

List of Figures

I	Von Hoerner-diagram.	xi
P 1.1	GMRT 45-m telescope (Pune, India).	4
P 1.2	Effelsberg 100-m telescope (Germany).	4
P 1.3	Green Bank (GBT) 100-m telescope (WVA, USA).	5
P 1.4	IRAM 30-m telescope (Pico Veleta, Spain).	5
P 1.5	VLA 25-m telescope (NM, USA).	6
P 1.6	SEST 15-m telescope (La Silla, Chile).	6
P 1.7	Plateau de Bure Interferometer (French Alps, 2 500 m altitude).	7
1.1.a	Alidade supported radio telescope.	11
1.1.b	Pedestal-Yoke supported radio telescope.	11
1.1.c	Pedestal-Fork supported radio telescope.	12
2.1	Geometry of the parabolic reflector.	15
2.2	Geometry of the Cassegrain system.	16
2.3	Geometry of the Gregory system.	17
2.4	Effelsberg 100-m as example of an Alidade supported telescope.	20
2.5	IRAM 30-m as an example of a Pedestal-Yoke supported telescope.	23
2.6	IRAM 15-m (and similar SEST) as example of a Pedestal-Fork supported telescope.	27
2.7	Schematic view of a closed BUS.	30
2.8	Effelsberg 100-m telescope (horizon position) illustrating the connection of the BUS to an octahedron and pyramidal support.	31
2.9	IRAM 30-m telescope illustrating the connection of the BUS network to the roof (membrane) of the yoke.	32
2.10	IRAM/SEST 15-m telescope illustrating the connection of the BUS to the central hub.	32
2.11	(a) Mass-Diameter relation of BUS constructions. (b) Mass-Surface ratio, as function of the normalized BUS radius.	33

2.12	IRAM 30-m telescope. (a) Homology deformations at horizon and zenith. (b) Thermal reflector deformations derived from measured BUS temperatures.	36
2.13.a	Aluminium plate panel.	41
2.13.b	Machined Aluminium panel (IRAM 15-m telescope).	41
2.13.c	Honeycomb core.	41
2.14	Partial view of the BUS tube network inside the IRAM 30-m telescope. ...	42
3.1	Astrodome of the 10-m Heinrich-Hertz Telescope (HHT, Arizona, USA, 3 200 m altitude).	50
3.2	Astrodome of the 10-m Caltech Submillimeter Observatory Telescope (CSO, Hawaii, 4 000 m altitude).	50
3.3	Astrodome of the 15-m James Clerk Maxwell Telescope (JCMT, Hawaii, USA, 4 000 m altitude).	51
3.4	Radome of the 20-m Onsala Space Observatory Telescope (OSO, Sweden, sea level).	52
3.5	FCRAO telescope (Amherst, USA) inside its radome.	53
4.1	Thermal interaction of an open-air telescope with the variable local thermal environment.	56
4.2	Weather station on a 10 m high tower; VLA site (NM, USA).	58
4.3.a	View of the low altitude forested site Effelsberg, Germany (320 m alt.). ...	60
4.3.b	View of the mountain site Pico Veleta, Spain. The IRAM 30-m telescope (at 2 900 m altitude) can be seen in the upper right corner.	60
4.3.c	View of the high altitude site Chajnantor, Chile (5 000 m).	60
4.4	Seasonal variation of the ambient air temperature at Effelsberg, Pico Veleta and Chajnantor.	61
4.5	Seasonal distribution of the ambient air temperature at Effelsberg (320 m), Pico Veleta (2 900 m) and Chajnantor (5 000 m).	61
4.6	Example of measured regular variations of the ambient air temperature at (a) Effelsberg (summer) and (b) Chajnantor (winter).	62
4.7	Example of irregular variations and of an extreme and fast decrease of the ambient air temperature at Pico Veleta.	63
4.8	Daily ambient air temperature variation at (a) Effelsberg, (b) Pico Veleta and (c) Chajnantor.	63
4.9	Calculated (a) and measured (b) change of the ambient air temperature within a time interval of $\delta t = 1/4, 1/2, 1$ and 2 hours.	64
4.10	Wind speed measured at Plateau de Bure (French Alps, 2 500 m).	66
4.11	Wind speed measured at the VLA site (NM, USA, 1 500 m).	66
4.12	Seasonal change of the wind speed at the sites of Effelsberg, Pico Veleta and Chajnantor.	67
4.13	Yearly cumulative distribution of the wind speed at Effelsberg, Pico Veleta and Chajnantor.	67
4.14	Average wind speed throughout a day at Effelsberg, Pico Veleta and Chajnantor; during winter: W, and summer: S.	68

