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Introduction to the book

The use of atomic properties for time measurement was born in 1955 when the first caesium beam frequency standard began regular operation in the United Kingdom. Of course, other types of atomic frequency standard had already been attempted. However, they had proved unable to provide a unit of time and uniform time scales superior to those based on celestial motions, in the way that the caesium standard could. Caesium standards soon proliferated, whilst their accuracy advanced by leaps and bounds. The good agreement between them inspired confidence and, in 1967, it was possible to make an atomic definition of the second to replace the previously used astronomical definition. Several years later, the existence of an adequate atomic time scale for the management of world affairs was officially recognised by the 14th General Conference on Weights and Measures (1971).

Despite these achievements, over a quarter of a century later, the atomic measurement of time has still not really become familiar. Could this be due to a deeply ingrained habit of measuring out our everyday existence by the movements of the celestial bodies? Or could it be a reaction to the lack of poetry in atomic clocks, or their inscrutable accuracy? This may be so, but there are also more objective reasons that can sometimes make it difficult to accept atomic time. One of these is the need to formulate the measurement of time within a relativistic framework, and another is the complex relationships between atomic time and the time of the dynamical theories used by astronomers. The latter problem was a subject of controversy over twenty years or so, and even the International Astronomical Union was not completely able to lay the ghost with a resolution adopted in 1991. Recently, some have thought that the discovery of rapid pulsars, the so-called millisecond pulsars, might bring the measurement of time back within the jurisdiction of astronomy.

Meanwhile, in the peace of their laboratories, physicists are barely susceptible to such interpellations. Following a period of relative stagnation which lasted about twenty years, a sudden gain in the accuracy of frequency standards was achieved in 1994. The new techniques that made this improvement possible are also full of promise for further progress in the near future. On the other hand, the world of industry has not limited its involvement. Manufactured quartz clocks and atomic clocks of various types have shown continual improvement. The instrument favoured by fundamental metrological research has always been the caesium clock and thousands of these have already been produced. In 1994, a new manufactured version came out which scored a tenfold enhancement over the whole range of relevant qualities, compared with previous versions.

Through the industrial manufacture of timing equipment, important applications of time–frequency techniques have seen the light of day. An example is the Global Positioning System (GPS), in full operation by 1995. This interests a whole range of potential users, from geodesists seeking to represent the whole globe to the nearest centimetre, to ramblers, not forgetting the military applications for which the system was originally devised.

Considering these recent advances in the already well-tested atomic techniques of time measurement and the new problems posed by such a gain in quality, it seemed an opportune moment to present something of their foundations: the basic principles, construction of the best standards, ways of comparing frequencies and times with the ultimate accuracy, and ways of accessing the primary standards, that is, the best realisations of the second and the International Atomic Time at the highest level of accuracy. It also seemed useful to recall the role of astronomical time scales, which remain important for various reasons.

As we have already mentioned, the fundamental measurement of time can no longer be conceived of outside a relativistic framework. Up to the present time, Einstein's general relativity, the simplest of these theories, has always remained in agreement with experimental results. We shall therefore adopt it as our working hypothesis. However, we must express some reservations in this regard. To begin with, we had hoped to treat the measurement of time within the framework of classical physics and then indicate, in small print as it were, what would be required to take relativistic effects into account. But then it seemed to us that this method ran the risk of promoting a widely held view that general relativity is in some sense a mere addition to classical theory, that its contribution to science consists in making a set of relativistic corrections. In reality, general relativity is a complete model for the structure of space and time, as well as for gravitational effects. We have therefore directly established the useful developments within the context of this theory. The reader who is barely familiar with such questions should nevertheless persevere, for we shall go no further than recalling the postulates of the theory and its mathematical consequences in the greatest simplicity.

The inevitable linearity of a written account is poorly suited to the many interactions between the varied aspects of time measurement. The brief description given here of the various chapters in the book is intended to orient the reader with regard to this problem.

Chapter 2 recalls the fundamental principles of time measurement for macroscopic phenomena, the only ones to be considered here. In truth, this is essentially a review of H. Poincaré's analysis, whose relevance extends to the relativistic context.

Chapter 3 shows how time measurement relates to general relativity. In an extended space, time is one element of a four-dimensional coordinate system and cannot be dissociated from the spatial coordinates. We shall define the coordinate systems used and establish some equations relating local physics to spacetime coordinates. We shall also discuss the conventions involved in synchronisation and comparison of distant clocks.

