

# Contents

<i>List of contributors</i>	xvii
<i>Preface</i>	xxi
<i>Introduction</i>	xxiii
<b>PART I AN INTRODUCTION TO GRAVITATIONAL WAVES AND METHODS FOR THEIR DETECTION</b>	<b>1</b>
<b>1 Gravitational waves in general relativity</b>	<b>3</b>
<i>D. G. Blair</i>	
1.1 Introduction to general relativity	3
1.2 Stress energy and curvature	4
1.3 Non-linearity and wave phenomena	7
1.4 Introduction to gravitational waves	8
1.5 The effects of gravitational waves	10
References	15
<b>2 Sources of gravitational waves</b>	<b>16</b>
<i>D. G. Blair</i>	
2.1 Gravitational waves and the quadrupole formula	16
2.2 Strain amplitude, flux and luminosity	20
2.3 Supernovae	21
2.4 Binary coalescence	27
2.5 Other sources of gravitational waves	31
2.5.1 Black holes	31
2.5.2 Pulsars	33
2.5.3 Binary stars	33
2.5.4 Cosmological sources	34
2.6 The rate of burst events	35
2.6.1 Galactic high frequency sources	35
2.6.2 Massive black hole events	38
2.7 Thorne diagrams	38
2.8 Conclusion	40
References	41
<b>3 Gravitational wave detectors</b>	<b>43</b>
<i>D. G. Blair, D. E. McClelland, H.-A. Bachor and R. J. Sandeman</i>	
3.1 Introduction	43
3.2 Resonant-bar antennas	45

x Contents

3.3 Noise contributions to resonant bars	47
3.3.1 Brownian motion	48
3.3.2 Series noise	48
3.3.3 Back-action noise	48
3.4 Problems and progress with resonant bars	49
3.4.1 The acoustic-loss problem	50
3.4.2 The impedance-matching problem	52
3.4.3 The transducer problem	54
3.4.4 The quantum-limit problem	57
3.5 Electromagnetic detectors	58
3.6 The Michelson laser interferometer	60
3.6.1 Fundamental constraints	62
3.7 Michelson interferometer designs	64
3.7.1 Multi-pass Michelson (MPM)	64
3.7.2 The Fabry-Perot Michelson (FPM)	66
3.7.3 The locked double Fabry-Perot interferometer (LFP)	67
3.8 Conclusion	68
References	69
<b>PART II GRAVITATIONAL WAVE DETECTORS</b>	<b>71</b>
<b>4 Resonant-bar detectors</b>	<b>73</b>
<i>D. G. Blair</i>	
4.1 Introduction	73
4.2 Intrinsic noise in resonant-mass antennas	73
4.3 The signal-to-noise ratio	77
4.4 Introduction to transducers	80
4.5 Antenna materials	82
4.6 Antenna suspension and isolation systems	83
4.6.1 Cable suspension	85
4.6.2 Magnetic levitation	86
4.6.3 4-Cables	87
4.6.4 Four-point suspension	88
4.6.5 Nodal point suspension	89
4.6.6 Vibration isolation at room temperature	90
4.7 Excess noise and multiple antenna correlation	91
4.8 Quantum non-demolition and back-action evasion	95
References	98
<b>5 Gravity wave dewars</b>	<b>100</b>
<i>W. O. Hamilton</i>	
5.1 Introduction	100
5.2 Thermodynamic considerations	100
5.3 Mechanical considerations	108
5.4 Practical aspects	111
5.4.1 Pump out time	111
5.4.2 Cooldown time	112
5.4.3 Recovery from accidents	114
Acknowledgements	114
References	114

