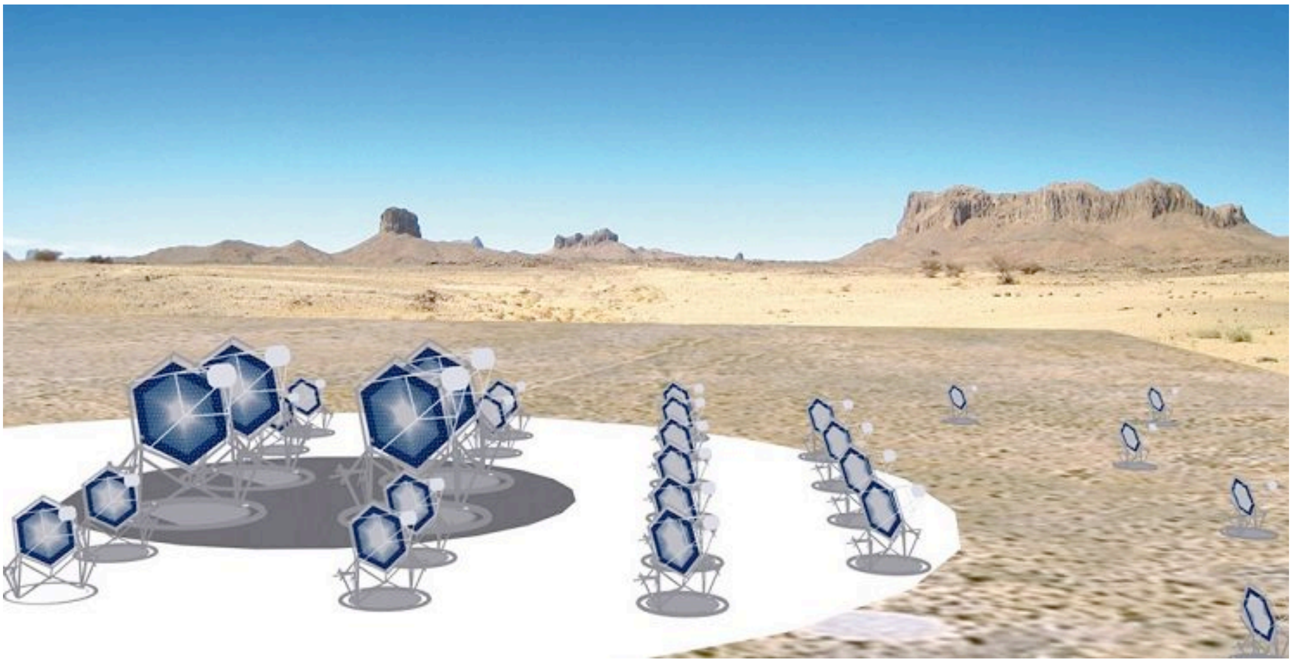
Simplified thermal analyses of the ASTRI SST-2M telescope structure



Prepared by:	Name: Rodolfo Canestrari	Signature:		Date:	10-01-2014
Reviewed by:	Name:	Signature:		Date:	
Approved by:	Name:	Signature:		Date:	

TABLE OF CONTENTS

DISTRIBUTION LIST

ASTRI mailing list	astri@brera.inaf.it

DOCUMENT HISTORY

Version	Date	Modification
1.0	10-01-2014	first version

LIST OF ACRONYMS

ASTRI	Astrofisica con Specchi a Tecnologia Replicante Italiana
AZ	Azimuth
EL	Elevation
H-C	Honeycomb
M1	Primary Mirror
M2	Secondary Mirror
SST-2M	Small Size Telescope – Dual Mirror

APPLICABLE DOCUMENTS

[AD1] ASTRI-ES-BCV-3100-041 *"ASTRI project: SST prototype telescope structure design report"*

REFERENCE DOCUMENTS

[RD1] http://www.esa.int/TEC/Thermal_control/TECASEPYAQE_0.html, ThermXL software

[RD2] Holman, J.P., *Heat Transfer*, McGraw Hill

1. INTRODUCTION

This document describes a simplified thermal analysis performed on the ASTRI SST-2M telescope in order to estimate temperature field and heat flow on the structure and mirrors under different thermal scenarios. These studies have been performed following the suggestions of the ASTRI/SST-GATE bilateral board and have been carried out by means of a contract with Engineer Enrico Buratti.

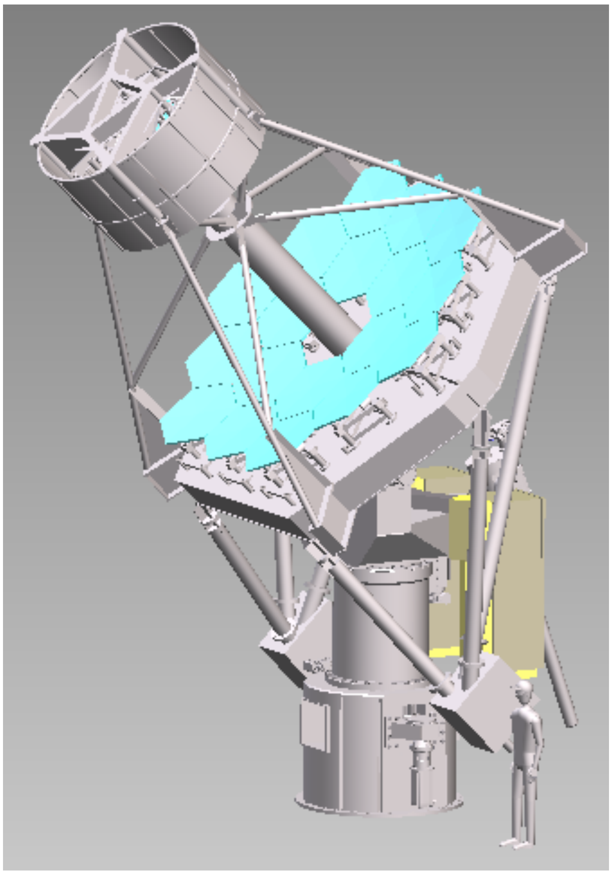
The software used to generate the thermal model of the telescope is ThermXL, a Microsoft Excel plug-in for ESATAN-like analysis [RD1].

Both steady state and transient cases are considered, the latter providing an order of magnitude of thermal time constant.

2. THERMAL MODEL DESCRIPTION

This model is considering 19 nodes thermally coupled by effect of conduction, convection and radiation. The distribution of the nodes across the structure is shown in Figure 1. The following parameters are considered, numerical values for the different links and conditions are reported in §4:

- conduction, by estimating thermal conductance between different nodes;
- convection, by estimating the convection coefficient acting on the outer surface;
- radiation, by assuming emissivity of surfaces and estimating view factors (not calculated in detail);
- Sun heat (day time), by assuming solar absorptivity of surfaces.



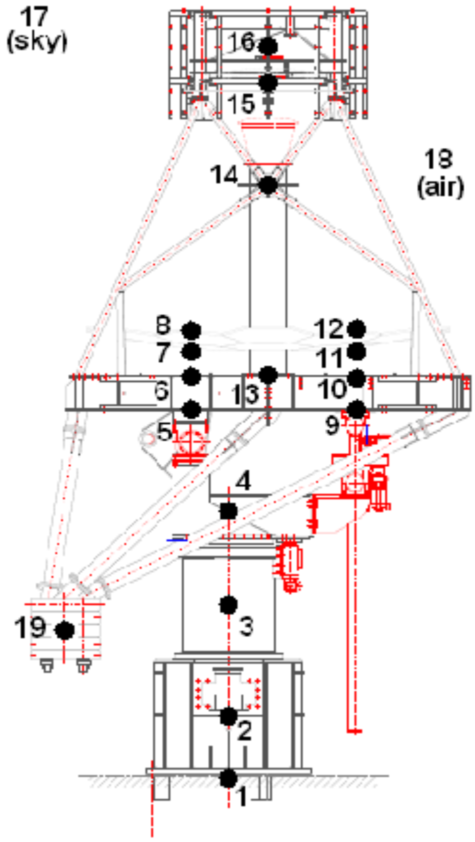


Figure 1 The ASTRI SST-2M telescope structure design (left panel). Distribution of the thermal nodes used in the analyses (right panel)

The list of the nodes with their thermal description is reported in Table 1, where "Type B" is a boundary fixed temperature as defined in §3, "Type D" is diffusion (temperature to be calculated). The column with the heat capacity has been calculated in accordance with the mass budget provided in §2.2.

Table 1 List of the thermal nodes implemented in the model.

Link number	Label	Type	Heat capacity m*c [J/K]	Temperature
1	Ground	B		Fixed
2	Base structure	D	1341500	
3	Azimuth column	D	1218500	
4	Azimuth fork	D	777500	
5	Dish Bottom Left	D	1379500	
6	Dish Top Left	D	767000	
7	Mirror Bottom Left	D	55200	
8	Mirror Top Left	D	32800	
9	Dish Bottom Right	D	1379500	
10	Dish Top Right	D	767000	
11	Mirror Bottom Right	D	55200	
12	Mirror Top Right	D	32800	
13	Dish center	D	185000	
14	Central tube top	D	210000	
15	M2	D	162400	
16	M2 Backup structure	D	366500	
17	Sky	B		Fixed
18	Air	B		Fixed
19	Counterbalances	D	2589000	

Results are to be considered approximated due to the several assumptions, missing data, geometry and modeling simplifications.

