

# Contents

<b>Acknowledgments</b> . . . . .	xi
<b>List of Acronyms</b> . . . . .	xiii
<b>Introduction</b> . . . . .	xxxi
Thierry PHULPIN	
<b>Part 1. Satellite Observation of the Earth's Atmosphere: International Cooperation</b> . . . . .	1
<b>Chapter 1. History of Meteorological Satellites</b> . . . . .	3
Sylvain LE MOAL	
1.1. The beginnings of remote sensing and the conquest of space . . . . .	3
1.2. It all began with Tiros-1, the first meteorological satellite . . . . .	6
1.3. American meteorological satellites . . . . .	8
1.3.1. Polar-orbiting satellites . . . . .	8
1.3.2. Geostationary satellites . . . . .	13
1.4. Russian meteorological satellites . . . . .	17
1.4.1. Polar-orbiting satellites . . . . .	17
1.4.2. Geostationary satellites . . . . .	20
1.5. European meteorological satellites . . . . .	21
1.5.1. The Meteosat saga . . . . .	21
1.5.2. 46 years after Tiros-1, MetOp enters the scene. . . . .	28
1.6. Elsewhere. . . . .	29
1.6.1. Japan . . . . .	29
1.6.2. China . . . . .	31
1.6.3. Korea . . . . .	33
1.6.4. India . . . . .	33
1.7. References . . . . .	35
1.8. Websites . . . . .	36

<b>Chapter 2. Contribution of the National Oceanic and Atmospheric Administration (NOAA, USA) Meteorological Satellites Program: An Overview . . . . .</b>	<b>37</b>
Sid-Ahmed BOUKABARA, Mitch GOLDBERG, Timothy J. SCHMIT, Andrew HEIDINGER, Satya KALLURI, Patricia WEIR, Frank GALLAGHER, David SPENCER and Ross N. HOFFMAN	
2.1. NOAA Satellite Program: historical background . . . . .	38
2.1.1. Origins of NASA-NOAA Polar and Geostationary Environmental Satellite Programs . . . . .	38
2.1.2. Low Earth orbit (LEO) missions. . . . .	40
2.1.3. Geostationary Earth orbit (GEO) missions . . . . .	43
2.2. NOAA Current Space Constellation . . . . .	45
2.2.1. The NOAA Joint Polar Satellite System (JPSS) Program . . . . .	45
2.2.2. GOES-R series . . . . .	49
2.2.3. Collaborative programs. . . . .	51
2.3. Applications . . . . .	52
2.4. Looking ahead: designing the next-generation architecture . . . . .	57
2.4.1. Factors impacting the NOAA strategy . . . . .	57
2.4.2. Next-generation NOAA space architecture. . . . .	59
2.5. Summary . . . . .	62
2.6. Acknowledgments . . . . .	62
2.7. References . . . . .	63
<b>Chapter 3. The Role of the National Aeronautics and Space Administration (NASA, USA) . . . . .</b>	<b>67</b>
Michael SEABLUM	
3.1. The beginnings of the National Aeronautics and Space Administration (NASA) . . . . .	67
3.2. The Nimbus Era (1964–1979) . . . . .	68
3.3. The Earth Observing System (1982–2004) . . . . .	72
3.4. The “A-train” (2004–present). . . . .	81
3.5. Decadal surveys and technological disruption (2007–present) . . . . .	84
3.6. References . . . . .	87
<b>Chapter 4. The Role of the European Space Agency (ESA) . . . . .</b>	<b>89</b>
Paul INGMANN	
4.1. Missions in geostationary Earth orbit (GEO) – ESA’s Start in Earth Observation . . . . .	89
4.2. Missions in low Earth orbit (LEO) . . . . .	92
4.2.1. ERS . . . . .	92
4.2.2. Envisat . . . . .	94
4.2.3. MetOp . . . . .	95