Chapter 4 has a historical objective. It shows how time measurement has evolved, in particular, during the twentieth century. We shall discuss the development of ideas stimulated by development of techniques, as well as the problems raised by transition from astronomical measurement of time to its atomic measurement.

Chapter 5 describes the tools involved in using atomic time standards, and in particular, methods for characterising their metrological qualities and comparing one with another. The characterisation of frequency stability has led to new developments in statistics. These refer to time series of measurements and the definition of variances which allow manufacturers and users of frequency standards to speak a common language. The characterisation of the accuracy of a frequency is also a problem specific to time measurement, although it could be extended to any physical quantity whose unit is directly defined by a natural phenomenon that is considered to be reproducible. Concerning the comparison of frequencies and time scales at a distance, we shall see that it is a crucial question in the sense that it often gives rise to greater uncertainties than those involved in the quantities to be compared.

Chapter 6 treats atomic frequency and time standards, also called atomic clocks. We shall begin by reviewing, on an elementary level, the main ideas of atomic physics and spectroscopy required to understand the workings of these standards and their principal features. There are several sorts of atomic clock, all making use of some transition between atomic levels of the same type, but in different atoms, such as caesium, hydrogen and rubidium. Even ions are used, like the mercury ion. It is the caesium clocks built and used in metrological laboratories that best achieve the definition of the second. These are the primary frequency and time standards. Their main feature is accuracy. Industrial versions of the caesium clock allow a relatively inexpensive dissemination of the unit of time, and hence of atomic time itself. Other types of atomic clock will also be described. They have been built or developed because they are specially suited to certain fields of application. Some are bulky but exceptionally stable, whilst others are less stable but rather compact. In this chapter, we shall go into the principles by which atoms are manipulated using the radiation from lasers. This experimental technique, which appeared recently, makes it possible to slow down and trap atoms before launching them in a highly controlled manner at very low speeds. Since 1996, this technique has led to an accuracy that excels that of all other primary frequency and time standards. The potential in these methods for manipulating atoms by laser beams, combined with the extraordinary international competition that they arouse, are a firm guarantee of future improvement in the performance of atomic clocks.

Chapter 7 is mainly devoted to the construction of the unique atomic time scale taken by convention as the international standard, namely, the International Atomic Time (denoted in all languages by TAI, from the French name Temps atomique international). We shall see how worldwide cooperation has been able to establish and maintain such a scale, and we shall investigate its qualities and the way it is disseminated. But we shall also see how it has been necessary to compromise, accepting as the practical standard a time scale based on the TAI but ingeniously adapted to maintain connections with the Universal Time (UT) as specified by Earth's rotation. This hybrid is known as Coordinated Universal Time (officially denoted by the acronym UTC). We shall show how the so-called proper second required for laboratory work can be obtained from the TAI or UTC.

Chapter 8 gives definitions of the various astronomical times in common use. These time scales have been gradually elaborated by observation of celestial bodies throughout a long period of history. Their usual definitions carry the traces of such historical developments and are thereby somewhat obscured for those unfamiliar with astronomy. We have thus made every effort to bring out the basic concepts upon which the operational definitions given by astronomers are founded. We shall investigate the purpose of these time scales. In particular, the Universal Time, witness to Earth's rotation, is a very important physical quantity requiring continuous measurement. Indeed, the efforts devoted to measuring Universal Time remain on a par with those required to maintain atomic time. Concerning pulsars, although they cannot provide a good measure for time, their study is nevertheless hampered by the uncertainties involved in atomic time. This is one of the most demanding applications for atomic clocks.

Finally, Chapter 9 presents some applications selected for the high level of quality in the time and frequency standards they require. Naturally, these applications belong to the area of fundamental research. The use of time standards in more utilitarian programmes is concomitant with a certain degree of sacrifice as far as their ultimate qualities are concerned, in favour of reliability and reduced costs. However, the more practical instruments sometimes lag only slightly behind those destined for laboratory use when it comes to accuracy and stability. The Global Positioning System provides a good illustration for this. As we are all either direct or indirect users of this system, we shall go into some degree of detail. We shall also show, as an example, how the measurement of time is relevant to a space-based oceanographic mission, TOPEX/POSEIDON. Indeed, we shall see that it underlies many aspects of the mission, with a high requisite level of quality.

2

The principles of time measurement

2.1 Introduction

The range of physical time spans is vast, from the Planck time of 10^{-43} s, which is the shortest we can conceive of in physics, to those encountered in cosmology, of the order of tens of billions of years, or 10^{17} to 10^{18} s.