<b>6 Internal friction in high <math>Q</math> materials</b>	<b>116</b>
<i>J. Ferreira</i>	
6.1 Introduction	116
6.2 Anelastic relaxation	120
6.2.1 The anelastic model	120
6.2.2 Thermal activation	125
6.3 Anelastic relaxation mechanisms in crystalline solids	126
6.3.1 Outline	126
6.3.2 Relaxation mechanisms in a perfect crystal	127
6.3.3 Defect relaxation mechanisms	141
6.4 Measured internal friction in niobium and other high $Q$ materials	152
6.4.1 Internal friction in polycrystalline niobium	152
6.4.2 Aluminium alloys	162
6.4.3 Sapphire	163
6.4.4 Quartz	163
6.4.5 Silicon	164
6.5 Summary and comparison of relevant properties of high $Q$ materials	164
6.5.1 Covalently bonded materials—sapphire, quartz and silicon	164
6.5.2 Suggestions for further work on other bcc transition metals	165
References	166
<b>7 Motion amplifiers and passive transducers</b>	<b>169</b>
<i>J.-P. Richard and W. M. Folkner</i>	
7.1 Introduction	169
7.2 Multi-mode system analysis	170
7.2.1 Two-mode systems	170
7.2.2 Three-mode systems	172
7.2.3 Generalization to $n$ -mode systems	173
7.3 Passive transducers and associated amplifiers	174
7.3.1 Capacitance transducer coupled to an FET	174
7.3.2 Inductance modulation transducer coupled to a SQUID	176
7.3.3 Capacitive transducer coupled to a SQUID amplifier	178
7.4 Analysis of multi-mode systems	178
7.4.1 Signal-to-noise ratio with the optimum filter	178
7.4.2 Analysis of a three-mode system	179
7.4.3 Analysis of a five-mode system	183
References	184
<b>8 Parametric transducers</b>	<b>186</b>
<i>P. J. Veitch</i>	
8.1 Introduction	186
8.2 The Manley-Rowe equations	189
8.3 Impedance matrix description	190
8.4 Modification of the antenna's frequency and acoustic quality factor by the transducer	194
8.5 Calculation of the transducer sensitivity and noise characteristics using the equivalent electrical circuit	198
8.5.1 Transducer sensitivity	201
8.5.2 Calibration of the transducer	206
8.5.3 Modification of pump noise by the transducer	209

8.5.4 Power dissipated in the transducer	210
8.5.5 Nyquist noise produced by the transducer resonant circuit	211
8.6 Noise analysis: general comments	211
8.6.1 Description of the phase bridge	212
8.7 Practical implementation of parametric transducers	216
8.7.1 The UWA transducer	216
8.7.2 The Tokyo transducer	220
8.7.3 The Moscow transducer	222
8.7.4 The LSU transducer	223
8.8 Conclusion	224
Acknowledgements	224
References	224
<b>9 Detection of continuous waves</b>	<b>226</b>
<i>K. Tsubono</i>	
9.1 Antenna properties	227
9.2 Frequency tuning	232
9.3 Cold damping	236
9.4 Detector sensitivity	239
References	242
<b>10 Data analysis and algorithms for gravitational wave antennas</b>	<b>243</b>
<i>G. V. Pallottino and G. Pizzella</i>	
10.1 Introduction	243
10.2 The antenna response to a gravitational wave	243
10.3 The basic block diagram and the wide band electronic noise	245
10.4 The narrow band noise and the total noise	248
10.5 Data filtering	250
10.5.1 Detection of short bursts	251
10.5.2 Detection of longer bursts	256
10.5.3 Detection of periodic signals	259
10.6 The cross-section and the antenna sensitivity	260
10.7 Coincidence techniques	263
References	264
<b>PART III LASER INTERFEROMETER ANTENNAS</b>	<b>267</b>
<b>11 A Michelson interferometer using delay lines</b>	<b>269</b>
<i>W. Winkler</i>	
11.1 Principle of measurement	269
11.2 Sensitivity limits	270
11.3 The optical delay line	274
11.3.1 A laser beam in an optical delay line	274
11.3.2 Imperfect spherical mirrors	276
11.3.3 Mirror size	279
11.3.4 Misalignment and path length variations	282
11.4 Mechanical noise	283
11.5 Thermal mechanical noise	285
11.6 Laser noise and a Michelson interferometer with delay lines	289
11.6.1 Power fluctuations	289

11.6.2	Frequency noise	290
11.6.3	Instabilities in beam geometry	291
11.7	Scattered light	293
11.7.1	Amplitudes of scattered light interfering with the main beam	293
11.7.2	Scattered light and spurious interferometer signals	296
11.8	Multi-mirror delay line	300
11.9	Sensitivity of prototype experiments	302
11.10	Conclusion	304
	Acknowledgement	304
	References	304
<b>12</b>	<b>Fabry-Perot cavity gravity-wave detectors</b>	<b>306</b>
	<i>R. W. P. Drever</i>	
12.1	Introduction	306
12.2	Principle of basic interferometer	308
12.3	Enhancement of sensitivity by light recycling	312
12.4	Resonant recycling and dual recycling	314
12.4.1	Resonant recycling	314
12.4.2	Dual recycling	316
12.4.3	Resonant recycling interferometers in general	317
12.5	Other techniques for achieving high sensitivity	318
12.5.1	Use of squeezed light techniques	318
12.5.2	Use of auxiliary interferometers to reduce seismic noise	318
12.6	Experimental strategies with Fabry-Perot systems	319
12.6.1	Use of interferometers of different length	320
12.6.2	Concurrent operation of interferometers for different purposes	320
12.6.3	Detector and vacuum system arrangements to facilitate efficient experiments	322
12.7	Some practical issues	324
12.7.1	Mode cleaners and fibre filters	324
12.7.2	Beam heating effects in mirrors and other components, and techniques for reducing it	325
12.8	Conclusion	327
	Acknowledgements	327
	References	327
<b>13</b>	<b>The stabilisation of lasers for interferometric gravitational wave detectors</b>	<b>329</b>
	<i>J. Hough, H. Ward, G. A. Kerr, N. L. Mackenzie, B. J. Meers, G. P. Newton, D. I. Robertson, N. A. Robertson and R. Schilling</i>	
13.1	Introduction	329
13.2	Laser frequency stability	330
13.2.1	Delay line systems	330
13.2.2	Cavity systems	331
13.2.3	Laser frequency stabilisation	331
13.2.4	Optical cavity as a frequency discriminator	332
13.2.5	Transducers for laser frequency control	337
13.2.6	Feedback amplifying system	338
13.2.7	Design of the servo system	338
13.2.8	Typical performance of such a system	339
13.2.9	Current developments	341
13.2.10	Future prospects	342