2.1 Assumptions and boundary conditions

2.1.1 Assumptions

Main assumptions are listed below:

- only main structural parts are implemented, simplified geometry is considered for simplicity
  - asymmetry at elevation bearing is neglected
  - piston for elevation control is neglected
- drive/electronics generated heat is neglected;
- shielding plates (i.e. snow shields) are applied at top half of dish, it is therefore assumed that mirrors are shielded from sun radiation;
- surface emissivity/solar absorptivity of the different materials are assumed according to Table 2;
- thermal conductivity and specific heat of the main structural materials are assumed as reported in Table 3;
- conductance of mechanics (bearings, supports, screws) and mirrors are assumed as in Table 4.

Table 2 List of the emissivity and absorptivity of the main surface materials.

Component		Surface material	Emissivity, e	Solar absorptivity, a
Structural elements		Red paint RAL 3016	0.9	0.6
Mirror	Reflecting face	Al coating	0.1	0.25
	Backing face	Glass	0.9	0.5
Ground		-	0.5	-
Sky		-	0.85	-

Table 3 List of thermal properties of the main structural materials.

Material	Component	Conductivity [W/mK]	Specific heat [J/kgK]
Steel S355	Structure	45 (TBC, alternative value 16)	500
Glass	Mirrors	0.9	800 (typical for glass)
Adhesive	M1 sandwich bonding	0.5	
Al h-c	M1 sandwich core	120	

Table 4 List of the conductivity values adopted for different components.

Components	Conductance [W/K]	Note
AZ. bearings	0.5	Each one
EL. bearings	0.5	Each one
M1 axial supports	0.5	Each one
M2 supports	0.5	Each one
Screw M6	0.3	Assumption
Screw M12	1.36	Scaled by section
Screw M16	2.42	Scaled by section
Screw M20	3.78	Scaled by section
Screw M24	5.44	Scaled by section
Screw M30	8.50	Scaled by section

Layer	Material	Thickness [mm]	Area [m²]	Conductivity [W/mK]
1	Glass	0.0020	1.000	0.9
2	Glue	0.0001	0.051	0.5
3	Al H-C	0.0200	0.026	120
4	Glue	0.0001	0.051	0.5
5	Glass	0.0020	1.000	0.9
M1 conductance		per m^2	53.2 $W/K/m^2$	
		per segment	33.0 W/K	

2.1.2 Environmental boundary conditions

Thermal boundary conditions have been defined as follow:

- Temperature range definition:
  - operative temperature: -10°C / +30°C
  - survival temperature: -25°C / +60°C
  - reference temperature: +15°C
- Max solar radiation: 1200 W/m^2
- Site altitude: 1800m (representative of 1500–3800m)
- Air density: 1.0 kg/m^3 at 10°C

2.2 Mass budget

Structural model of the telescope and links between components have been taken from [AD1], while thermal modeling and assumptions have been taken from [RD2]. Anyhow, we report in the following Table 5 the distribution of mass at different thermal nodes (as concentrated mass, approximation) used in the calculations.

Table 5 Distribution of the mass across the different thermal links.

Node	Component	Location	Mass [kg]		Material	Note
			Value	Formula		
1	Ground		-		-	
2	Base structure		2683		steel	
3	Azimuth column		2437		steel	
4	Azimuth fork		1555		steel	
5	Dish	Bottom left	2759	(4764+0.9*1523)/4+(424 + 2027)/2	steel	25% of (M1 Dish + 90% Supports) + 50% of Devices
6		Top left	1534	(4764+0.9*1523)/4	steel	25% of (M1 Dish + 90% Supports)
7	Mirror	Bottom left	69	(12.2-7/2*1.3)/2*18	glass 2 mm + Al H-C 20 mm	25% of (Optical devices – M2 – Camera)
8		Top left	41	7/2*18*1.3/2		25% of (Optical devices – M2 – Camera)
9	Dish	Bottom right	2759	(4764+0.9*1523)/4+(424 + 2027)/2	steel	25% of (M1 Dish + 90% Supports)+ 50% of Devices
10		Top right	1534	(4764+0.9*1523)/4	steel	25% of (M1 Dish + 90% Supports)
11	Mirror	Bottom right	69	(12.2-7/2*1.3)/2*18	glass 2 mm + Al H-C 20 mm	25% of (Optical devices – M2 – Camera)
12		Top right	41	7/2*18*1.3/2		25% of (Optical devices – M2 – Camera)
13	Dish center		370	740/2	steel	50% of Mast + Central Tube
14	Central tube top		420	740/2+50	steel	50% of Mast + Central Tube + Camera
15	M2	Centre	203		glass	See BCV document
16	M2-BUS		733	205 + 376 + 1523*0.1	steel	M2 BUS + Baffles + 10% Supports
17	Sky		-	-	-	
18	Air		-	-	-	
19	Counterba.		5178	4500+678		Counterbalances + Structures
		Total	22400			

3. LOAD CASES

Load cases considered are divided in operational time (i.e. night time) and not operational (i.e. day time). The following subset of selected scenarios is considered interesting and has been studied:

1. Steady-state – operational
   - S1 cold night (air -10°C, zenith pointing, no wind)
   - S2 hot night (air 30°C, zenith pointing, no wind)

2. Steady-state – not operational
   - S3 hot day (air 30°C, parking position, no wind, sun from back)
   - S4 hot day, lateral gradient (air 30°C, parking position, no wind, sun from back/side), not operational
   - S5 hot day, axial gradient (air 30°C, parking position, no wind, sun from back)

3. Transient – operational
   - T1 air temp change as step -10°C, zenith pointing, no wind
   - T2 transition day-night (linear from 0 to -10°C in 1 h, zenith pointing, no wind)
   - T3 transition day-night (linear from 0 to -10°C in 4 h, zenith pointing, no wind)
   - T4 transition day-night (half-sine curve -10°C in 10 hours, zenith pointing, no wind)
   - T5 transition day-night (typical temp. curve from erection site, zenith pointing, no wind), TBD

For reference, we report in Table 6 the values given in the text above and used for the boundaries elements (ground, air and sky) during the simulations.

Table 6 Boundaries temperatures values for the different load cases.

<table>
<tr><th>Number</th><th>Label</th><th colspan="10">Load cases</th></tr>
<tr><th></th><th></th><th>S1</th><th>S2</th><th>S3</th><th>S4</th><th>S5</th><th>T1</th><th>T2</th><th>T3</th><th>T4</th><th>T5</th></tr>
<tr><td>1</td><td>Ground</td><td>-10</td><td>30</td><td colspan="3">30</td><td colspan="3" rowspan="2">From 0 to -10
(step for T1; linear in T2-T3)</td><td rowspan="2">Half-sine curve from 0 to -10 to 0</td><td rowspan="2">typical temp. curve from site, TBD</td></tr>
<tr><td>18</td><td>Air</td><td>-10</td><td>30</td><td colspan="3">30</td></tr>
<tr><td>17</td><td>Sky</td><td>-50</td><td>-10</td><td colspan="3">20</td><td colspan="5">-10</td></tr>
</table>

4. THERMAL LINKS

4.1 Conductive links

In Table 7 are reported the conductive links, with their values, established between the main parts of the structure of the ASTRI SST-2M telescope and the surrounding environment.

Table 7 List of the conductive links between the main components of the telescope.

1st Node	2nd Node	Conductance [W/K]	Area [m²]	Length [m]	Conductivity [W/mK]	Note	Screws
1	2	1.12E+01	0.17	0.7	45		24xM30
2	3	1.51E+00	0.07	1	45	2 az. bearings in parallel	neglected
3	4	1.73E+00					
4	5	1.29E+00	0.03	0.4	45	2 el. bearings in parallel	8xM30, 12xM24
4	9	1.29E+00					
5	6	2.43E+01	0.40	0.4	45		
5	13	1.17E+00	0.05	1.0	45		
6	13	1.17E+00					
6	7	1.35E+01					
6	14	5.93E-02	0.003	2.1	45		neglected
6	16	3.67E-02	0.003	3.4	45		neglected
7	8	2.97E+02				simplified	
9	10	2.43E+01					
9	13	1.17E+00					
10	13	1.17E+00					
10	11	1.35E+01					
10	14	5.93E-02					
10	16	3.67E-02					
11	12	2.97E+02					
13	14	1.62E-01	0.008	2.2	45		neglected
14	16	1.28E-01	0.003	1.0	45		neglected
15	16	4.50E+00					
19	5	1.78E-01	0.010	2.5	45		neglected

4.2 Convective links – cold night case (zenith pointing)

In Table 8 are reported the convective links established between the main parts of the structure of the ASTRI SST-2M telescope and the surrounding environment for the cold case scenario as defined in §3. The values of the convective coefficients have been calculated accordingly with the parameters reported in Table 9 and Table 10. They depend of the air/wall temperature and geometry. Geometry cases have been simplified to horizontal and vertical plates only.