4.15	Yearly wind direction at Pico Veleta. The circles give wind speeds of 10, 20 and 30 m/s.	68
4.16	Ground temperature of (a) a grey asphalted surface (rail bedding at Plateau de Bure) and (b) of the same surface covered with a thick layer of snow.	70
4.17	Surface layer temperature of the sandy ground at Chajnantor.	70
4.18	IRAM 15-m telescope showing frost and ice at cold edges (near panel gaps) of rear side heated panels.	72
4.19	IRAM 30-m reflector during heating for de-icing and after the heating has been switched off.	73
4.20	Relative humidity H at (a) Pico Veleta, and (b) Chajnantor.	74
4.21	Effective sky temperature T_S measured on Plateau de Bure.	75
4.22	Effective sky temperature for a clear sky and an overcast sky.	76
4.23	Effective sky temperature T_S calculated from Eqs.(4.17)–(4.21) for Effelsberg, Pico Veleta and Chajnantor.	77
4.24	Illustration of Eq.(4.23) for Effelsberg (a) and Chajnantor (b).	78
4.25	Cloud coverage at Pico Veletain in 1998.	79
4.26	Normalized solar radiation at the top of the atmosphere.	80
4.27	Solar radiation measured at Plateau de Bure and at Chajnantor during 4 summer days and 4 winter days.	81
5.1	(a) Definition of the horizon H at the location P on Earth. (b) Orientation of the Horizon System $[x,y,z]$ at location P	86
5.2	Insolation at Chajnantor ($\varphi = -23^\circ$) during one year.	87
5.3	Solar illumination of a horizontal plane (a) and vertical plane (b).	89
5.4	(a) Elevation $\beta(t)$ of the Sun at Plateau de Bure ($\varphi = 45^\circ$) as function of the time of the day.(b) illumination \mathcal{S}_v of a vertical surface, (c) illumination \mathcal{S}_h of a horizontal surface.	90
5.5	Temperature T_h of a horizontal surface. $S(\beta)$ is the elevation of the Sun (normalized).	91
5.6	Solar illumination of a tube of length L and diameter D	91
5.7	Asymmetric solar illumination of parabolic reflectors of the VLA array (NM, USA).	92
5.8	Geometry of shadow in a parabolic reflector.	93
5.9	Shadow in a parabolic reflector for the Sun shining from the left side, at the elevation α indicated above the figure.	93
5.10	Solar illumination of a parabolic reflector, shown as a two-dimensional cut.	94
5.11	Illumination (power) of a stationary reflector (at horizon position, facing South).	96
5.12	Open BUS.	97
5.13	Closed BUS.	97
5.14	Normal vector description of flat surfaces of a box-type enclosure.	98
5.15	(a) Side view of a cylindrical enclosure of radius R and height H . (b) View from the top.	99

5.16	Illustration of an over-hemispherical radome of radius R	100
5.17	Contour lines of solar illumination of a radome.	100
5.18	Solar energy incident (1), absorbed (3) and transmitted (2) into the On-sala radome during summer (Aug 22).	101
5.19	Scattering of on-axis incident solar radiation on a parabolic reflector surface.	105
6.1	PT 100 TM electric resistance temperature sensor installed inside the VertexRSI ALMA 12-m prototype antenna.	108
6.2	Temperature monitoring of a plate.	109
6.3	Infrared image of one Plateau de Bure telescope.	111
6.4	Temperature sensors on the VertexRSI ALMA 12-m prototype.	112
6.5.a	Temperature sensors on the pedestal of the VertexRSI ALMA 12-m prototype telescope.	112
6.5.b	Temperature sensors on the fork support of the VertexRSI ALMA 12-m prototype telescope.	113
6.6	IRAM 30-m telescope, BUS and yoke.	116
6.7	AEC ALMA 12-m prototype telescope, pedestal and fork.	116
6.8	IRAM 30-m telescope. Illustration of thermally important elements.	117
6.9	IRAM 30-m telescope. Reflector surface deformations derived from a holography measurement and calculated from the FEM.	118
6.10	IRAM 30-m telescope. Measurement of focus variations using a radio source and predictions using temperature measurements of the telescope structure and the FEM.	119
6.11	IRAM 30-m telescope. Measurement of pointing corrections using a radio source, and predictions using temperature measurements of the telescope and the FEM.	120
6.12	Kitt Peak 11-m telescope (NRAO, USA). Empirical correlation between the focus position and the temperature difference between the reflector surface and the BUS.	121
7.1	Illustration of heat transferred by conduction through a plate (a), by convection to a plate immersed in a flow of air (b) and by radiation between two plates facing each other (c).	125
7.2	Illustration of heat transfer by conduction in a rod.	128
7.3	Double-mode heat transfer between the walls W_1 and W_2	129
7.4	Conductive heat transfer in radial direction through a pipe without insulation (a), with insulation (b).	130
7.5	Illustration of convective heat transfer between a fluid/gas and a body.	131
7.6	Illustration of heat transfer by convection and conduction through a plate immersed in an inner (v_1) and outer (v_2) fluid/gas stream.	132
7.7	Black Body radiation at $T = 243$ K, $T = 273$ K and $T = 323$ K, normalized to the peak $B(273$ K).	142
7.8	Explanation of the view factor $\phi_{1,2}$ of the surface elements dA_1 , dA_2 at the temperature T_1 , T_2 and at distance r	143