13.3 Laser beam geometry stabilisation	344
13.3.1 Passive suppression of geometry fluctuations	345
13.3.2 Active control of beam pointing	347
13.4 Laser intensity stabilisation	347
13.4.1 Fringe detection process	347
13.4.2 Radiation pressure effects	348
13.4.3 Methods of intensity stabilisation	348
13.5 Conclusion	351
References	351
<b>14 Vibration isolation for the test masses in interferometric gravitational wave detectors</b>	<b>353</b>
<i>N. A. Robertson</i>	
14.1 Introduction	353
14.1.1 Why good broadband seismic isolation is an essential design feature for laser interferometric antennas	353
14.1.2 The spectrum of seismic noise	353
14.2 Methods of isolation	356
14.2.1 Passive techniques	356
14.2.2 Active techniques	362
14.3 Conclusions	367
Acknowledgements	367
References	367
<b>15 Advanced techniques: recycling and squeezing</b>	<b>369</b>
<i>A. Brillet, J. Gea-Banacloche, G. Leuchs, C. N. Man and J. Y. Vinet</i>	
15.1 Introduction to recycling	369
15.2 Theory of recycling interferometers	369
15.2.1 Optics in a weakly modulating medium	370
15.2.2 Standard recycling	376
15.2.3 Numerical estimations	381
15.3 Experimental results	383
15.3.1 Internal modulation	383
15.3.2 External modulation	384
15.4 Recycling: the current status	387
15.5 Use of squeezed states in interferometric gravitational-wave detectors	388
15.6 The principles of noise reduction using squeezed states	390
15.7 Squeezed states for non-ideal interferometers	396
15.8 Squeezing and light recycling	401
Acknowledgments	404
References	404
<b>16 Data processing, analysis and storage for interferometric antennas</b>	<b>406</b>
<i>B. F. Schutz</i>	
16.1 Introduction	406
16.1.1 Signals to look for	407
16.2 Analysis of the data from individual detectors	407
16.2.1 Finding broad-band bursts	408
16.2.2 Extracting coalescing binary signals	411
16.2.3 Looking for pulsars and other fixed-frequency sources	427
16.3 Combining lists of candidate events from different detectors	438

16.3.1	Threshold mode of data analysis	438
16.3.2	Deciding that a gravitational wave has been detected	439
16.4	Using cross-correlation to discover unpredicted sources	440
16.4.1	The mathematics of cross-correlation: enhancing unexpected signals	441
16.4.2	Cross-correlating differently polarized detectors	444
16.4.3	Using cross-correlation to search for a stochastic background	445
16.5	Reconstructing the signal	446
16.5.1	Single bursts seen in several detectors	446
16.6	Data storage and exchange	448
16.6.1	Storage requirements	449
16.6.2	Exchanges of data among sites	449
16.7	Conclusions	450
	Acknowledgements	451
	References	451
<b>17</b>	<b>Gravitational wave detection at low and very low frequencies</b>	<b>453</b>
	<i>R. W. Hellings</i>	
17.1	Introduction	453
17.2	LF and VLF gravitational waves	453
17.3	The effect of a gravitational wave on electromagnetically tracked free masses	454
17.3.1	One-way tracking	455
17.3.2	Two-way tracking	457
17.3.3	Interferometers	459
17.4	Pulsar timing analysis	459
17.5	Doppler spacecraft tracking	465
17.6	Space interferometer gravitational wave experiments	470
17.6.1	Microwave interferometer	471
17.6.2	Laser interferometers	473
	References	474
	<i>Index</i>	477