Table 8 List of the convective links between the main components of the telescope for a cold night case, zenith pointing.

1st Node	2nd Node	Conductance [W/K]	Convective coefficient, h [W/m²K]	Surface, A [m²]
2	18	1.41E+01	2.20E+00	6.43E+00
3	18	8.77E+00	2.20E+00	3.99E+00
4	18	1.98E+01	2.20E+00	9.00E+00
5	18	1.66E+01	2.48E+00	6.70E+00
6	18	6.09E+00	9.10E-01	6.70E+00
7	18	1.38E+01	2.48E+00	5.58E+00
8	18	5.08E+00	9.10E-01	5.58E+00
9	18	1.66E+01	2.48E+00	6.70E+00
10	18	6.09E+00	9.10E-01	6.70E+00
11	18	1.38E+01	2.48E+00	5.58E+00
12	18	5.08E+00	9.10E-01	5.58E+00
13	18	0.00E+00	0.00E+00	1.00E-12
14	18	6.63E+00	2.20E+00	3.01E+00
15	18	7.79E+00	2.48E+00	3.14E+00
16	18	3.32E+01	2.20E+00	1.51E+01
19	18	1.47E+01	2.20E+00	6.68E+00

Table 9 Natural convection for horizontal plates, cold case.

characteristic length	L =	1.0	m	
air temperature	Tair =	-10	°C	
wall temperature	Tw =	-14	°C	
film temperature	Tf =	-12	°C	
temperature difference	DT =	-4	°C	
thermal conductivity	k =	0	W/mK	*evaluated at Tf*
dynamic viscosity	m =	1.658E-05	kg/ms	*evaluated at Tf*
specific heat	cp =	1006	J/kg°C	
Prandtl number	Pr =	0.726		*mean value for Tf = 0 ÷ 50° C*
altitude	*z =*	*1800*	*m*	
air pressure	p =	0.795	atm	
air density	r =	1.074	kg/m^3	*evaluated at Tf*
kinematic viscosity	n =	1.54E-05	m^2/s	
Grashof number	Gr =	6.31E+008		
Rayleigh number	Ra =	4.59E+08		
upper face (heated plates) or lower face for cooled plates				
Nusselt number	NuT =	108.2		
convection coefficient	hT =	2.48	W/m^2K	*8E+06 < Ra <1E+11*
lower face (heated plates) or upper face for cooled plates				
Nusselt number	Nu =	39.5		
convection coefficient	h =	0.91	W/m^2K	*1E+05 < Ra <1E+11*

Table 10 Natural convection for vertical isothermal plates, cold case.

Surface height	H =	4	m	
Fluid temperature	Tfluid =	-10	°C	
Surface temperature	Tw =	-15	°C	
Film temperature	Tfilm =	-12.5	°C	Tfilm = (Tw + Tfluid)/2
Volume exp.coeff.	beta =	0.00384	K^{-1}	for ideal gases (air also)
Density	ro =	1.07	kg/m^3	
Dynamic viscosity	mu =	1.66E-05	kg/ms	
Kinematic viscosity	nu =	1.54E-05	m^2/s	
Thermal conductivity	k =	2.30E-02	W/mK	
Specific heat	cp =	1.01E+03	J/kg°C	
Prandtl number	Pr =	7.26E-01		
Grashof number	Gr =	5.06E+10		
Rayleigh number	Ra =	36774779633.2		0.1 < Ra < 10^12
Nusselt number	Nu =	382.8		(Eq. 7-29, Holman)
Convection coefficient	h =	2.20	W/m^2K	

4.3 Convective links – hot day case (parking position)

In Table 11 are reported the convective links established between the main parts of the structure of the ASTRI SST-2M telescope and the surrounding environment for the hot case scenario as defined in §3. The values of the convective coefficients have been calculated accordingly with the parameters reported in Table 12 and Table 13. They depend of the air/wall temperature and geometry. Geometry cases have been simplified to horizontal and vertical plates only.

Table 11 List of the convective links between the main components of the telescope for a hot day case, parking position.

1st Node	2nd Node	Conductance [W/K]	Convective coefficient, h [W/m²K]	Surface, A [m²]
2	18	1.84E+01	2.86E+00	6.43E+00
3	18	1.42E+01	3.55E+00	3.99E+00
4	18	3.20E+01	3.55E+00	9.00E+00
5	18	2.38E+01	3.55E+00	6.70E+00
6	18	2.38E+01	3.55E+00	6.70E+00
7	18	1.60E+01	2.86E+00	5.58E+00
8	18	1.60E+01	2.86E+00	5.58E+00
9	18	2.38E+01	3.55E+00	6.70E+00
10	18	2.38E+01	3.55E+00	6.70E+00
11	18	1.60E+01	2.86E+00	5.58E+00
12	18	1.60E+01	2.86E+00	5.58E+00
13	18	0.00E+00	0.00E+00	1.00E-12
14	18	8.62E+00	2.86E+00	3.01E+00
15	18	8.98E+00	2.86E+00	3.14E+00
16	18	4.31E+01	2.86E+00	1.51E+01
19	18	1.91E+01	2.86E+00	6.68E+00

Table 12 Natural convection for horizontal plates, hot case.

characteristic length	L =	1.0 m	
air temperature	Tair =	30 °C	
wall temperature	Tw =	45 °C	
film temperature	Tf =	37.5 °C	
temperature difference	DT =	15 °C	
thermal conductivity	k =	0 W/mK	*evaluated at Tf*
dynamic viscosity	m =	1.898E-05 kg/ms	*evaluated at Tf*
specific heat	cp =	1006 J/kg°C	
Prandtl number	Pr =	0.710	*mean value for Tf = 0 ÷ 50° C*
altitude	*z =*	1800 *m*	
air pressure	p =	0.820 atm	
air density	r =	0.932 kg/m^3	*evaluated at Tf*
kinematic viscosity	n =	m^2/s	
Grashof number	Gr =	2.04E-05	
Rayleigh number	Ra =	1.14E+09	
upper face (heated plates) or lower face for cooled plates			
Nusselt number	NuT =	130.6	
convection coefficient	hT =	3.51 W/m^{2}K	*8E+06 < Ra <1E+11*
lower face (heated plates) or upper face for cooled plates			
Nusselt number	Nu =	45.6	
convection coefficient	h =	1.23 W/m^{2}K	*1E+05 < Ra <1E+11*

Table 13 Natural convection for vertical isothermal plates, cold case.

Surface height	H =	4	4	m	
Fluid temperature	Tfluid =	30	30	°C	
Surface temperature	Tw =	45	60	°C	
Film temperature	Tfilm =	37.5	45	°C	Tfilm = (Tw + Tfluid)/2
Volume exp.coeff.	beta =	0.00322	0.00314	K^{-1}	for ideal gases (air also)
Density	ro =	0.93	0.93	kg/m^3	
Dynamic viscosity	mu =	1.90E-05	1.90E-05	kg/ms	
Kinematic viscosity	nu =	2.04E-05	2.04E-05	m^2/s	
Thermal conductivity	k =	2.69E-02	2.69E-02	W/mK	
Specific heat	cp =	1.01E+03	1.01E+03	J/kg°C	
Prandtl number	Pr =	7.10E-01	7.10E-01		
Grashof number	Gr =	7.31E+10	1.43E+11		
Rayleigh number	Ra =	5.19E+010	1.01E+011		0.1 < Ra < 10^12
Nusselt number	Nu =	425.9	527.9		(Eq. 7-29, Holman)
Convection coefficient	h =	2.86	3.55	W/m^2K	

4.4 Radiative links – cold night case (zenith pointing)

In the following table are reported the radiative links established between the main parts of the structure of the ASTRI SST-2M telescope and the surrounding environment for the cold case scenario as defined in §3. The values of the links have been calculated accordingly with:

$$\varepsilon_{eff}A_{eff} = \frac{1}{\frac{(1-\varepsilon_i)}{(\varepsilon_i A_i)} + \frac{1}{F_{ij}} + \frac{(1-\varepsilon_j)}{(\varepsilon_j A_j)}}$$