7.9	Combination of conductive, convective and radiative heat transfer.	146
7.10	Radiative heat transfer between black body surfaces facing each other (a) and grey surfaces facing each other (b).	147
7.11	Radiative resistance of a grey surface in an enclosure.	148
7.12	Configuration of parallel plates (a), of right-angle plates (b).	150
7.13	Internal view factors of a beam (enclosure property).	150
7.14	View factors of parallel plates and off-set parallel plates.	151
7.15	Cylindrical coordinates used in Eq.(7.71). The heat transfer can occur in radial direction: A, azimuth direction: B and vertical direction: C.	153
7.16	Illustration of the thermal time constant and associated exponential change in temperature of the IRAM 15-m telescope fork, not insulated. . .	157
8.1	Infrared picture of the IRAM 30-m telescope facing the horizon (left side) and pointing at 45° elevation (right side).	162
8.2	IRAM 30-m telescope. Panel temperatures measured with the reflector at horizon position H and zenith position.	162
8.3	IRAM 15-m telescope. The reflector pointed during nighttime towards horizon so that the lower part faced the cool sky and is iced up while the upper part faced the relatively warm layer of snow.	163
8.4	Illustration of a vertical wall facing the very extended ground (or sky). ...	163
8.5	Illustration of the view factor calculation of a radome, or of the curved slit of an astrodome.	165
8.6	Illustration of a parabolic reflector, tilted at the elevation E, seeing the sky (element ΔA_S) and the ground (element ΔA_G).	166
8.7	(a) Illustration of a parabolic reflector tilted at the elevation E, seeing the sky within the angle α_S and the ground within the angle α_G . (b) Coordinate system and angles used to calculate the view factors for the position P ₁	167
8.8	View factor ϕ_S and ϕ_G of a parabolic reflector for the sky (lines S) and the ground (lines G).	169
8.9	Model calculation of the panel surface temperature (28 sectors) of a parabolic reflector when pointing towards horizon ($E = 0^\circ$) and being tilted at $E = 60^\circ$	170
8.10	Infrared picture of the IRAM 30-m telescope (pointing at 45° elevation) showing the warm lower rear cladding (light areas) facing the warm ground and the cool upper rear cladding (dark areas) facing the cool sky. Note the warm exhaust air in the yoke area.	171
9.1	Temperature induced inclination of a pedestal with associated tilt Δ of the Az-bearing and AZ-axis.	175
9.2	SEST 15-m telescope. Change of the AZ-axis tilt Δ due to a tilt of the concrete pedestal, derived from changes of the pointing model parame- ters P ₄ , P ₅	176

9.3.a,b	IRAM 30-m telescope. (a) Change of the AZ-axis tilt Δ due to an inclination of the concrete pedestal, derived from changes of the pointing model parameters P_4 , P_5 . (b) Correlation of the tilt amplitude with the ambient air temperature.	176
9.3.c	IRAM 30-m. Inclinometer measurements of the AZ-axis tilt Δ	177
9.4	Temperature uniformity of the pedestal of the VertexRSI ALMA 12-m prototype telescope.	178
9.5.a	The alidade consists of the base frame and the A-towers A_1 , A_2 with interconnections, separated by the distance B	179
9.5.b	The differential thermal expansion ΔL between the front and the rear of the A-tower causes a tilt $\Delta \varepsilon_2$ perpendicular to the EL-axis and a rotation of the top of the alidade, with an associated encoder error.	180
9.6	Temperatures of the Effelsberg alidade (A-towers A_1 , A_2).	181
9.7	(a) Temperature difference between the Effelsberg alidade towers A_1 and A_2 . (b) Temperature difference between the front and rear of the alidade towers.	182
9.8	Medicina 32-m telescope. Inclinometer measurements compared with predictions from FEM calculations and from a temperature model.	183
9.9.a	Cambridge MERLIN 32-m telescope, alidade with temperature sensors. .	184
9.9.b	Cambridge MERLIN 32-m telescope. Measured pointing offset in elevation and correction using the measured temperature difference.	184
9.10	JCMT 15-m telescope. Temperature difference between the alidade front legs (side of the astrodome slit) and back legs.	185
9.11	Fork support and associated tilt errors.	186
9.12	VertexRSI ALMA 12-m telescope. (a) Average temperature of the left and right fork arm T_F and the ambient air temperature T_A . (b) Temperature difference between the left and right fork arm ΔT_{LR} , (c) Temperature difference ΔT_{fr} between the front and rear of the fork arms.	188
9.13	VertexRSI ALMA 12-m telescope. Upper panel: Temperature difference between the left and right fork arm, lower panel: temperature difference between the front and rear of the fork arms.	189
9.14	IRAM 15-m telescope. (a) Average temperature of the left and right fork arm. (b) Temperature difference between the Left and Right fork arm and between the front and rear of the fork.	190
9.15	IRAM 15-m telescope. Right-Left (a) and Front-Rear (b) temperature difference measured during six days. These figures determine the rate of change of the temperature differences.	191
9.16	IRAM 15-m interferometer telescopes. Pointing (arcsec) and focus (mm) corrections (from left to right) applied on the six telescopes (from top to bottom), during an observation lasting ~ 8 hours.	192
9.17	Laser interferometer measurement of the path length variation $\Delta z = \Delta L_2$ of a fork arm (Fig. 9.11) and position measurement of the base of the elevation bearing.	193

