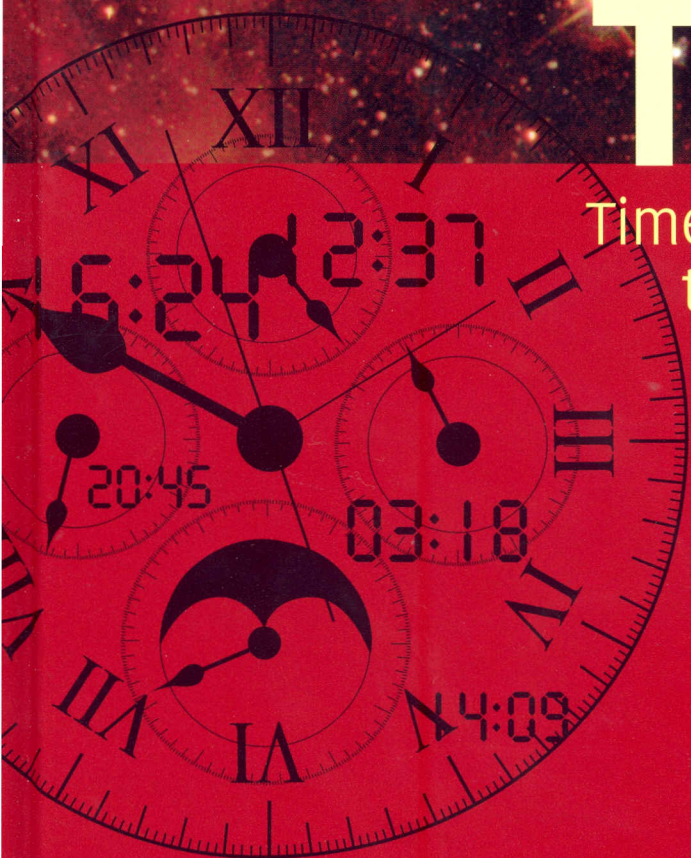


The Measurement of **TIME**

Time, Frequency and
the Atomic Clock



**Claude Audoin &
Bernard Guinot**

CAMBRIDGE

Contents

<i>Acknowledgements</i>	<i>page x</i>
1 Introduction to the book	1
2 The principles of time measurement	6
2.1 Introduction	6
2.2 Time and reproducibility: the notion of duration	7
2.2.1 Chaos	7
2.2.2 Transposing the measurement of time to the measurement of another quantity	7
2.2.3 The local nature of phenomena	8
2.2.4 Differential ageing?	9
2.2.5 Reproducibility and measurement standards	9
2.3 Time, evolution and time scales	10
2.4 The two modes of time measurement	11
2.4.1 Use of reproducibility	12
2.4.2 Use of a dynamical model	13
3 Time measurement and theoretical models	16
3.1 The Newtonian model and absolute time	17
3.2 Special relativity	19
3.2.1 Physics in inertial systems	19
3.2.2 Lorentz transformation and invariance of the interval	21
3.2.3 Time in special relativity	22
3.2.4 Field of application of special relativity	23
3.3 General relativity	24
3.3.1 Overview	24
3.3.2 Post-Newtonian approximation	27
3.4 Summary and conclusions	36

4	The evolution of time measurement	38
4.1	Date, calendar and hour	38
4.2	Time measurement based on alternation of day and night	40
4.2.1	Mean solar time	40
4.2.2	Universal time scales and time zones	41
4.2.3	Towards a unique realisation of Universal Time	43
4.2.4	Definition of the second before 1960: the second of mean solar time	46
4.3	Time based on Solar System dynamics: Ephemeris Time	46
4.3.1	First doubts on the uniformity of the Earth's rotation	46
4.3.2	Acceptance of irregularities in the Earth's rotation	47
4.3.3	Definition of the second from 1960 to 1967: the ephemeris second	50
4.3.4	Ephemeris Time: a scale reserved for astronomers	51
4.4	Atomic time measurement	51
4.4.1	Atomic frequency standards and the atomic definition of the second (1967)	51
4.4.2	From Universal Time to International Atomic Time	56
4.5	Coordinated Universal Time	61
4.6	Final comments	64
5	Clock time	65
5.1	Introduction	65
5.2	Frequency and time instability	67
5.2.1	Definitions	67
5.2.2	Notation	67
5.2.3	Measurements in the time domain	69
5.2.4	Measurements in the spectral domain	71
5.2.5	Modelling frequency and time fluctuations	72
5.2.6	Characterising frequency instability	73
5.2.7	Characterising time instability	81
5.2.8	Determining contributions from each oscillator	82
5.3	Mechanical oscillators	83
5.4	Piezoelectric oscillators	84
5.4.1	Resonators	84
5.4.2	Oscillators	86
5.4.3	Performance levels	87
5.5	Atomic time and frequency standards. The notion of accuracy	87
5.6	Time and frequency comparisons	89
5.6.1	General observations	89