1st Node	2nd Node	Value	View Factor, F_{ij}	ε_i	ε_j	A_i	A_j
2	1	2.96E+00	5.00E-01	9.00E-01	5.00E-01	6.43E+00	1.00E+02
3	1	1.85E+00	5.00E-01	9.00E-01	5.00E-01	3.99E+00	1.00E+02
4	1	2.09E+00	5.00E-01	9.00E-01	5.00E-01	4.50E+00	1.00E+02
5	1	3.07E+00	5.00E-01	9.00E-01	5.00E-01	6.70E+00	1.00E+02
6	1	6.70E-12	1.00E-12	9.00E-01	5.00E-01	6.70E+00	1.00E+02
7	1	5.58E-12	1.00E-12	9.00E-01	5.00E-01	5.58E+00	1.00E+02
8	1	5.58E-12	1.00E-12	1.00E-01	5.00E-01	5.58E+00	1.00E+02
9	1	3.07E+00	5.00E-01	9.00E-01	5.00E-01	6.70E+00	1.00E+02
10	1	6.70E-12	1.00E-12	9.00E-01	5.00E-01	6.70E+00	1.00E+02
11	1	5.58E-12	1.00E-12	9.00E-01	5.00E-01	5.58E+00	1.00E+02
12	1	5.58E-12	1.00E-12	1.00E-01	5.00E-01	5.58E+00	1.00E+02
13	1	1.00E-24	1.00E-12	9.00E-01	5.00E-01	1.00E-12	1.00E+02
14	1	5.86E-01	2.00E-01	9.00E-01	5.00E-01	3.01E+00	1.00E+02
15	1	2.72E-01	4.00E-01	1.00E-01	5.00E-01	3.14E+00	1.00E+02
16	1	3.45E+00	5.00E-01	9.00E-01	5.00E-01	7.54E+00	1.00E+02
19	1	3.07E+00	5.00E-01	9.00E-01	5.00E-01	6.68E+00	1.00E+02
2	17	1.26E+00	2.00E-01	9.00E-01	8.50E-01	6.43E+00	1.00E+06
3	17	5.88E-01	1.50E-01	9.00E-01	8.50E-01	3.99E+00	1.00E+06
4	17	4.45E-01	1.00E-01	9.00E-01	8.50E-01	4.50E+00	1.00E+06
5	17	6.70E-12	1.00E-12	9.00E-01	8.50E-01	6.70E+00	1.00E+06
6	17	6.62E-01	1.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
7	17	5.58E-12	1.00E-12	9.00E-01	8.50E-01	5.58E+00	1.00E+06
8	17	5.52E-01	9.00E-01	1.00E-01	8.50E-01	5.58E+00	1.00E+06
9	17	6.70E-12	1.00E-12	9.00E-01	8.50E-01	6.70E+00	1.00E+06
10	17	6.62E-01	1.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
11	17	5.58E-12	1.00E-12	9.00E-01	8.50E-01	5.58E+00	1.00E+06
12	17	5.52E-01	9.00E-01	1.00E-01	8.50E-01	5.58E+00	1.00E+06
13	17	1.00E-24	1.00E-12	9.00E-01	8.50E-01	1.00E-12	1.00E+06
14	17	7.33E-01	2.50E-01	9.00E-01	8.50E-01	3.01E+00	1.00E+06
15	17	3.14E-12	1.00E-12	1.00E-01	8.50E-01	3.14E+00	1.00E+06
16	17	3.57E+00	5.00E-01	9.00E-01	8.50E-01	7.54E+00	1.00E+06
19	17	1.63E+00	2.50E-01	9.00E-01	8.50E-01	6.68E+00	1.00E+06
4	5	1.08E+00	2.50E-01	9.00E-01	9.00E-01	4.50E+00	6.70E+00
4	9	1.08E+00	2.50E-01	9.00E-01	9.00E-01	4.50E+00	6.70E+00
6	7	5.38E+00	1.00E+00	9.00E-01	9.00E-01	6.70E+00	5.58E+00
8	15	1.52E-01	8.50E-02	1.00E-01	1.00E-01	5.58E+00	3.14E+00
10	11	5.38E+00	1.00E+00	9.00E-01	9.00E-01	6.70E+00	5.58E+00
12	15	1.52E-01	8.50E-02	1.00E-01	1.00E-01	5.58E+00	3.14E+00
15	16	2.71E+00	1.00E+00	9.00E-01	9.00E-01	3.14E+00	7.54E+00

4.5 Radiative links – hot day case (parking position)

In the following table are reported the radiative links established between the main parts of the structure of the ASTRI SST-2M telescope and the surrounding environment for the cold case scenario as defined in §3. The values of the links have been calculated accordingly with:

$$\varepsilon_{eff} A_{eff} = \frac{1}{\frac{(1-\varepsilon_1)}{(\varepsilon_1 A_1)} + \frac{1}{F_{12}} + \frac{(1-\varepsilon_2)}{(\varepsilon_2 A_2)}}$$

1st Node	2nd Node	Value	View Factor	ε_i	ε_j	A_i	A_j
2	1	2.96E+00	5.00E-01	9.00E-01	5.00E-01	6.43E+00	1.00E+02
3	1	1.85E+00	5.00E-01	9.00E-01	5.00E-01	3.99E+00	1.00E+02
4	1	2.09E+00	5.00E-01	9.00E-01	5.00E-01	4.50E+00	1.00E+02
5	1	3.07E+00	5.00E-01	9.00E-01	5.00E-01	6.70E+00	1.00E+02
6	1	6.70E-12	1.00E-12	9.00E-01	5.00E-01	6.70E+00	1.00E+02
7	1	5.58E-12	1.00E-12	9.00E-01	5.00E-01	5.58E+00	1.00E+02
8	1	4.83E-01	4.00E-01	1.00E-01	5.00E-01	5.58E+00	1.00E+02
9	1	2.50E+00	4.00E-01	9.00E-01	5.00E-01	6.70E+00	1.00E+02
10	1	6.70E-12	1.00E-12	9.00E-01	5.00E-01	6.70E+00	1.00E+02
11	1	5.58E-12	1.00E-12	9.00E-01	5.00E-01	5.58E+00	1.00E+02
12	1	4.83E-01	4.00E-01	1.00E-01	5.00E-01	5.58E+00	1.00E+02
13	1	1.00E-24	1.00E-12	9.00E-01	5.00E-01	1.00E-12	1.00E+02
14	1	1.14E+00	4.00E-01	9.00E-01	5.00E-01	3.01E+00	1.00E+02
15	1	1.65E-01	1.00E-01	1.00E-01	5.00E-01	3.14E+00	1.00E+02
16	1	3.45E+00	5.00E-01	9.00E-01	5.00E-01	7.54E+00	1.00E+02
19	1	3.07E+00	5.00E-01	9.00E-01	5.00E-01	6.68E+00	1.00E+02
2	17	1.26E+00	2.00E-01	9.00E-01	8.50E-01	6.43E+00	1.00E+06
3	17	5.88E-01	1.50E-01	9.00E-01	8.50E-01	3.99E+00	1.00E+06
4	17	1.72E+00	4.00E-01	9.00E-01	8.50E-01	4.50E+00	1.00E+06
5	17	1.94E+00	3.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
6	17	6.62E-01	1.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
7	17	5.58E-12	1.00E-12	9.00E-01	8.50E-01	5.58E+00	1.00E+06
8	17	4.85E-01	4.00E-01	1.00E-01	8.50E-01	5.58E+00	1.00E+06
9	17	2.56E+00	4.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
10	17	6.62E-01	1.00E-01	9.00E-01	8.50E-01	6.70E+00	1.00E+06
11	17	5.58E-12	1.00E-12	9.00E-01	8.50E-01	5.58E+00	1.00E+06
12	17	4.85E-01	4.00E-01	1.00E-01	8.50E-01	5.58E+00	1.00E+06
13	17	1.00E-24	1.00E-12	9.00E-01	8.50E-01	1.00E-12	1.00E+06
14	17	1.15E+00	4.00E-01	9.00E-01	8.50E-01	3.01E+00	1.00E+06
15	17	1.65E-01	1.00E-01	1.00E-01	8.50E-01	3.14E+00	1.00E+06
16	17	3.57E+00	5.00E-01	9.00E-01	8.50E-01	7.54E+00	1.00E+06
19	17	2.56E+00	4.00E-01	9.00E-01	8.50E-01	6.68E+00	1.00E+06
4	5	1.08E+00	2.50E-01	9.00E-01	9.00E-01	4.50E+00	6.70E+00

4	9	1.08E+00	2.50E-01	9.00E-01	9.00E-01	4.50E+00	6.70E+00
6	7	5.38E+00	1.00E+00	9.00E-01	9.00E-01	6.70E+00	5.58E+00
8	15	1.52E-01	8.50E-02	1.00E-01	1.00E-01	5.58E+00	3.14E+00
10	11	5.38E+00	1.00E+00	9.00E-01	9.00E-01	6.70E+00	5.58E+00
12	15	1.52E-01	8.50E-02	1.00E-01	1.00E-01	5.58E+00	3.14E+00
15	16	2.71E+00	1.00E+00	9.00E-01	9.00E-01	3.14E+00	7.54E+00

4.6 Heat from the Sun

		Load case				
		Operational		Not operational		
		S1	S2	S3 (1)	S4 (2)	S5 (1)
Link number	**Label**	**Qs [W]**				
1	Ground	-	-	-	-	-
2	Base structure	0	0	1475	1475	1475
3	Azimuth column	0	0	914	914	914
4	Azimuth fork	0	0	1620	1620	1620
5	Dish Bottom Left	0	0	1928	0	2128
6	Dish Top Left	0	0	1928	0	1928
7	Mirror Bottom Left	0	0	0	0	0
8	Mirror Top Left	0	0	0	0	0
9	Dish Bottom Right	0	0	1928	2411	2128
10	Dish Top Right	0	0	1928	2411	1928
11	Mirror Bottom Right	0	0	0	0	0
12	Mirror Top Right	0	0	0	0	0
13	Dish center	0	0	0	0	0
14	Central tube top	0	0	69	69	0
15	M2	0	0	471	471	0
16	M2 Backup structure	0	0	864	864	0
17	Sky	-	-	-	-	-
18	Air	-	-	-	-	-
19	Counterbalances	0	0	1203	1203	1203

Notes/assumptions:

(1) Sun from back side of telescope dish

(2) Sun from back/lateral side of dish

5. ANALYSIS RESULTS FOR THE STEADY CASES

In Table 14 we report the resulting temperature fields developed for the steady cases studied. As it can be observed, for the operational cases, the maximum temperature difference that the simplified model predicts between the elements of the structures generates thermal gradients in the same order of magnitude assumed and studied in [AD1]. These values ensure to keep the performance of the ASTRI SST-2M telescope within the specification.