9.18	VertexRSI ALMA 12-m prototype telescope. Linear displacement Δx , Δy and tilt measurement $\Delta\alpha$, $\Delta\beta$ of the elevation bearing platform with respect to the base of the fork traverse (Fig. 9.17), for two consecutive days.	193
9.19	Reference points and path lengths of a telescope used for interferometer or VLBI observations.	194
9.20	VertexRSI ALMA prototype telescope. Correlation between the path length variation ΔL_2 and the steel temperature of the fork arm.	195
9.21	VertexRSI ALMA prototype telescope. Path length variation ΔL_1 of the pedestal and ΔL_2 of the fork arm (see also Fig. 9.11). A similar result (L_2) is obtained for the AEC ALMA telescope.	195
9.22	View of a yoke with left (L) and right (R) yoke arm and counterweights at their ends. The BUS is attached to the yoke roof.	197
9.23.a	IRAM 30-m telescope. Location of temperature sensors (squares) in the yoke arms (J,L).	198
9.23.b	IRAM 30-m telescope. Location of temperature sensors (squares) in the yoke roof (J,K,L)	198
9.24	IRAM 30-m telescope. (a) Temperature uniformity of the yoke. (b) Temperature difference between Left and Right yoke arm. (c,d) Temperature difference in the yoke arms in up-down direction, for the left and the right arm. (e) Temperature uniformity of the yoke roof (membrane). (f) Temperature difference of the BUS base and the yoke roof.	200
9.25	IRAM 30-m telescope. Improvement of the thermal stability of the yoke by ventilation/heating, noticeable as reduction of the astigmatism of the reflector surface, expressed as the astigmatism amplitude $\alpha_{2,2}$	201
9.26	(a) IRAM/SEST 15-m telescope. Connection of the BUS network to the central hub and the connection of the central hub to the secondary focus cabin. (b) VertexRSI ALMA/APEX telescope. Connection of BUS plates to the invar ring and the connection of the invar ring to the secondary focus cabin.	202
9.27	SEST 15-m telescope. (a) Temperature uniformity (rms value) of the central hub. (b) Temperature difference between the central hub and the BUS. Measurements of 6 consecutive days.	202
9.28	VertexRSI ALMA 12-m prototype telescope. (a) Temperature uniformity (rms value) of the Invar Ring. (b) Temperature of the invar ring and of the backup structure. Measurements of 4 consecutive days.	203
9.29.a	Effelsberg 100-m telescope. The picture shows the rear side of the open BUS fully exposed to the thermal environment.	205
9.29.b	IRAM 15-m telescope of which the BUS is closed by the panels and the rear cladding; the BUS network is protected against solar illumination and, to a large extent, against the thermal environment.	205
9.29.c	ALMA VertexRSI 12-m telescope. Illustration of a closed BUS (the rear cladding is taken off) built from plates forming compartments.	206

