasa.gov/ag/
AVO Alaska Volcano Observatory (USA)
BARD Bay Area Regional Deformation Network (continuous GPS network)
BARGEN Basin and Range Geodetic Network (continuous GPS network)
BCE Before the Common Era (substitute for BC, Before Christ)
BM bench mark
BS backsight (leveling or triangulation)
°C degree(s) Celsius or degree(s) Centigrade
C&GS US Coast and Geodetic Survey
CAVW Catalog of Active Volcanoes of the World
C/A-code coarse/acquisition code (binary sequence used to modulate GPS carrier signals)
CCD charge coupled device
CDMA Code Division Multiple Access
CE Common Era (substitute for AD, Anno Domini)
CGPS continuous GPS
cm centimeter(s)
CNES Centre National d’Etudes Spatiales (France)
COSPEC Correlation spectrometer (trade name) used to measure SO\(_2\) concentration
CORS Continuously Operating Reference Station (GPS)
CP-FTIR closed-path Fourier transform infrared (spectrometer)
CRT cathode ray tube
CSA Canadian Space Agency
CVO David A. Johnston Cascades Volcano Observatory
CWAAS Canadian Wide Area Augmentation System for GPS, analogous to WAAS (USA), EGNOS (Europe), MSAS (Japan), GAGAN (India), and SNAS (China)
d day (e.g., mm d\(^{-1}\), millimeters per day)
DARA Deutsche Agentur für Raumfahrtangelegenheiten (former German Space Agency, reorganized as DLR in 1997)
dB decibel(s)
DC direct current
DEM digital elevation model
DLP deep long-period (earthquake)
DLR Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center, established 1997)
DRAO continuous GPS station located at the Dominion Radio Astrophysical Observatory south of Penticton, B.C., Canada; part of the Western Canada Deformation Array
DT differential transformer
Abbreviations and acronyms

DTED digital terrain elevation data
DTM digital terrain model
EBRY Eastern Basin-Range (Wasatch Front) and Yellowstone Hotspot (Yellowstone–Snake River Plain) Network (continuous GPS network)
EDM electro-optical distance meter, electronic distance meter, or electronic distance measurement
EGNOS European Geostationary Navigation Overlay Service for GPS (Europe), a regional augmentation service analogous to WAAS (USA), CWAAS (Canada), MSAS (Japan), GAGAN (India), and SNAS (China)
EEPROM Electrically Erasable Programmable Read Only Memory (computing)
EPROM Erasable Programmable Read Only Memory (computing)
ERS European Remote-Sensing Satellite (ERS-1 and ERS-2)
ESA European Space Agency
ETS episodic tremor and slip
FAA Federal Aviation Administration (USA)
FBN Federal Base Network
FDMA Frequency Division Multiple Access
FFT Fast Fourier Transform
FLIR forward looking infrared radiometer
FM frequency modulated
FOC full operational capability (GPS and GLONASS)
FS foresight (leveling or triangulation)
FTIR Fourier transform infrared spectrometer
FTP File Transfer Protocol
g gram(s) or gravitational acceleration at Earth’s surface ($g \approx 9.81 \text{ m s}^{-2}$)
GAGAN GPS and Geo Augmented Navigation system for GPS (India), analogous to WAAS (USA), CWAAS (Canada), EGNOS (Europe), MSAS (Japan), and SNAS (China)
Galileo Global Navigation Satellite System being developed by the European Space Agency (ESA)
GEONET GPS Earth Observation Network (continuous GPS network, Japan)
GHz gigaHertz (frequency unit, $10^9$ Hertz)
GIS geographic information system
GLONASS Global Navigation Satellite System (Russia)
GLORIA Geologic Long-Range Inclined Asdic (side-scanning sonar system)
GMT Greenwich Mean (or Meridian) Time, defined as the mean solar time at the Royal Greenwich Observatory in Greenwich near London, England, which by convention is at 0 degrees geographic longitude
GNSS Global Navigation Satellite System (see Glossary)
GPS Global Positioning System, specifically the US NAVSTAR GPS Global Navigation Satellite System
GPa gigaPascal(s)
GRS 80 Geodetic Reference System
GPa gigaPascal(s)
GPa gigaPascal(s)
GHz gigaHertz (frequency unit, $10^9$ Hertz)
GLONASS Global Navigation Satellite System (Russia)