Table 14 Summary of the temperature fields developed in the telescope.

		Load case				
		Operational		**Not operational**		
		S1	**S2**	**S3** (1)	**S4** (2)	**S5** (1)
Link number	**Label**	**Temperatures [C]**				
1	Ground	-10.0	30.0	30.0	30.0	30.0
2	Base structure	-13.9	24.8	53.6	52.1	53.6
3	Azimuth column	-14.0	24.9	57.4	57.2	57.4
4	Azimuth fork	-12.0	27.3	56.8	54.3	57.3
5	Dish Bottom Left	**-11.8**	**27.7**	60.7	31.6	62.9
6	Dish Top Left	-13.8	24.6	**64.6**	30.2	**65.1**
7	Mirror Bottom Left	-13.6	24.7	50.8	**30.0**	50.9
8	Mirror Top Left	-13.8	24.5	49.2	**30.0**	49.3
9	Dish Bottom Right	**-11.8**	**27.7**	60.2	66.0	62.4
10	Dish Top Right	-13.8	24.6	64.4	**70.7**	64.9
11	Mirror Bottom Right	-13.6	24.7	50.7	53.1	50.8
12	Mirror Top Right	-13.8	24.5	49.1	51.1	49.2
13	Dish center	-12.9	25.9	61.4	49.0	62.6
14	Central tube top	**-18.0**	**19.3**	**30.4**	30.3	**27.4**
15	M2	-14.4	23.7	49.7	49.2	29.6
16	M2 Backup structure	-17.0	20.7	39.9	39.8	28.0
17	Sky	-50.0	-10.0	20.0	20.0	20.0
18	Air	-10.0	30.0	30.0	30.0	30.0
19	Counterbalances	-16.3	22.0	48.2	48.1	48.2
	Max temperature	-11.8	27.7	64.6	70.7	65.1
	Min temperature	-18	19.3	30.4	30.0	27.4
	M1 mean gradient through thickness	-0.15	-0.23	-1.56	-1.01	-1.64

5.1 Thermal networks – Operational cases

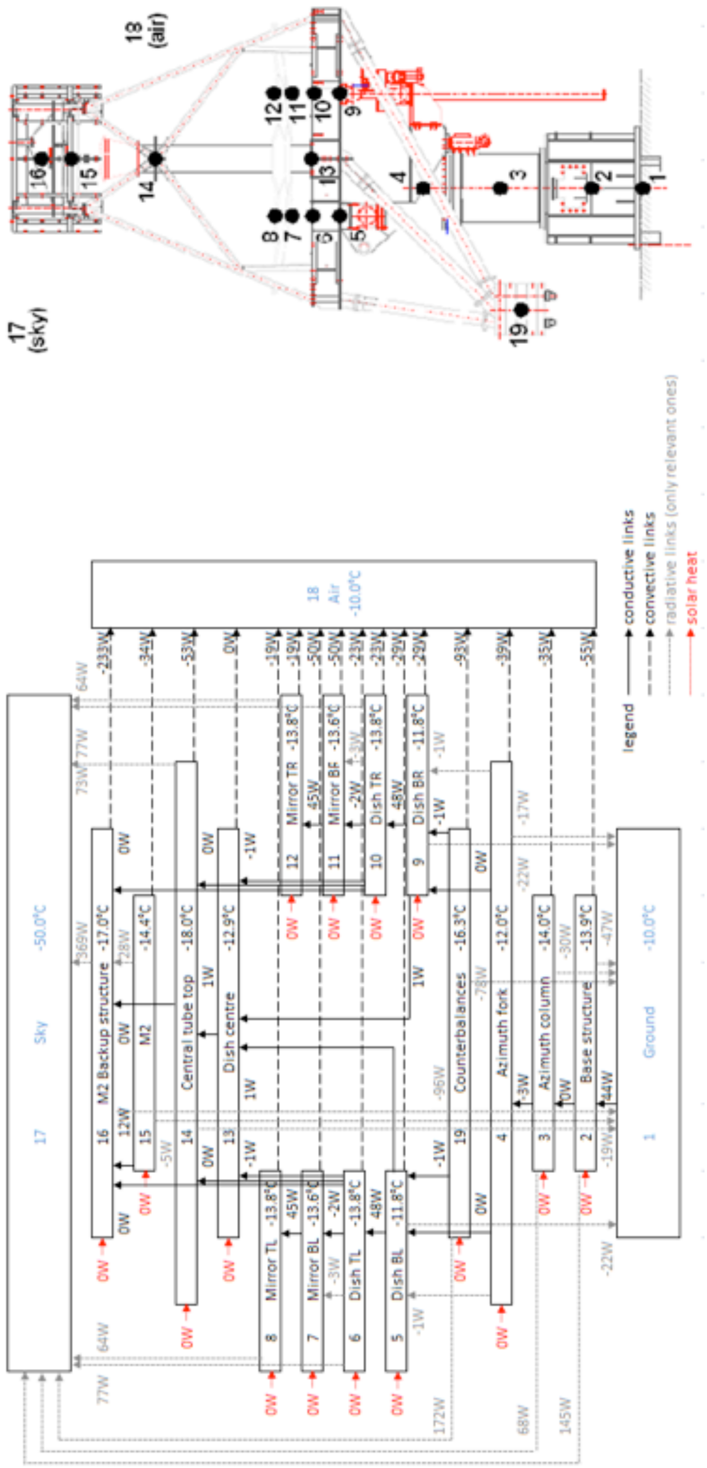


Figure 2 Thermal network for the load case S1 cold night (air -10°C, zenith pointing, no wind)

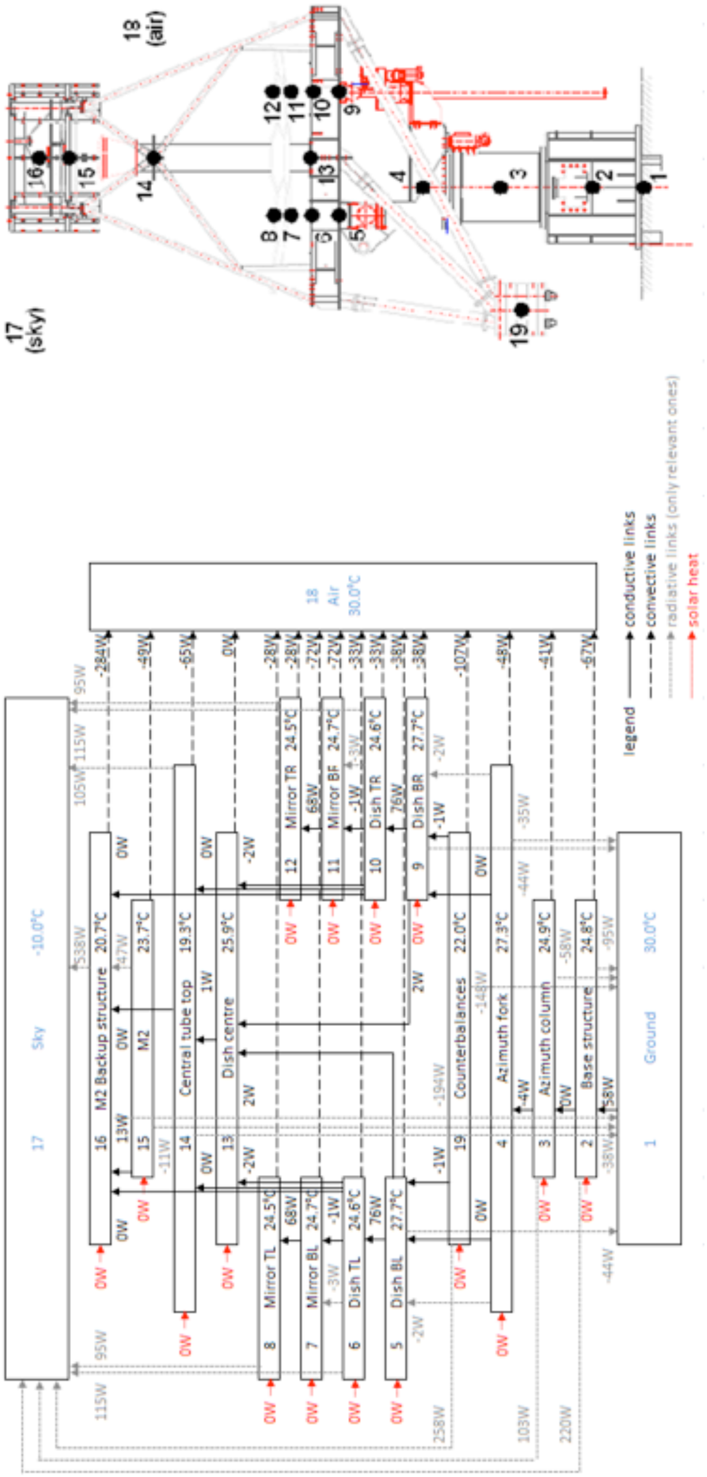


Figure 3 Thermal network for the load case S2 hot night (air +30°C, zenith pointing, no wind)