9.30	Temperature distribution and gradients measured on the Leighton 10.4-m telescope BUS at OVRO. (a) temperature at multiple points in the BUS compared to the air temperature, (b) maximum rate of temperature change, (c) maximum difference between any two sensors, (d) front to back difference, (e) left to right gradient, (f) top to bottom gradient and (g) radial gradient	207
9.31	Effelsberg 100-m telescope. Temperature of the BUS and of the ambient air; for a winter day and a summer day.	209
9.32	Effelsberg 100-m telescope. (a) Correlation between the average temperature of the alidade and the ambient air temperature; (b) correlation between the average temperature of the BUS and the ambient air temperature, (c) correlation between the quadripod temperature and the ambient air temperature; for summer and for autumn-winter.	209
9.33	IRAM/SEST 15-m telescope. Location of temperature sensors on the BUS network, horizon position of the reflector.	210
9.34	IRAM 15-m telescope. (a) Average temperature of the BUS and ambient air temperature, (b) Temperature uniformity of the BUS expressed as $\text{rms}(T_{\text{BUS}})$, derived from 8 sensors.	211
9.35	IRAM 15-m telescope. (a) Temperature difference of the BUS in the direction Up-Down, (b) temperature difference ΔT_{LR} of the BUS in the direction Left-Right. The black and grey dots are for a summer and winter period.	212
9.36	IRAM 15-m telescope. Lack of a correlation between the temperature difference ΔT_{UD} of the BUS in the direction Up-Down and the ambient air temperature T_{A} , and similar for the wind speed. The black and grey dots are for a summer and winter period.	212
9.37	SEST 15-m telescope. Average temperature of the BUS and temperature of the ambient air. The width of the BUS temperature recording represents the temperature uniformity $\text{rms}(T_{\text{BUS}})$	213
9.38	SEST 15-m telescope. Upper panel: Temperature uniformity of the BUS expressed by the value $\text{rms}(T_{\text{BUS}})$, lower panel: Temperature gradients in the direction Up-Down (grey) and Left-Right (black). Nighttime is from ~ 0 h to 10 h UT	213
9.39	IRAM 30-m telescope. Temperature uniformity of the BUS $\text{rms}(T_{\text{BUS}})$ and associated thermal surface deviation σ_{T} (rms value). Black and grey dots: summer and winter period.	214
9.40.a	VertexRSI ALMA 12-m prototype telescope. Left panel: deviation of the 24 BUS elements, with sensors, from the average BUS temperature. Right panel: average temperature of the BUS and temperature of the ambient air. The measurements were made during a clear day.	215
9.40.b	VertexRSI ALMA 12-m prototype telescope. Temperature difference $T[i] - T_{\text{BUS}}$ between the BUS element [i] and the average temperature of the BUS. Black dots: 4 days of 24-hour measurements, not in the direction of the Sun; grey dots: measurement during a day while tracking the Sun.	216

9.41	NRO 45-m telescope. Radial temperature difference $T_{\text{BUS}} - T_{\text{A}}$ between the BUS and the ambient air, during daytime and nighttime.	217
9.42.a	IRAM 30-m telescope. Temperature recordings of the BUS, the yoke, the quadripod and the ambient air when the BUS was only ventilated (no heating/cooling). Note the temperature uniformity when the thermal control is fully working.	218
9.42.b	IRAM 30-m telescope. Temperature uniformity for the time of no heating/cooling (see Fig. 9.42.a) expressed as rms value of the BUS temperature and rms value of the yoke temperature.	218
9.43.a	Illustration of radial ventilation.	221
9.43.b	IRAM 30-m telescope. Illustration of circular ventilation.	221
9.44	NRO 10-m telescopes. Statistics of temperature uniformity of the BUS expressed as daily maximum value $\text{rms}(T_{\text{BUS}})$, for radial ventilation and circular ventilation.	222
9.45.a	IRAM 30-m telescope. Location of temperature sensors on the BUS, face on view.	223
9.45.b	IRAM 30-m telescope. Location of temperature sensors on the BUS, side view.	223
9.46	IRAM 30-m telescope. Temperature regulation and temperature of the BUS sectors (see Fig. 9.45) and of the yoke sectors (see Fig. 9.23).	224
9.47	IRAM 30-m telescope. (a) Temperature uniformity of the BUS expressed by the value $\text{rms}(T_{\text{BUS}})$, (b) temperature gradient in the BUS in the direction Up-Down, (c) in the direction Left-Right, (d) between front (panel) and rear and (e) between the roof of the yoke and the base of the BUS. The measurements are shown for a 14-day period in July and October 2004.	225
9.48.a	Metsähovi 14-m telescope. Average reflector (BUS) temperature: T_{R} , outside ambient air temperature: T_{A} , insolation: S (9 Apr: $\max S = 660 \text{ W/m}^2$, 20 Mar: $\max S = 500 \text{ W/m}^2$).	227
9.48.b	Metsähovi 14-m telescope. Temperature uniformity of the reflector. Each trace is a different day.	227
9.49	MIT-Haystack 37-m telescope. (a) Average temperature of the BUS: T_{B} , of the air inside the radome: $T_{\text{A, RD}}$ and of the outside ambient air: T_{A} . (b) Temperature difference between an upper (top) and lower (bottom) BUS member: $\Delta T_{\text{UD}}(\text{BUS})$	228
9.50	JCMT 15-m telescope. BUS support (centre beams, cone bars) and BUS; the dots indicate the location of temperature sensors.	229
9.51.a	JCMT 15-m telescope. Temperature measurements (June 2004) of the BUS network and cone and spine bars.	230
9.51.b	JCMT 15-m telescope. Temperature measurements (June 2004) of the BUS centre beams, cone bars and spine bars.	231