Contents

5.6.2	Relationship between frequency and proper time increment	90
5.6.3	Time comparisons	90
5.6.4	Frequency comparisons	104
6	Atomic frequency standards	109
6.1	Spectroscopic basis for atomic frequency standards	109
6.1.1	Invariance and universality of atomic properties	109
6.1.2	Spectral properties of alkali atoms	110
6.1.3	Selection rules	116
6.1.4	Resonance width	118
6.2	Operations involved in an atomic clock	119
6.2.1	Observation in very dilute media	119
6.2.2	Preparation and detection of atomic states	119
6.2.3	Eliminating the Doppler effect	123
6.2.4	Interaction between atoms and electromagnetic field	125
6.2.5	Associated electronic systems	126
6.3	Realising an approximation to the isolated atom at rest	127
6.4	Caesium beam clocks	129
6.4.1	Magnetically deflected caesium beam clock	130
6.4.2	Optically pumped caesium beam clock	162
6.4.3	Laser-cooled caesium clock	170
6.4.4	Laser-cooled rubidium clock	184
6.5	Hydrogen masers	184
6.5.1	Basic principles of the hydrogen maser	185
6.5.2	Oscillation condition	187
6.5.3	Active hydrogen maser	191
6.5.4	Passive hydrogen maser	201
6.5.5	Metrological properties of the hydrogen maser	206
6.5.6	Cryogenic hydrogen masers	210
6.6	Rubidium cell clocks	211
6.6.1	Description	211
6.6.2	Operating principles	213
6.6.3	Electronics	215
6.6.4	Metrological properties of rubidium cell clocks	215
6.6.5	Current studies and prospects	217
6.7	Stored ion clocks	217
6.7.1	Confining ions in a radiofrequency trap	218
6.7.2	Confinement of a cloud of ions	222
6.7.3	Description of a frequency standard using a cloud of mercury ions	224

Contents

6.7.4	Metrological properties of frequency standards using a cloud of mercury ions	228
6.7.5	Ytterbium ion frequency standard	229
6.7.6	Laser-cooled mercury ion frequency standard	229
6.8	Other atomic frequency standards	230
6.8.1	Magnesium beam frequency standard	231
6.8.2	Optical frequency standards	231
6.8.3	Optical frequency standards based on individual ions at rest	231
6.8.4	Optical frequency standards for time measurements	233
6.9	Conclusion	234
7	Atomic time measurement	236
7.1	Definitions	236
7.1.1	Definition of the second	236
7.1.2	International Atomic Time and its relationship with geocentric and barycentric coordinate times	237
7.2	Establishing International Atomic Time	240
7.2.1	Time scale algorithms	240
7.2.2	Algorithm for International Atomic Time	241
7.3	Properties of TAI and UTC	252
7.3.1	Reliability	252
7.3.2	Accuracy of readings	252
7.3.3	Frequency stability	254
7.3.4	Frequency accuracy	254
7.4	World organisation of time measurement	255
7.4.1	Coordinated Universal Time	255
7.4.2	Local representations of UTC and independent local atomic times	258
7.4.3	Other forms of atomic time	259
7.5	Dissemination of time and frequency	260
7.5.1	Frequency	260
7.5.2	Time	261
7.6	Summary and prospects	262
8	Astronomical times	264
8.1	Universal Time	264
8.1.1	Conceptual definition	264
8.1.2	Practical definition of UT1	266
8.1.3	Other forms of Universal Time	269
8.1.4	Measurement techniques	269
8.1.5	Irregularities in the Earth's rotation	273

8.1.6	Use of Universal Time	276
8.2	Ephemeris Time	278
8.2.1	Definition	278
8.2.2	Determining Ephemeris Time	279
8.2.3	Difficulties and current solutions	280
8.3	Pulsar Time	281
9	Ultraprecise time and frequency applications	286
9.1	Fundamental research	287
9.1.1	Metrology	287
9.1.2	Measuring physical constants	289
9.1.3	Impact on atomic physics	290
9.1.4	Spacetime structure and gravity	291
9.2	Positioning, geodesy and navigation	295
9.2.1	Principles of time and frequency methods	295
9.2.2	The Global Positioning System	297
9.2.3	Other positioning systems	301
9.3	Very Long Baseline Interferometry (VLBI)	302
9.4	The TOPEX/POSEIDON mission	303
9.5	Telecommunications	306
Appendices		
Appendix 1 Acronyms for time laboratories		308
Appendix 2 Abbreviations		311
Appendix 3 Definitions of base units in the SI system		313
Appendix 4 International services		315
References		317
Index		331