5.2 Thermal networks – Not operational cases

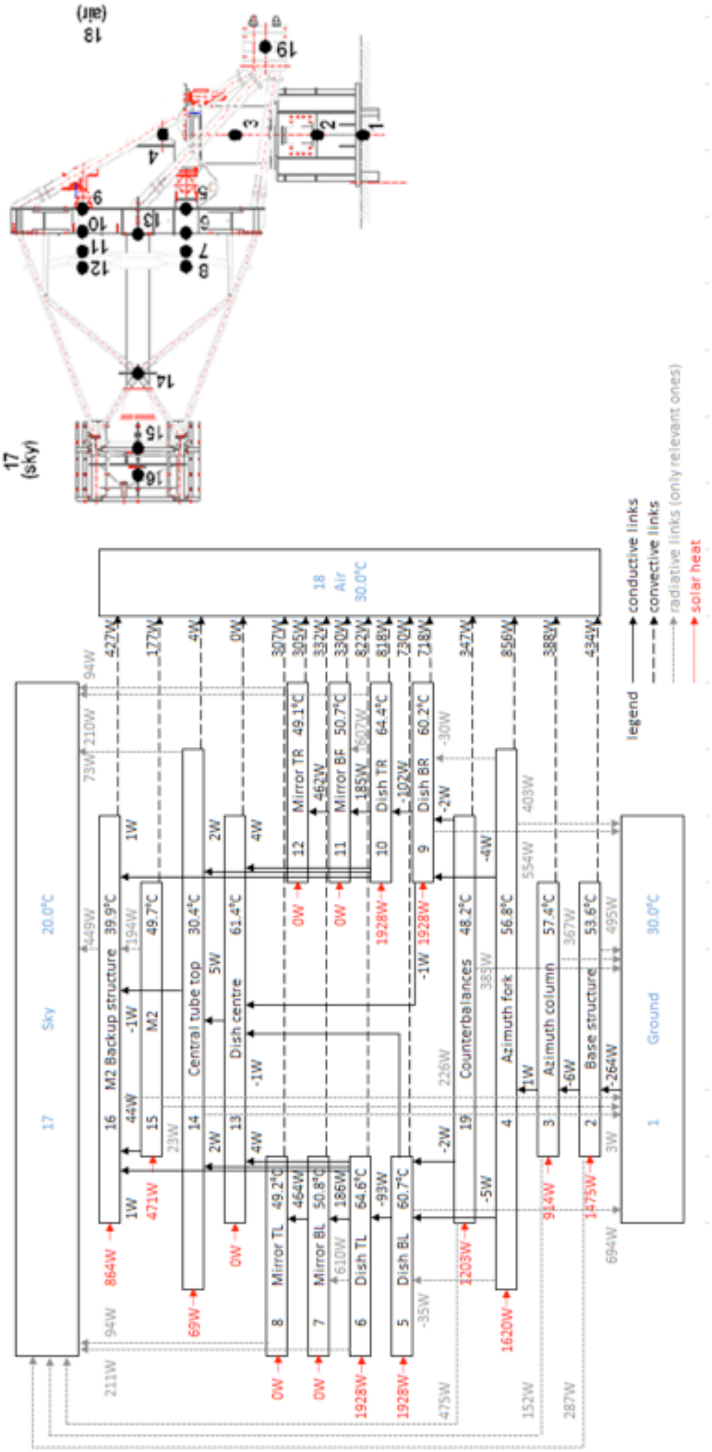


Figure 4 Thermal network for the load case S3 hot day (air +30°C, parking position, no wind, Sun from back)

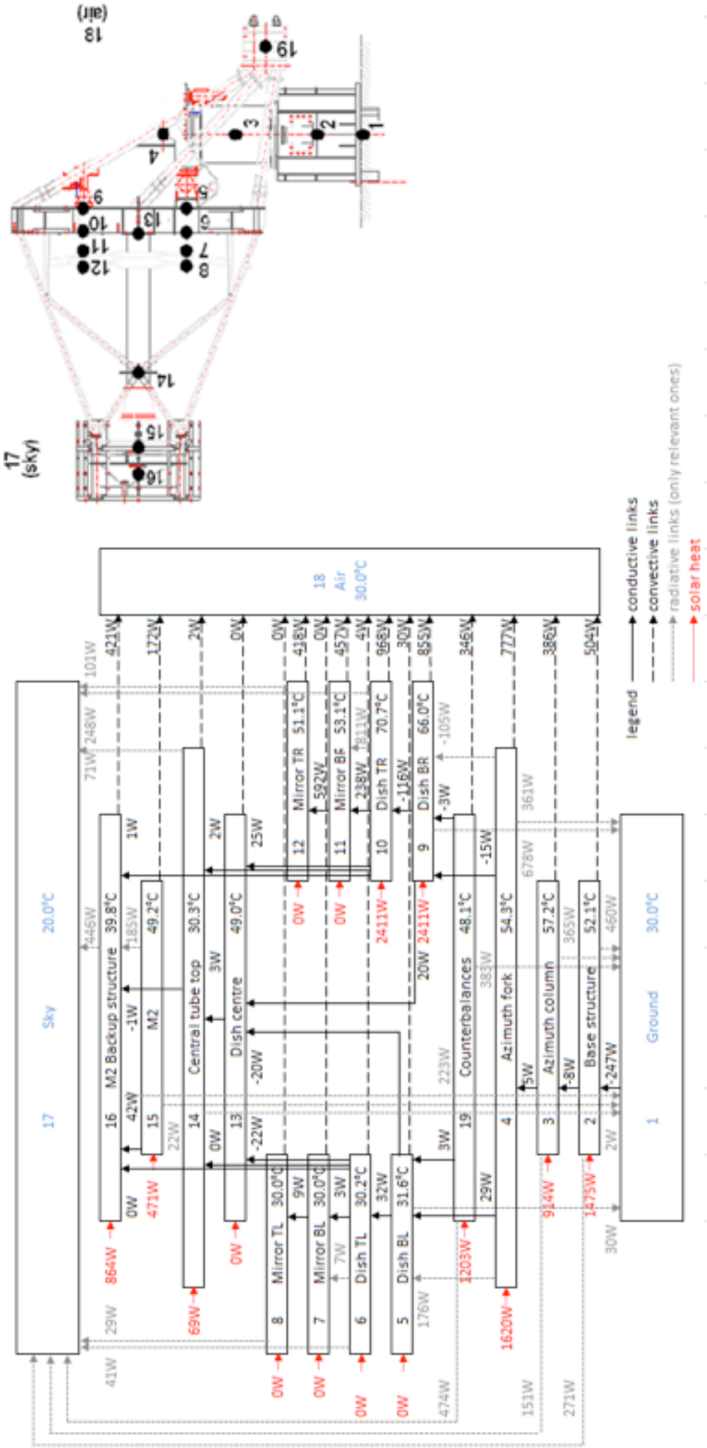


Figure 5 Thermal network for the load case S4 hot day lateral gradient (air +30°C, parking position, no wind, Sun from back/side)