9.52	Temperature of Al-honeycomb panels with white front and rear (1), with white front side and 2.5 cm insulation on the rear (2) and with Al-foil cover on front and rear (3). (a) average panel temperature $\langle T(P) \rangle$, ambient air temperature T_A ; (b) temperature gradient $\Delta T_{fb} = T(\text{front}) - T(\text{back})$ through the panels.	233
9.53	Effelsberg 100-m telescope. Panel temperature T_P and ambient air temperature T_A , during a winter and a summer day.	235
9.54	IRAM 30-m telescope. Panel temperature and ambient air temperature. ...	235
9.55	Azimuth-averaged thermal panel buckling of the IRAM 30-m telescope and the Effelsberg 100-m telescope.	236
9.56	Possible thermal panel buckling on the APEX 12-m telescope. The figure shows the difference map between night and day.	236
9.57	JCMT telescope and thermal panel buckling. The figure shows the difference map between morning (8.5 h) and afternoon (17.5 h).	237
9.58	Illustration of a buckled panel with temperature gradient ΔT . The buckling direction is different during daytime (towards the focus) and nighttime (towards the BUS).	238
9.59	Difference between the panel temperature and the BUS temperature measured on the Effelsberg 100-m telescope, during 5 consecutive days in summer while the telescope was observing.	238
9.60	IRAM 30-m telescope. Temperature gradient $\Delta T(\text{frame})$ through a panel frame.	239
9.61	Media-Lario TM panel design of back (a) and front (b) heating.	240
9.62	Measured average temperature $\langle T_P \rangle$ of the Media-Lario TM panel with front and back heating.	241
9.63	Temperature gradient through the front heated and back heated Media-Lario TM panel as function of the wind speed.	241
9.64	Effelsberg 100-m telescope. Left: Temperature of opposite quadripod legs and ambient air temperature, during a winter and summer day. Right: Temperature difference of opposite quadripod legs.	244
9.65	Effelsberg 100-m telescope. Temperature difference $\langle T_Q \rangle - \langle T_{BUS} \rangle$ between the quadripod and the BUS, for a winter and summer period.	244
9.66	(a) Temperature T_Q of the IRAM 15-m telescope quadripod, T_A is the temperature of the ambient air. (b) Temperature difference between the quadripod and the BUS.	245
9.67	IRAM 15-m telescopes. Correlation of the temperature difference between the quadripod temperature and the ambient air temperature $T_Q - T_A$ with wind speed.	245
9.68.a	IRAM 30-m telescope. Temperature of the quadripod legs (T_Q) with no thermal control.	246
9.68.b	IRAM 30-m telescope. Temperature difference $\langle T_Q \rangle - \langle T_{BUS} \rangle$ between the quadripod and the BUS, for October and July. The climatisation control of the telescope is working; the oscillations illustrate the control cycle.	246