From this range, we shall be concerned with only that very small part which has given rise to accurate measurements. Roughly speaking, this extends from periods of the order of 10^{-15} s, associated with visible atomic transitions, to periods of several thousand years, let us say 10^{11} s, over which astronomical observations have been made. This is the domain of typical laboratory experiments and dynamical astronomy, which have each in turn required or supplied time standards: the domain of time metrology.

Until the birth of relativistic theories at the beginning of the twentieth century, time and space formed an external and immutable framework within which our various activities could be accomplished. We were there to perceive this framework through the presence and evolution of beings and objects. At the same time, we were convinced that it existed independently of its content, and even that it would have existed without any content at all. Today, it is thought that spacetime cannot be conceived of without mass and energy, and that there is no privileged time such as Newtonian absolute time. Such a conception forces us into redoubled humility before nature. Let us admit that we do not know what time is. We know only that we need a temporal coordinate and three spatial coordinates to represent physical phenomena and invent mathematical models for them. Why these four independent coordinates and not five, or more? It is quite simply because four are enough to ensure that no measurable inconsistency occurs in our physical models.

Freed from absolute time, it becomes easier to accept a pragmatic approach to defining, or rather, to measuring time. Indeed, time is defined in such a way that mathematical models of nature remain simple. It is worth adding that the other physical quantities, such as length, mass, and so on, should be defined in the same way. It is thus by examining criteria of simplicity that we shall be able to tackle the basics of time measurement, define a unit of time and choose a time scale that can be taken as a world standard for dating events.

2.2 Time and reproducibility: the notion of duration

Nothing could be simpler than to take a well-known observational feature of our relationship with nature and turn it into a postulate. This feature is the reproducibility of any experience in time and in space. It was H. Poincaré who first stated this postulate in his discussion on the measurement of time [2.1] (translation): 'When we use the pendulum to measure time, what postulate do we implicitly assume: it is that the duration of two identical phenomena is the same; or, if we prefer, that the same causes require the same time to produce the same effects.'

However, this simplicity is illusory. Several claims demand our attention.

2.2.1 Chaos

Experience teaches us only [2.1]: 'that approximately like causes take roughly the same time to produce roughly the same effects.'

Poincaré's assertion here may be somewhat surprising. He was one of the pioneers in the study of deterministic chaos according to which roughly similar causes can produce quite different effects in the same time.

The existence of chaotic phenomena does not contradict the reproducibility postulate. It merely reminds us that caution is of the essence when applying it. In metrology, the aim is to provide reproducible standards, and it is founded on well-behaved phenomena for which an approximate application of the reproducibility postulate remains possible. It is indeed precisely the role of the metrologist to recognise and use such phenomena, whose dependence on poorly controllable perturbing causes remains weak and bounded.

2.2.2 Transposing the measurement of time to the measurement of another quantity

When Poincaré speaks of the same causes and the same effects, he assumes that we already have standards for assessing them. A measurement of time, that is, in this case, duration, can only ever be accessible to us through the measurement of another quantity.

Returning to his pendulum example, if we wish to obtain the unit duration, the second, by a single there-and-back oscillation, we must define with great accuracy some 'point' of reference through which the pendulum passes and obtain a signal at the moment it passes there. In practice, nothing is instantaneous. A photoelectric method could give a signal extending over 0.001 s. The second would then only be given to a relative accuracy of 10^{-3}. But the reproducibility postulate becomes useful when we can repeat the experiments without interruption. For then, although the read time remains unchanged, the error in the unit is, on average, divided by the number of cycles observed. In the pendulum example, it reduces to 10^{-8} after one day's observation. At the present time, the second is defined as the duration of 9 192 631 770 periods corresponding to a specified atomic transition. Simply counting periods would lead in one day, provided none were missed, to a relative uncertainty in the second of 10^{-15}.

In the two examples above, a measurement of time is converted into a voltage measurement, but the reproducibility postulate can reduce this measurement to a simple, almost qualitative act of recognition, in such a way that any uncertainty in the volt has no effect whatever on that in the second. This highlights the advantages of referring to phenomena of very short duration.

2.2.3 The local nature of phenomena

In order to control the causes of the phenomenon, in the hope that they will be the same whenever we wish to reproduce it, the experiment must be a *local* experiment, that is, rather close to the experimenter.

Are there any naturally reproducible large scale or distant phenomena that are sufficiently rapid to answer the needs of accuracy? At the present time, we do not know of any. The rotation of the Earth seemed for a long time to fulfill these requirements, until there came proof of its irregularities, during the second half of the twentieth century. The rapidly rotating pulsars discovered since 1982, with periods in the millisecond range, would have been excellent standards for duration, had the rotation not been slowing down!