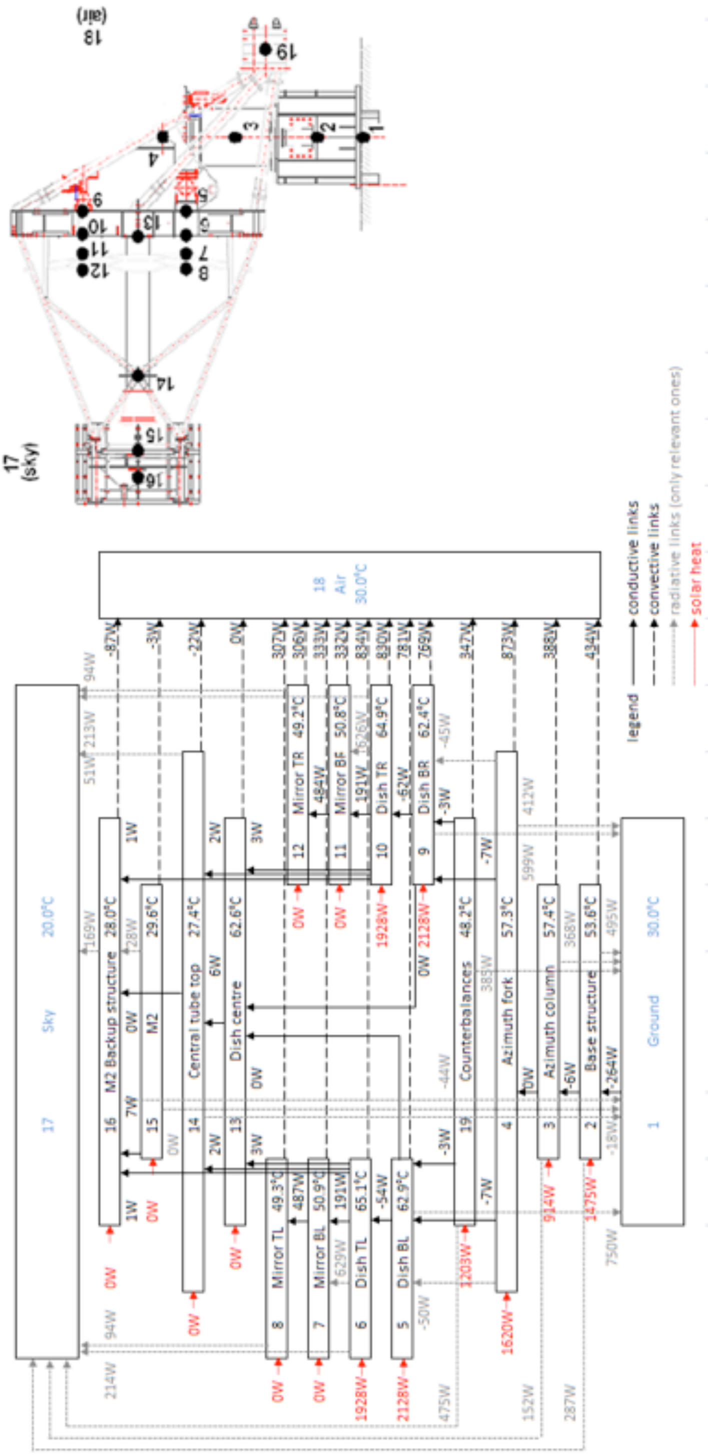


Figure 6 Thermal network for the load case S5 hot day axial gradient (air +30°C, parking position, no wind, Sun from back)

6. ANALYSIS RESULTS FOR THE TRANSIENT CASES

In the following chapters we report a series of plots that show the behaviour, given by the simplified implemented model, of the telescope main components. For each load case, the chapter is structured as follow:

- the first plot shows a general summary where all the thermal nodes are presented together with the air temperature profile. In the same plot, the dashed line represents the telescope equivalent temperature.
- The second set of plots shows the temperature profiles and gradients on the telescope structures.
- The third set of plots is focused on the mirrors (both temperature profiles and gradients).

6.1 T1 – air step change (step -10°C, zenith pointing, no wind)

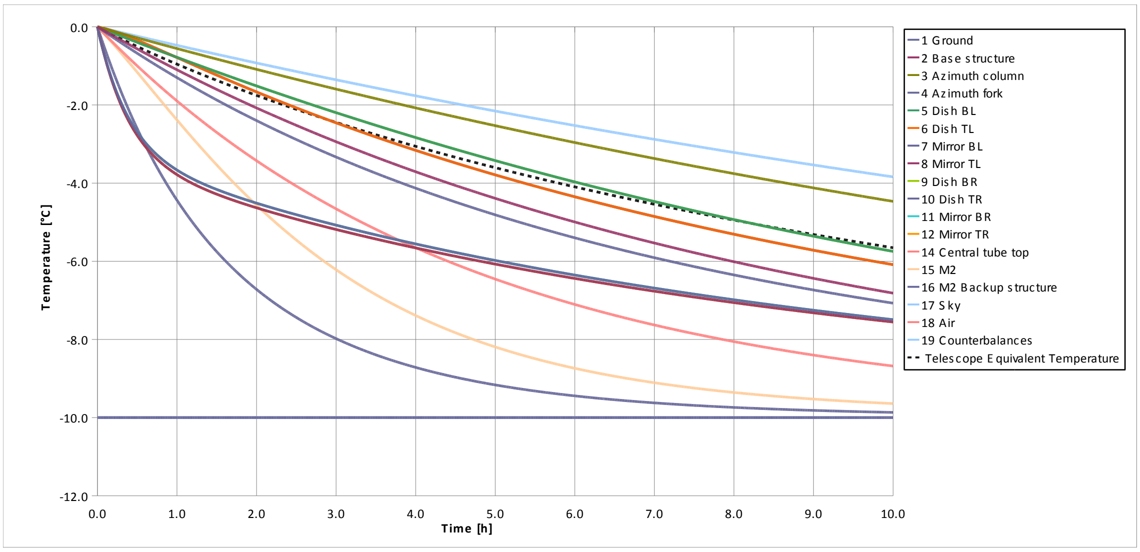


Figure 7 Global behaviour of all the thermal nodes implemented in the model and air temperature profile for the T1 load case (coloured lines). Telescope equivalent temperature (dashed line).

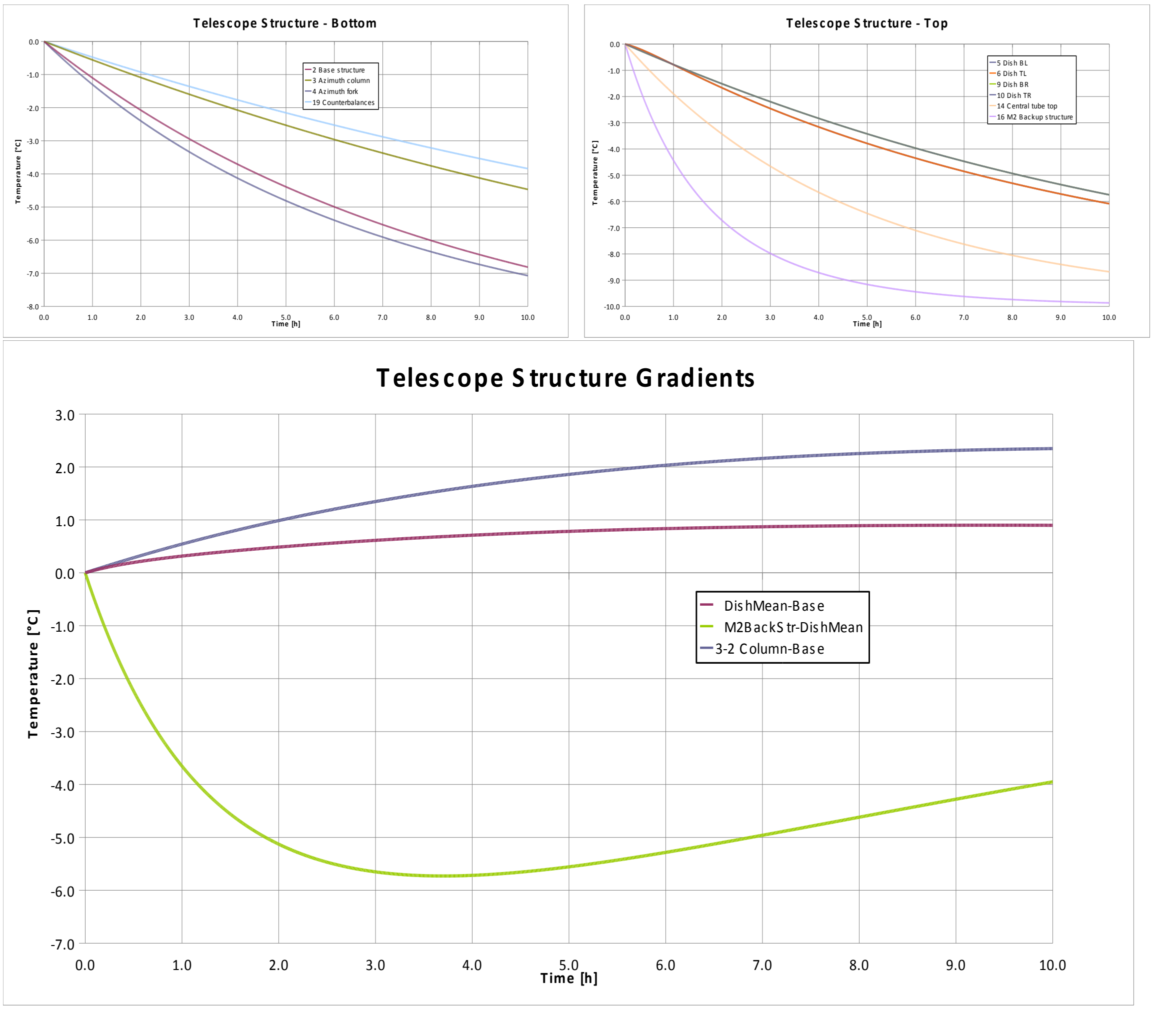


Figure 8 Temperature profiles and gradients across the telescope structures for the T1 load case.