9.69	Temperature measurement of the IRAM 30-m telescope subreflector. The days were clear, the telescope was used for observations.	247
9.70	IRAM 30-m subreflector temperature T_{SR} during observations of the Sun.	249
9.71	VertexRSI ALMA 12-m prototype telescope at the VLA test site (NM, USA). Temperature measurement of the BUS when tracking the Sun (13 June, 2004) and not observing the Sun one day later, under similar meteorological conditions.	250
9.72	IRAM 30-m telescope and temperature of the yoke. The thermally controlled state of the telescope $T_B(BUS) = T_Y(Yoke) = T_Q(Quadripod)$ is deregulated when de-icing is switched on.	251
9.73	Temperature uniformity of Effelsberg 100-m telescope, measured at the positions shown in Fig. 2.4.	252
9.74	Temperature uniformity of Effelsberg 100-m telescope.	253
9.75	IRAM 15-m telescope. Temperature uniformity between the backup structure, the quadripod and the fork.	253
9.76	Temperature uniformity of the VertexRSI ALMA 12-m prototype.	254
9.77.a	IRAM 30-m telescope. Variation of the yoke reference temperature throughout the year 2004.	255
9.77.b	Temperature uniformity of the thermally controlled IRAM 30-m telescope displayed as the temperature difference of the BUS – reference temperature (upper panel), quadripod – reference temperature (centre panel), yoke – reference temperature (lower panel).	256
10.1	(a) Average temperature $\langle T \rangle = (T_{top} + T_{bottom})/2$ of the air inside the radome of Metsähovi 14-m telescope. (b) Vertical temperature gradient between the air at the top and the bottom layers of the radome.	264
10.2	Temperature (24 May to 4 Jun) of the air inside the radome of the MIT-Haystack 37-m telescope.	265
11.1	Temperature measurement of an Al-honeycomb panel, painted white.	269
11.2	Model of a fork arm ('chimney' experiment) for the study of different types of insulation.	269
11.3	'Chimney' experiment simulating a section of the IRAM 15-m telescope fork arm and its thermal protection by insulation, air gap and radiation shield.	270
11.4	Model of an open air telescope illustrating the thermal interaction of the telescope components (i,j,k) with themselves and the thermal interaction of the telescope with the environment.	272
11.5	Thermal model of a plate panel either on an open BUS (a) or on a closed BUS (b). Dots: thermal material nodes, open circles: radiative nodes.	276
11.6	Thermal model calculation of the front side temperature of a plate panel on a closed BUS (a,b) and an open BUS (c).	277
11.7	Thermal model of a front/back heated panel (Media-Lario TM).	278

11.8	Result of thermal model calculations of panels (Media-Lario TM) with Front Heating (b) and Back Heating (c).....	279
11.9	Thermal model of a beam, without insulation.	280
11.10	Thermal calculations of an alidade beam with side AD in sunshine and side BC in shadow.....	281
11.11	Heat conduction through a plate (x-direction) and in the plane of the plate.....	282
11.12	Exploratory fork models investigating temperature differences due to asymmetric and variable solar illumination.....	283
11.13	Schematic illustration of a thermal façade around a fork arm (cross section view).	283
11.14	Thermal model of a fork with insulation (Left Side) and a fork with insulation and radiation shield (Right Side).	284
11.15	IRAM 15-m telescopes. The applied thermal protection consists of insulation (5 cm), aluminium foil, an air gap (2 cm) and a radiation shield (Al-plate) that is the outer surface.	285
11.16	IRAM/SEST 15-m telescope. The fork model consists of the left fork arm and the right fork arm connected by the traverse.	287
11.17.a	IRAM 15-m telescope. Measured temperatures of a fork arm.	287
11.17.b	IRAM 15-m telescope. The thermal model calculation of the fork structure reproduces with good detail and accuracy the measured temperatures shown in Fig. 10.17.a, using the recorded parameters of the environment as input.	288
11.18	Model of asymmetric solar illumination of a reflector, for investigation of the efficiency of thermal protection.	289
11.19	Thermal model calculations of 'lump-sections' of an open BUS network under the influence of asymmetric solar illumination as shown in Fig. 11.18.	290
11.20	Illustration of natural convection.....	291
11.21	Model calculation of a closed BUS with natural ventilation. The natural convection causes a temperature gradient in the BUS in the direction Up-Down.	292
11.22	(a) Model of radial ventilation, (b) model of circular ventilation.....	292
11.23	IRAM 30-m telescope: thermal model of the BUS and yoke.	293
11.24	Node structure of a BUS thermal model (IRAM 30-m telescope) of which two adjacent sections are shown.	295
11.25	IRAM 30-m telescope. Measurement of the BUS (T _B) and yoke (T _Y) temperature in the cases of simple ventilation and full climatisation.	296
11.26	Model calculations of the IRAM 30-m telescope closed BUS with ventilation and with climatisation (heating/cooling).	296
11.27	Model of a telescope in a radome with 6 horizontal air layers and azimuthal subdivisions.....	297
11.28	Model of an astrodome with basement (concrete), a steel housing (side walls and rear wall) and a membrane-covered opening. There are ventilation fans and louvres.	298