If a distant and well reproducible phenomenon were discovered, we could base the definition of the unit of duration on observations of it. In fact, we would certainly do so, if there were some advantage to it. However, this would require recourse to theory, if only to the theory of propagation of electromagnetic waves. Used in the purest possible way, without appealing to any theory that might one day be contested, reproducibility leads to local measurement standards.

2.2.4 Differential ageing?

Poincaré's postulate mentions causal relations. We may wonder what happens when two phenomena occur in parallel, independently of one another. If a chemical reaction reaches conclusion whilst our atomic clock counts 10^{10} periods, can we be sure that in a million years from now, the same reaction will still take the same number of periods? The postulate allows us to assert that it will indeed be the same number. In fact, there is nothing to stop us establishing a causal connection between the two phenomena, for example, by triggering the reaction after n atomic periods and considering the global phenomenon 'period counting and chemical reaction'. The duration of this global phenomenon must be invariable. The postulate leaves no room for differential ageing of the various natural phenomena. Concerning the question as to whether local phenomena and their laws age globally, this would suppose the existence of some fictional time by which we could make our assessment. The existence of such a time is a pointless hypothesis.

Notwithstanding, it is as well to refrain from unjustified overconfidence as regards the reproducibility postulate. Although it has never yet been found to fail, it may one day be brought into question by experimental progress.

2.2.5 Reproducibility and measurement standards

From the above discussion, we can conclude that the definition of measurement units to be used for local physics can be based upon the reproducibility of local experiments. Examining the definitions of the seven basic units in the SI system (Système international d'unités), viz., the metre, the kilogram, the second, the ampere, the kelvin, the mole and the candela (definitions given in Appendix 3), reveals that this is currently the case for five of them. The exceptions are the kilogram and the kelvin. The definition of the kilogram as the mass of a unique object appeals to the supposed permanence of a property of this object, which is a form of reproducibility. With regard to the kelvin, its definition appeals to a more complex model, namely, the laws of thermodynamics based on additional postulates.

The unit of duration, the second, normally referred to as the unit of time, is therefore, in its present definition, a unit to be established locally, just like the other units. This has consequences when we have to treat measurements within the model provided by general relativity, and this is often necessary, precisely because of the great accuracy with which we can determine the second.

2.3 Time, evolution and time scales

Let us now turn to evolving phenomena which we have no reason to believe are reproducible. Whilst such phenomena abound, we shall be concerned with those belonging to the dynamics of celestial bodies, because of the high quality of the mathematical models developed to describe them, and perhaps also because, in the past, time was always associated with the motions of such heavenly objects.

In order to describe these motions, we need only a scale of coordinates in time, that is, a time scale, whose main qualities are that everyone should accept it and that it should be accessible to all. (This already raises the question of how to synchronise clocks used by distant observers, a discussion we shall postpone until Chapter 3. Let us just say for the moment that we can synchronise.) But if we wish to establish a model for these motions that allows us to predict them as in the astronomical ephemerides, the temporal argument in the theory must satisfy further criteria. What are these criteria? Let us turn once again to Poincaré's own account, rather than attempting to paraphrase:

> They [astronomers] define duration in the following way: time must be defined in such a way that Newton's law of gravitation and second law of motion both hold. The law of gravitation is an observational truth and, as such, is only approximate. This shows that we have once again only an approximate definition. If we assume that we now adopt another means of measuring time, the experiments upon which Newton's law of gravitation is founded would nevertheless have the same meaning. It is just the statement of the law that would change, because it would be translated into another language. It would obviously be much less simple. The definition implicitly adopted by astronomers can thus be resumed in the following way: time must be defined in such a way that the equations of mechanics become as simple as possible. In other words, there is no way of measuring time that is truer than all others. The one that is generally adopted is merely the most convenient.

We thus find ourselves with two definitions for the measurement of time, namely, the time which stems from the reproducibility of local phenomena, and the time that arises from Newtonian dynamics. Are these two definitions equivalent? Until the beginning of the twentieth century, there was every reason to believe that either of these definitions would lead to representations of the same absolute time, differing only by their level of quality. However, since then, Einstein's general relativity has appeared on the scene. According to this theory, only local time can be directly measured with a clock. In other words, it is the *proper time* of this clock or an observer in the immediate vicinity that is measured. The time which now renders the equations of motion simple (or rather, the least complicated), over an extended region of space including, for example, the Solar System, is just a coordi-