4.2.4. The Earth Explorer and Earth Watch Concept . . . . .	96
4.3. ESA's Climate Change Initiative (CCI) . . . . .	113
4.4. References . . . . .	114
<b>Chapter 5. The Role of EUMETSAT (Europe).</b> . . . . .	117
François MONTAGNER	
5.1. Introduction: What does EUMETSAT do? . . . . .	117
5.1.1. Public service value of weather satellites . . . . .	117
5.1.2. EUMETSAT, a key player in Europe . . . . .	117
5.1.3. Climate and environment. . . . .	118
5.2. The organization . . . . .	118
5.2.1. First steps . . . . .	118
5.2.2. Stability and growth . . . . .	120
5.2.3. Government . . . . .	120
5.2.4. European pooling: EUMETSAT, ECMWF and EUMETNET . . . . .	121
5.2.5. Global pooling by the World Meteorological Organization (WMO). . . . .	122
5.3. Geostationary weather satellites: from synoptic to regional zoom . . . . .	122
5.3.1. Meteosat first generation . . . . .	122
5.3.2. Meteosat second generation . . . . .	125
5.3.3. Agility of geostationary missions . . . . .	127
5.3.4. Stabilization by rotation or on three axes: system aspects. . . . .	128
5.3.5. Meteosat Third Generation. . . . .	128
5.4. MetOp satellites, the first source for numerical weather forecasting . . . . .	130
5.4.1. Synergy of observations . . . . .	131
5.4.2. Continuity and innovation . . . . .	132
5.4.3. The second generation of the European Polar System. . . . .	133
5.4.4. Scale economies. . . . .	134
5.4.5. Cooperation regarding the polar orbit. . . . .	135
5.5. Weather perspective and innovation . . . . .	136
5.6. Climate . . . . .	137
5.7. EUMETSAT and Copernicus. . . . .	137
5.7.1. A convenient partnership. . . . .	137
5.7.2. EUMETSAT and the Copernicus services . . . . .	138
5.7.3. Continuity and expansion: the challenge of CO <sub>2</sub> . . . . .	139
5.8. References . . . . .	139
<b>Chapter 6. The Role of the National Center for Space Studies (CNES, France)</b> . . . . .	141
Carole DENIEL and Pierre TABARY	
6.1. The CNES and its scientific missions . . . . .	141
6.2. Greenhouse gases and composition of the atmosphere. . . . .	142
6.2.1. Merlin, a political French–German will. . . . .	143

6.2.2. Microcarb, a strategic and continuous project.....	144
6.2.3. TRAQ, Geotrope, Mageaq, promising projects but no future developments... ..	146
6.3. IASI and IASI-NG, for meteorology, atmospheric composition and climate . . . . .	147
6.4. Physical properties of the atmosphere . . . . .	151
6.4.1. Aerosols and clouds: PARASOL, CALIPSO and the A-Train . . . . .	152
6.4.2. Next: 3MI and EarthCare. . . . .	154
6.4.3. A study in the longer term: ACCP. . . . .	155
6.4.4. Megha-Tropiques and rainfall . . . . .	156
6.5. Additional facilities and means of observation . . . . .	157
6.6. The role of numerical models. . . . .	159
6.7. References . . . . .	160
<b>Chapter 7. A Coordinated International Effort . . . . .</b>	<b>163</b>
Jérôme LAFEUILLE	
7.1. The challenges of international coordination . . . . .	163
7.2. Multilateral coordination instances. . . . .	165
7.2.1. Overview . . . . .	165
7.2.2. The World Weather Watch and its space component . . . . .	165
7.2.3. CGMS . . . . .	169
7.2.4. CEOS . . . . .	172
7.3. The benefits of coordination . . . . .	174
7.3.1. Mission continuity . . . . .	174
7.3.2. Intercalibration of instruments in orbit . . . . .	175
7.3.3. The climate observation strategy . . . . .	177
7.3.4. Use of the radio frequency spectrum . . . . .	178
7.3.5. Access to data . . . . .	179
7.3.6. Bilateral cooperation . . . . .	181
7.4. An extended community of space operators. . . . .	182
7.4.1. A growing number of national operational agencies. . . . .	182
7.4.2. The emergence of the private sector. . . . .	183
7.5. Conclusion . . . . .	184
7.6. References . . . . .	184
<b>Part 2. The Physical Basis. . . . .</b>	<b>187</b>
<b>Chapter 8. Satellite Orbits for Atmospheric Observation. . . . .</b>	<b>189</b>
Michel CAPDEROU	
8.1. Introduction . . . . .	189
8.2. Preliminaries . . . . .	190
8.3. Satellites in low Earth orbit . . . . .	192