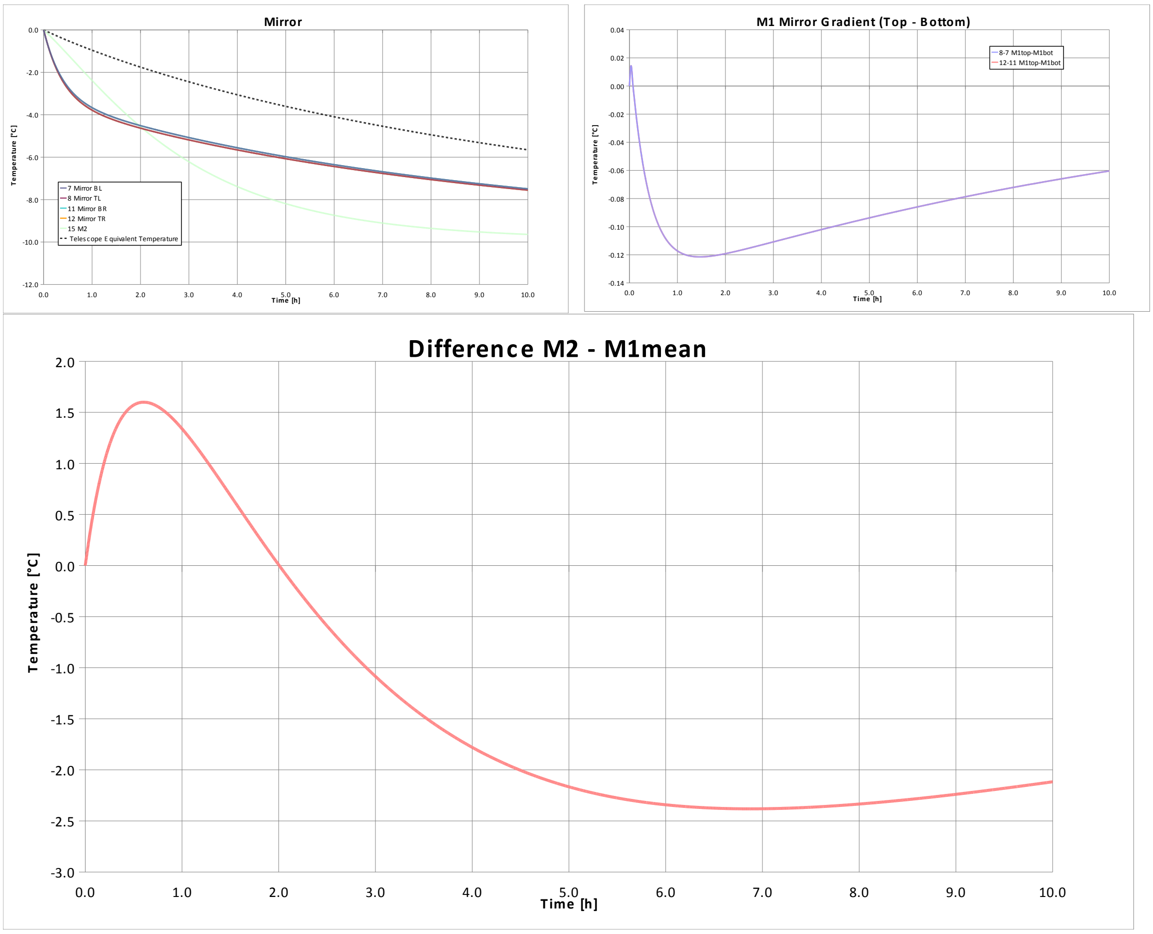


Figure 9 Temperature profiles and gradients across the mirrors for the T1 load case.

6.2 T2 – transition day-night (linear from 0 to -10°C in 1 h, zenith pointing, no wind)

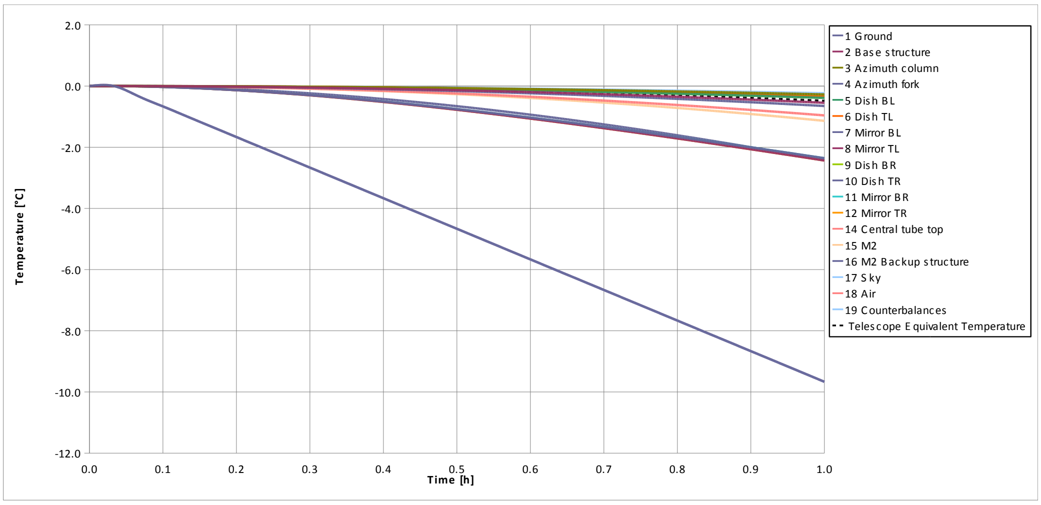


Figure 10 Global behaviour of all the thermal nodes implemented in the model and air temperature profile for the T2 load case (coloured lines). Telescope equivalent temperature (dashed line).

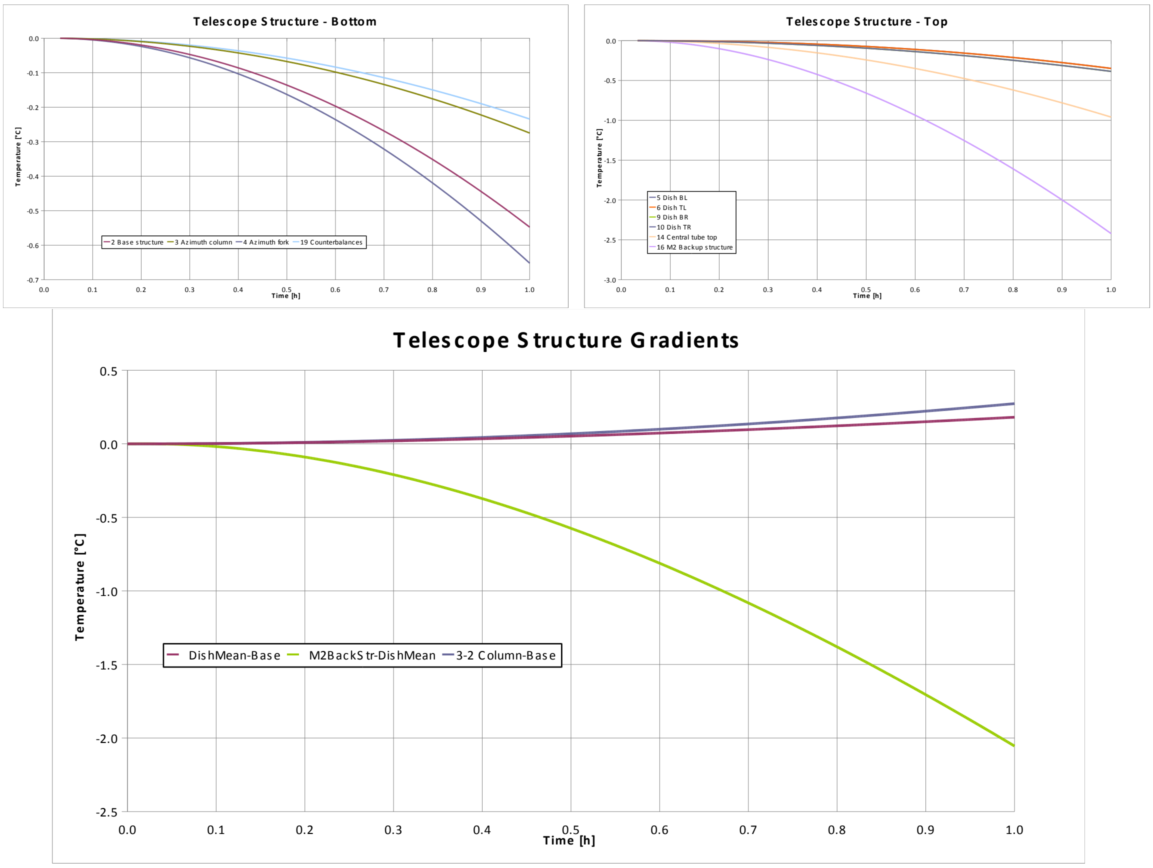


Figure 11 Temperature profiles and gradients across the telescope structures for the T2 load case.