

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	The different MIMO approaches . . . . .	1
1.2	The project background of the thesis . . . . .	2
1.3	State of the art . . . . .	3
1.4	Properties of millimetre waves . . . . .	4
<b>2</b>	<b>Electromagnetic wave propagation</b>	<b>7</b>
2.1	The source problem and Huygen's principle . . . . .	7
2.2	The scattering problem . . . . .	8
2.3	The Born approximation . . . . .	10
2.4	Rytov approximation . . . . .	11
<b>3</b>	<b>Antenna arrays and MIMO radar signal theory</b>	<b>13</b>
3.1	From vector potentials to array factor . . . . .	13
3.2	The array factor . . . . .	18
3.3	Phase relations and steering vector . . . . .	20
3.3.1	Visible region, grating lobes and angular resolution .	22
3.3.2	Array steering . . . . .	24
3.4	The general bistatic antenna array . . . . .	26
3.5	The virtual array principle . . . . .	31
3.5.1	The position of virtual elements by convolution . .	32
3.5.2	Description by grid vectors . . . . .	35
3.6	The MIMO radar signal structure . . . . .	35
3.7	Output power and SNR . . . . .	38
<b>4</b>	<b>Modulation, demodulation, signal design</b>	<b>41</b>
4.1	Generation of complex signals . . . . .	41
4.1.1	Complex signal generation by IQ-demodulation . .	41
4.1.2	Analytic signal generation by Hilbert transformation	42
4.2	Fundamental parameters . . . . .	44
4.3	Pulse radar systems . . . . .	44
4.4	Modulated radars . . . . .	47
4.4.1	Linear frequency modulation . . . . .	47
4.4.2	Compressing chirps by matched filter . . . . .	49
4.4.3	The FMCW principle . . . . .	52

4.4.4	The SFCW radar vs. sampled FMCW radar . . . . .	60
4.4.5	Different ramp signals . . . . .	62
4.5	Sidelobe reduction in range compression . . . . .	63
4.5.1	Windowing and mismatched filters . . . . .	64
4.5.2	Nonlinear frequency modulation . . . . .	64
4.6	Doppler compensation . . . . .	67
4.7	Constant false alarm rate algorithms . . . . .	67
<b>5</b>	<b>Angular signal processing</b>	<b>69</b>
5.1	Array windows and spatial correlation . . . . .	69
5.2	Range dependent curvature filter . . . . .	70
5.3	Analysis of FMCW-signal . . . . .	71
5.3.1	The covariance matrix of general FMCW signal . . . . .	72
5.3.2	Covariance matrix of resampled signal . . . . .	75
5.3.3	Eigenanalysis on covariance matrix . . . . .	77
5.3.4	Covariance matrix in filter design . . . . .	78
5.4	Angular processing methods . . . . .	79
5.4.1	Conventional beamformer . . . . .	79
5.4.2	Augmentation for sparse arrays . . . . .	79
5.4.3	Cyclic methods . . . . .	80
<b>6</b>	<b>MIMO radar with minimum redundancy</b>	<b>85</b>
6.1	The principle of minimum redundancy arrays . . . . .	85
6.1.1	Principal considerations from radio-astronomy . . . . .	86
6.1.2	From ULA to sparse array . . . . .	87
6.1.3	Zero redundancy sub-arrays . . . . .	89
6.1.4	MIMO radar combined with minimum redundancy .	90
6.2	A design algorithm for a linear MR array . . . . .	92
6.2.1	Brute force algorithm for restricted linear MR arrays	92
6.2.2	Simulation results . . . . .	94
6.2.3	Relaxation for general arrays . . . . .	101
6.3	Analytical approach . . . . .	101
6.3.1	MR-MIMO setup as nested minimum redundancy approach . . . . .	104
6.3.2	MR-MIMO setup as braced and nested zero redundancy approach . . . . .	109
6.3.3	Augmentation of sparse covariance matrix . . . . .	113
<b>7</b>	<b>Cascaded minimum redundancy arrays</b>	<b>117</b>
7.1	The linearly cascaded minimum redundancy array . . . . .	117
7.1.1	Cascading MR-MIMO arrays by nesting . . . . .	117