---

8.3.1. Orbital characteristics . . . . .	192
8.3.2. Sun-synchronous satellites . . . . .	194
8.3.3. Non-Sun-synchronous satellites . . . . .	200
8.3.4. Recurrent satellites . . . . .	200
8.3.5. Spatio-temporal sampling . . . . .	202
8.3.6. Collaboration with LEO satellites . . . . .	208
8.4. Satellites in geostationary orbits . . . . .	209
8.4.1. Orbit characteristics . . . . .	209
8.4.2. Observation conditions . . . . .	210
8.5. Other types of orbits used . . . . .	211
8.5.1. Satellites in HEO orbits . . . . .	211
8.5.2. Uses of satellites in MEO orbit . . . . .	212
8.6. References . . . . .	213
<b>Chapter 9. Measurement Physics . . . . .</b>	<b>215</b>
Clémence PIERANGELO, Fatima KARBOU and Claude CAMY-PEYRET	
9.1. Physical principles of observation of the atmosphere by satellite . . . . .	215
9.1.1. Basic principles of remote sensing . . . . .	215
9.1.2. Absorption, scattering, emission . . . . .	218
9.1.3. Spectroscopy of gaseous species . . . . .	219
9.1.4. Optical properties of particles . . . . .	220
9.1.5. At the surface: reflection and emission . . . . .	222
9.1.6. Spectroscopic parameter database . . . . .	224
9.1.7. Aerosol and cloud databases . . . . .	224
9.1.8. Atmospheric profile databases . . . . .	224
9.1.9. Surface databases . . . . .	225
9.2. Radiative transfer equation . . . . .	225
9.2.1. Differential RTE . . . . .	225
9.2.2. Integration of the RTE . . . . .	226
9.2.3. Polarized RTE . . . . .	228
9.2.4. Recent advances for radiative transfer . . . . .	229
9.2.5. RTE analysis and implications for space-based remote sensing of the atmosphere . . . . .	229
9.2.6. Example: the 4A/OP source code . . . . .	232
9.3. Passive optical sensors: radiometers and spectrometers . . . . .	233
9.3.1. Radiometers . . . . .	234
9.3.2. Spectrometers . . . . .	235
9.3.3. Level 1 processing . . . . .	238
9.3.4. The sensors of the future . . . . .	238
9.4. Active optical sensors: lidars . . . . .	239
9.4.1. Lidar principle . . . . .	239
9.4.2. Lidar equation . . . . .	240

9.4.3. Different types of spatial Lidar . . . . .	240
9.4.4. Comparison of optical sensors . . . . .	246
9.5. Passive and active microwave sensors . . . . .	247
9.5.1. Specificities of microwave sensors . . . . .	247
9.5.2. Passive microwave sensors. . . . .	247
9.5.3. Active microwave sensors . . . . .	249
9.5.4. List of microwave instruments. . . . .	249
9.6. References . . . . .	249
<b>Chapter 10. The Inverse Problem and Techniques for Atmospheric Variable Retrieval . . . . .</b>	<b>253</b>
Clémence PIERANGELO	
10.1. General remarks on the inversion of atmospheric parameters . . . . .	253
10.2. Matrix expression of the direct problem . . . . .	254
10.2.1. Matrix expression . . . . .	254
10.2.2. Linearization of the problem . . . . .	255
10.2.3. Typical dimensions of the problem . . . . .	255
10.3. Solutions to the inverse problem . . . . .	256
10.3.1. Least squares. . . . .	256
10.3.2. Probabilistic methods . . . . .	258
10.3.3. Methods with pre-calculated bases. . . . .	262
10.4. References . . . . .	265
<b>Appendices . . . . .</b>	<b>267</b>
<b>Appendix 1. . . . .</b>	<b>269</b>
Claude CAMY-PEYRET	
<b>Appendix 2. . . . .</b>	<b>277</b>
Claude CAMY-PEYRET	
<b>Appendix 3. . . . .</b>	<b>287</b>
<b>Appendix 4. . . . .</b>	<b>301</b>
<b>Glossary . . . . .</b>	<b>307</b>
<b>List of Authors . . . . .</b>	<b>321</b>
<b>Index. . . . .</b>	<b>325</b>
<b>Summary of Volume 2 . . . . .</b>	<b>329</b>