11.29	Comparison of measured and calculated temperatures of the air inside the MIT–Haystack and Onsala radome.	300
11.30	Temperature of a panel with white TiO_2 paint surface finish or shiny aluminium surface finish, surrounded by air at constant temperature.	301
11.31	IRAM 30–m telescope. The figure shows the temperature difference between the BUS and the yoke when the reflector is exposed to maximum solar illumination and when the ventilation and cooling is switched on at noon of the second day. The capacity of the cooling is indicated by the numbers (in kW).	302
11.32	Determination of the efficiency of BUS ventilation (expressed by the convective heat transfer coefficient h) that produces a temperature uniformity of $\Delta T_{\text{RL}} \lesssim 3^\circ\text{C}$ of the SRT BUS under asymmetric solar illumination (Fig. 11.18).	303
12.1.a	Illustration of the <i>Huygens</i> Principle.	306
12.1.b	Illustration of imaging through a lens, which operates in an equivalent way as a complex radio telescope.	307
12.2	Phase modulation $\Omega_0 \equiv \Delta$ of a reflector.	309
12.3	(a) Field distribution E_T and (b) power distribution A_T of a perfect telescope with -15 dB edge taper.	312
12.4	(a) Taper across the aperture of the main reflector. (b) Focal plane beam pattern $A_T(\theta, \phi)$. (c) Cut through the beam pattern $A_T(\theta, \phi)$	312
12.5	(a) Wavefront deformation of defocus, coma and astigmatism of amplitude $\alpha = 0.5 \lambda$. (b) Beam patterns A_T of defocus, coma and astigmatism. (c) Cut through the beam patterns of defocus, coma and astigmatism: heavy lines. The thin line is the perfect beam pattern.	314
12.6	(a) Degradation of the beam pattern (scans across Jupiter) introduced by defocusing the IRAM 15–m telescope. (b) Calculated loss of main beam intensity of the defocused telescope.	315
12.7	Measurement ($\lambda = 3$ mm) of a comatic beam (scanned in the direction of the coma) produced on the IRAM 15–m telescope by shifting the subreflector by the amount S perpendicular to the main reflector axis.	316
12.8	(a) Astigmatic beam pattern measured at 1.3 mm wavelength at best focus. (b) Calculated beam pattern inside the best focus, at best focus and outside the best focus.	316
12.9	(a) Repetitive panel buckling for $n = 7$ zones (rings) and $m = 16$ sectors of panels. (b) Calculated power pattern of deformation amplitude $\alpha = \lambda/6$ at $\lambda = 1.3$ mm wavelength (230 GHz).	317
12.10	IRAM 30–m telescope. Differentiated Moon limb scan measured at 230 GHz (1.3 mm) showing the main beam, the 1st order diffraction ring due to thermal panel buckling and the underlying error beam pattern.	318
12.11	(a) Gaussian distribution of random reflector surface errors of the Effelsberg 100–m telescope. (b) Similar Gaussian distribution of random surface errors on the IRAM 30–m telescope. (c) Surface deformations on the IRAM 30–m corresponding to the statistics shown in (b).	320

12.12	The beam pattern of the real telescope, as described by Eq.(12.25), consists of the main beam, side lobes and an underlying error beam. The main beam and the error beam can be approximated by Gaussian profiles.....	321
12.13	IRAM 30–m telescope. Illustration of systematic reflector surface deformations due to de–icing, and corresponding beam patterns.	323
12.14	IRAM 30–m telescope with surface deformations due to heating for de–icing. (a) Amplitudes of Zernike polynomials of the associated systematic surface deformations. (b) Corresponding rms values.	324
13.1	IRAM 30–m telescope. (a) Pointing (b) Focus correction.	326
13.2	IRAM 30–m telescope. Transient comatic aberration.....	326
13.3	Temperature gradient through a BUS in axial direction (a), along the BUS diameter (b) and in radial direction (c).....	328
13.4	Illustration of misalignments of a Cassegrain system.	332
13.5	(a) System alignment errors and corresponding wavefront deformations (b) corresponding beam patterns in arcseconds (IRAM 30–m telescope at 230 GHz)	335
13.6	IRAM 30–m telescope. Thermal rms value σ_T derived from temperature measurements of the BUS and yoke and FEM calculations.	338
13.7	Temperature distribution of the BUS of the IRAM 30–m telescope (104 temperature sensors) and the BUS of the ALMA VertexRSI 12–m prototype telescope (24 temperature sensors).....	339
13.8	Thermal deformations δ_T of the IRAM 30–m telescope reflector surface derived from temperature measurements, and surface rms from FEM calculations.....	340
14.1	Conventional dome with slit of the ESO 3.6–m telescope (La Silla, Chile).....	344
14.2	Very–Large–Telescope VLT (Paranal, Chile) with box–type enclosure and louvres for ventilation with ambient air.	345
15.1	Temperature difference between one fork arm in sunshine and the other one in shadow. (a) Influence of the aging of white paint (b) Influence of the contact resistance between the insulation and the steel walls of the fork.....	351
15.2	IRAM 30–m telescope. Zernike decomposition of temperature induced and gravity induced reflector surface deformations.....	354
15.3	IRAM 30–m telescope. Thermal surface deformations represented by the Zernike polynomials $L = 3, 9$ and 15	354
C.1	IRAM 30–m telescope. Variation of the pointing model parameters P_i throughout the years 1991 – 1992.....	365