7.1.2	Cascading braced MR-MIMO arrays by nesting . . . . .	121
7.2	The two dimensional cascaded minimum redundancy case . .	123
7.3	Description of cascading . . . . .	125
7.4	Relation to Coded aperture imaging . . . . .	127
<b>8</b>	<b>Noise and error propagation</b>	<b>129</b>
8.1	Noise contribution to virtual elements . . . . .	129
8.1.1	Systematic errors . . . . .	132
8.2	Propagation of errors . . . . .	135
8.2.1	Error propagation in virtual arrays . . . . .	135
8.2.2	Error propagation in virtual arrays with minimum redundancy . . . . .	135
8.2.3	Errors in cascaded virtual arrays . . . . .	136
<b>9</b>	<b>MIMO radar with compressed sensing</b>	<b>137</b>
9.1	A short introduction to compressed sensing . . . . .	137
9.2	Methods for compressed sensing . . . . .	141
9.2.1	Method of frames . . . . .	142
9.2.2	Best ortho basis . . . . .	142
9.2.3	Matching pursuit . . . . .	143
9.2.4	Reduced matching pursuit . . . . .	145
9.2.5	Simplex method . . . . .	146
9.2.6	Basis pursuit . . . . .	146
9.3	Sparse setups and compressed sensing . . . . .	147
9.4	Simulation results . . . . .	150
9.5	CS as remedy for coherent signal scenario . . . . .	151
<b>10</b>	<b>Implemented systems</b>	<b>155</b>
10.1	SUM system . . . . .	157
10.1.1	The consortium for the sensor set . . . . .	157
10.1.2	Data fusion . . . . .	158
10.1.3	The MMW radar . . . . .	158
10.1.4	Antenna configuration . . . . .	161
10.1.5	Operational modes . . . . .	163
10.1.6	Array ambiguities . . . . .	164
10.2	Helicopter landing aid radar . . . . .	165
10.2.1	Array with minimum redundancy . . . . .	166
10.2.2	Antenna pattern . . . . .	167
10.2.3	Helicopter mount . . . . .	168
10.2.4	Tough housing . . . . .	169

<b>11 Correction of modulation and calibration</b>	<b>173</b>
11.1 Distortions in radar hardware . . . . .	173
11.1.1 Complex signals' amplitude and phase errors . . . . .	173
11.1.2 IF filter and amplifier nonlinearities . . . . .	175
11.1.3 AM and FM noise effects . . . . .	176
11.1.4 Dispersion by transmission lines . . . . .	177
11.2 Modulation nonlinearities and calibration . . . . .	180
11.2.1 VCO predistortion . . . . .	181
11.2.2 Ramp linearization . . . . .	182
11.2.3 Retrieval of frequency deviation . . . . .	183
11.2.4 Internal transmission line lengths . . . . .	186
11.3 Data interpolation and resampling . . . . .	196
11.3.1 Coherent resampling . . . . .	210
11.3.2 Separation of phase deviation and phase noise . . . . .	218
11.3.3 Correction of statistic frequency deviation . . . . .	223
11.3.4 Mismatched filter by windowing . . . . .	226
11.3.5 Range dependent curvature filter . . . . .	226
11.3.6 Summary of proposed pre-processing . . . . .	227
11.3.7 Further methods . . . . .	228
<b>12 Angular processing results</b>	<b>233</b>
12.1 Linear array . . . . .	233
12.2 Cascaded linear array . . . . .	235
<b>13 Conclusion</b>	<b>241</b>
<b>A Mathematical methods</b>	<b>245</b>
A.1 Functional analysis . . . . .	245
A.1.1 Norms in vector spaces . . . . .	245
A.1.2 Unitary vector spaces . . . . .	245
A.1.3 Hilbert spaces . . . . .	246
A.1.4 Orthogonal and orthonormal vector spaces . . . . .	246
A.2 Fresnel integrals . . . . .	246
A.3 Method of stationary phase . . . . .	248
A.4 Linear coordinate transformation . . . . .	249
<b>B System theory on electromagnetics</b>	<b>251</b>
B.1 Electromagnetic fields from vector potentials . . . . .	251
B.2 The rectangular hollow waveguide . . . . .	251
B.3 Radiation from apertures . . . . .	252
B.4 Horn antennas . . . . .	253

B.4.1	Radiated fields from horn antennas . . . . .	255
B.4.2	Directivity and footprint . . . . .	256
<b>C</b>	<b>Signal theory</b>	<b>259</b>
C.1	The residual video phase method . . . . .	259
C.2	Zero-padding . . . . .	260
C.3	Window functions . . . . .	260
C.3.1	Taylor and Hamming window . . . . .	261
C.3.2	The Kaiser window . . . . .	262
<b>D</b>	<b>Array processing fundamentals</b>	<b>265</b>
D.1	Steering weights from Laurent series . . . . .	265
D.2	Zero redundancy arrays . . . . .	266
D.3	Array processing algorithms . . . . .	268
D.3.1	Capon's minimum variance estimator . . . . .	268
D.3.2	Linear estimation, auto-regressive models or maximum entropy method . . . . .	268
D.3.3	Eigenanalysis methods . . . . .	269
<b>E</b>	<b>List of variables</b>	<b>279</b>
	<b>Bibliography</b>	<b>285</b>