Abbreviations and acronyms

GMT Greenwich Mean (or Meridian) Time, defined as the mean solar time at the Royal Greenwich Observatory in Greenwich near London, England, which by convention is at 0 degrees geographic longitude
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Abbreviations and acronyms

IERS The IERS was established as the International Earth Rotation Service in 1987 by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). In 2003 it was renamed to International Earth Rotation and Reference Systems Service. One of its primary objectives is to provide the International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).
IGS International GPS Service

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IGS International GPS Service

Abbreviations and acronyms

IERS The IERS was established as the International Earth Rotation Service in 1987 by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). In 2003 it was renamed to International Earth Rotation and Reference Systems Service. One of its primary objectives is to provide the International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).
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Abbreviations and acronyms

InSAR Interferometric synthetic-aperture radar
IOC initial operational capability (GPS and GLONASS)
ITRF International Terrestrial Reference Frame (currently ITRF2000, updated regularly)
IUGG International Union of Geodesy and Geophysics
IUSS Integrated Undersea Surveillance System (US Navy)
JAMSTEC Japan Marine Science and Technology Center
JAXA Japan Aerospace Exploration Agency (formerly NASDA, National Space Development Agency of Japan)
JERS Japanese Earth Resources Satellite
JPL Jet Propulsion Laboratory
JRO Johnston Ridge Observatory (US Forest Service visitor center near Mount St. Helens)
JRO1 Continuous GPS station at the Johnston Ridge Observatory near Mount St. Helens
°K degree(s) Kelvin
ka thousands of years before present
kbar kilobar(s)
kg kilogram(s)
km kilometer(s)
KPa kilopascal(s)
L1, L2 Primary carrier frequencies for NAVSTAR and GLONASS satellite signals. See Chapter 4 and Table 4.1 for details
L3 Military signal broadcast discontinuously at 1381.05 MHz by NAVSTAR satellites. Also, a particular linear combination of the L1 and L2 carrier frequencies. See Chapter 4 for details
L5 A third civilian carrier frequency to be broadcast in addition to L1 and L2 by Block IIF NAVSTAR satellites starting in 2006 and by Block III satellites starting in 2012. See Chapter 4 for details
LAN local area network
LBT long-base tiltmeter
Lidar light detection and ranging
LF low-frequency (earthquake)
LP long-period (earthquake)
LVO Long Valley Observatory (USA)
m meter(s)

$M$ magnitude (earthquake) on the Richter scale, assumed to be local magnitude, $M_L$, unless specified otherwise
$M_L$ local magnitude (earthquake) as originally defined by C.F. Richter and B. Gutenberg in 1935; the scale is based on the maximum amplitude of a seismogram recorded on a standard Wood–Anderson torsion seismograph body magnitude (earthquake), based on the amplitude of P body-waves; this scale is most appropriate for deep-focus earthquakes

$M_s$ surface-wave magnitude (earthquake), based on the amplitude of Rayleigh surface waves measured at a period near 20 s; appropriate for distant earthquakes

$M_w$ moment magnitude (earthquake), based on the moment of the earthquake, which is equal to the rigidity of the Earth times the average amount of slip on the fault times the area of the fault that slipped

$M_b$ Mach number of the gas in a separated gas–liquid flow through a nozzle under choked conditions (Section 3.1.4)

M-code Military code modulation structure, analogous to C/A-code and P-code, implemented on Block IIR-M and subsequent NAVSTAR satellite series starting in September 2005

Ma millions of years before the present
Mbyte megabyte ($10^6$ bytes)
mg milligram(s)
mGal milliGal (gravitational acceleration unit, $10^{-3}$ Gal)
MHz megaHertz (frequency unit, $10^6$ Hertz)
MITI Ministry of International Trade and Industry (Japan)
mm millimeter(s)
MPa megaPascal (pressure unit, $1$ MPa = $10^6$ Pascals = 10 bar)
ms millisecond(s)
$\mu$Gal microGal(s) (gravitational acceleration unit, $10^{-6}$ Gal)
$\mu$rad microradian(s) (angular tilt unit, $10^{-6}$ radian)

MSAS MTSAT Satellite-based Augmentation System for GPS (Japan), MTSAT being Multi-functional Transport Satellite, analogous to WAAS (USA),