TIME: FROM EARTH ROTATION TO ATOMIC PHYSICS

In the 21st century, we take the means to measure time for granted, without contemplating the sophisticated concepts on which our timescales are based. This volume presents the evolution of concepts of time and methods of timekeeping up to the present day. It outlines the progression of time based on sundials, water clocks, and the Earth's rotation, to time measurement using pendulum clocks, quartz crystal clocks, and atomic frequency standards. Timescales created as a result of these improvements in technology and the development of general and special relativity are explained. This second edition has been updated throughout to describe 20th- and 21st-century advances and discusses the redefinition of SI units and the future of Coordinated Universal Time (UTC). A new chapter on time and cosmology has been added. This broad-ranging reference benefits a diverse readership, including historians, scientists, engineers, and educators, and it is accessible to general readers.

DENNIS D. McCARTHY is former Director of Time at the US Naval Observatory and the leading authority in the United States for astronomical and timing data. He has led and been a member of various commissions and working groups within the International Astronomical Union and has authored and edited numerous publications dealing with fundamental astronomy, time, and Earth orientation.

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SECOND EDITION

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In honor of our wives, Diane McCarthy and Bobbie Seidelmann, and our families.
Dedicated to the scientists who preceded us and taught, mentored,
and inspired us.

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Preface

This second edition is an updated version of the first edition with various additions that reflect recent developments in timekeeping as specified in what follows.

Everyday use of time in one form or another is a common experience for everyone throughout their lives. The availability of a means to measure the passage of time with the required accuracy is taken for granted. However, the concepts on which timescales are based and the requirements for accuracy in many applications can be both sophisticated and complex. Time is not a simple subject.

During the 20th century the variability of the Earth's rotational speed was established. The basis for time that had served for so many centuries was no longer adequate to meet the more demanding needs for time. A search for the definition and introduction of a uniform second and timescale led to Ephemeris Time, based on the orbital motions of solar system bodies. At that time atomic clocks were being developed that offered a more convenient and accurate basis for time. Time measurement progressed from timescales based on astronomical phenomena to atomic physics. In addition, improvements in the accuracy of planetary positions required the introduction of dynamical timescales that recognized the role of general relativity in timekeeping. Over the same period of time the accuracies of timekeeping and time transfer improved significantly, and requirements for time have become even more demanding. The atomic Système International (SI) second quickly achieved recognition as the most accurate and fundamental unit of measure.

Although the Earth was no longer the basis for the most precise timekeeping, the demands of new technologies made it even more critical to observe, analyze, and predict the actual variations of its rotation. The motions of its rotational axis, both in space and in the Earth itself, also required a parallel effort of observations, analysis, and prediction. These activities pushed the improvement of celestial and terrestrial reference frames by orders of magnitude and encouraged new developments in the study of the dynamics of the Earth, including the core, mantle, atmosphere, oceans, etc., and the forces acting on it due to the Sun, Moon, and planets. These studies have gone on to spur the further development of even more accurate methods of observations.

This book is intended to tell the story of the progress in timekeeping over the past century. It begins with time solely based on the rotation of the Earth, and proceeds through the discovery of the variations in Earth rotation and motions of the Earth's pole. During that time clocks progressed through improvements in mechanical clocks to the development and improvements of atomic clocks. The availability of atomic time, the routine observations of the variable Earth rotation, and the development of the theory of relativity led to the introduction of Universal Time, International Atomic Time, Coordinated Universal Time, and a family of dynamical timescales. In the process there have been a number of scientific discoveries, significant improvements in accuracy, the development of new applications of accurate time, and the growth of the scientific field of Earth dynamics.

Additions in this edition include a chapter on Time and Cosmology, developments in optical frequency standards, possible redefinition of the second, and the future of UTC and leap seconds, as well as discussions of the difference between UT1 and mean solar time, the "move" of the Greenwich prime meridian, geomagnetic jerks and their effects on Earth orientation, possible timescales constructed from pulsar and white dwarf observations, and applications of time and frequency for intelligent highways and self-driving cars.

A list of acronyms and a glossary are included to ease the use of a number of specialized terms that have developed over the years in this field.

It is our pleasure to acknowledge and thank our colleagues: Professor Chris Impey, whose presentation at the Science of Time Symposium in June 2016 provided the inspiration and outline of the chapter on Time and Cosmology; Professor Mark Whittle corrected and improved our draft of that chapter; and Paul Hughes assisted in literature searches to update this book.