Proc. of SPIE Vol. 1690, Design of Optical Instruments, ed. D M Aikens, V L Genberg, G C Krumweide, M J Thomas (Sep 1992) Copyright SPIE

Design of a Modified Serrurier Truss for an Optical Interferometer

Keith Doyle
Dan Vukobratovich
Optical Science Center
University of Arizona
Tucson, AZ

ABSTRACT

A modified Serrurier truss was designed to support a beam collapser for the USNO Optical Interferometer. The truss was designed to maintain the primary and secondary mirrors within the allowed specified optical and stress tolerances under gravity, wind, thermal, and earthquake loading. A NASTRAN finite element model and closed-form equations were developed to design the truss members.

1.0 INTRODUCTION

The optical interferometer consists of four stellar interferometers designed to provide measuring capabilities including stellar diameters, binary star orbits, parallaxes, positions, proper motions and astrometric detection of extra-solar planets. Each interferometer consists of a Gregorian beam collapser and a siderostat. The configuration of the beam collapser includes a 30-inch diameter f/2.7 primary mirror and a 4.6-inch diameter secondary mirror with a vertex-to-vertex spacing of 92-inches. The primary and secondary mirrors form an afocal system which compresses the beam by the ratio 6.5:1.

The beam collapser is designed to support the primary and secondary mirrors while maintaining the relative separation, centration, and tilt of the optical elements to the following tolerances: vertex-to-vertex separation of the primary and secondary mirrors of 2 μm; relative decenter of 25 μm; and primary and secondary mirror tilt of 3 and 6 arcsecs, respectively. The observation tolerances are to be maintained under gravity loading, wind loading for a nine meters per second wind (20 MPH), and thermal loads. The structural integrity of the beam collapser is to be maintained for wind speeds up to 44.7 meters per second (100 MPH) and under earthquake loads. The fundamental frequency of the structure is to be greater than 10 Hz.

2.0 HISTORICAL OVERVIEW

It is a difficult problem to reduce gravity induced deflection of optical support structures to an acceptable level in the design of large optical telescopes. Mis-alignment tolerances as small as 2 μm are sometimes required to satisfy optical performance specifications. In the past, conventional truss type structures were used. As telescope size increased, ordinary truss structures proved incapable of providing sufficient stiffness. The 74-inch Pretoria telescope built in 1938, for example, has a total gravity induced tube deflection of 0.10 inch[1]. That same year, Mark Serrurier designed a new type of truss which provided an effective solution to gravity deflection[2]. The Serrurier truss is a two-bay, center-supported truss designed to produce equal and parallel end-ring deflections with essentially no rotation of the optical elements (Figure 1). The loads at the end of the truss members, the primary and secondary mirrors and their mounts, act through the apex of the truss so that the turning moment is zero. The top and bottom set of links insure that the end-rings remain parallel. Existing telescopes which utilize the Serrurier truss include the Hale 5-m on Mt. Palomar, the 6-m BTA (Large Azimuthal Telescope) at the Crimean Observatory, and the 4-m Mayall at the Kitt Peak National Observatory.

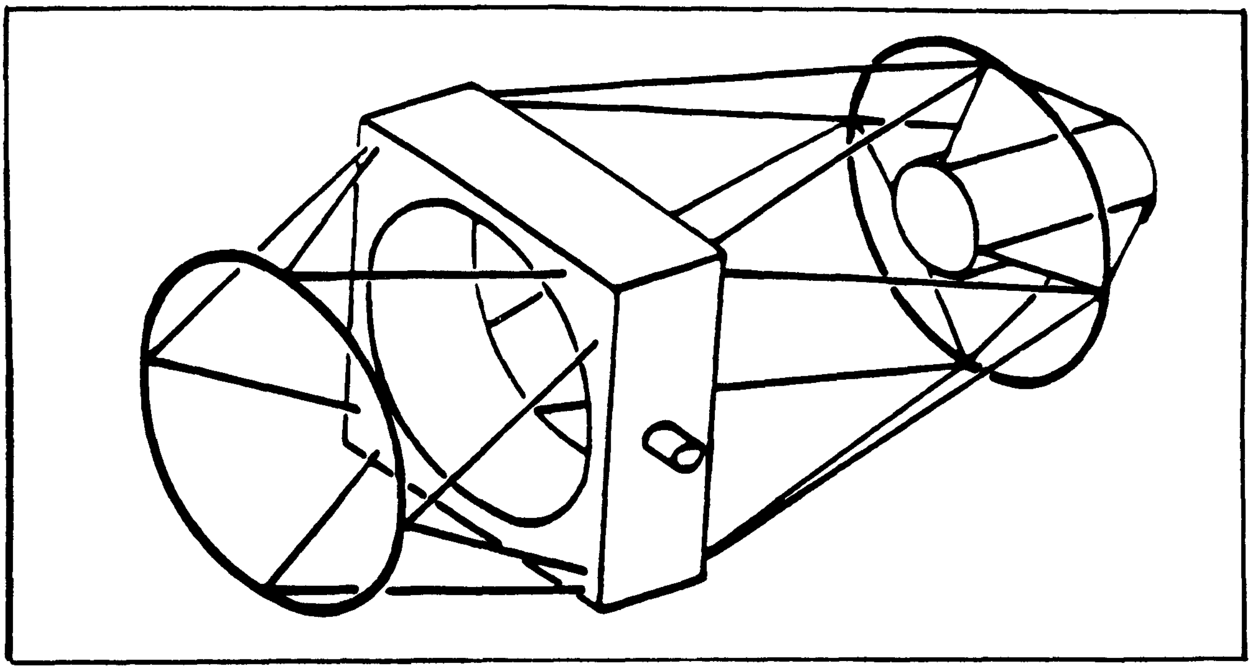

Figure 1. Serrurier Truss

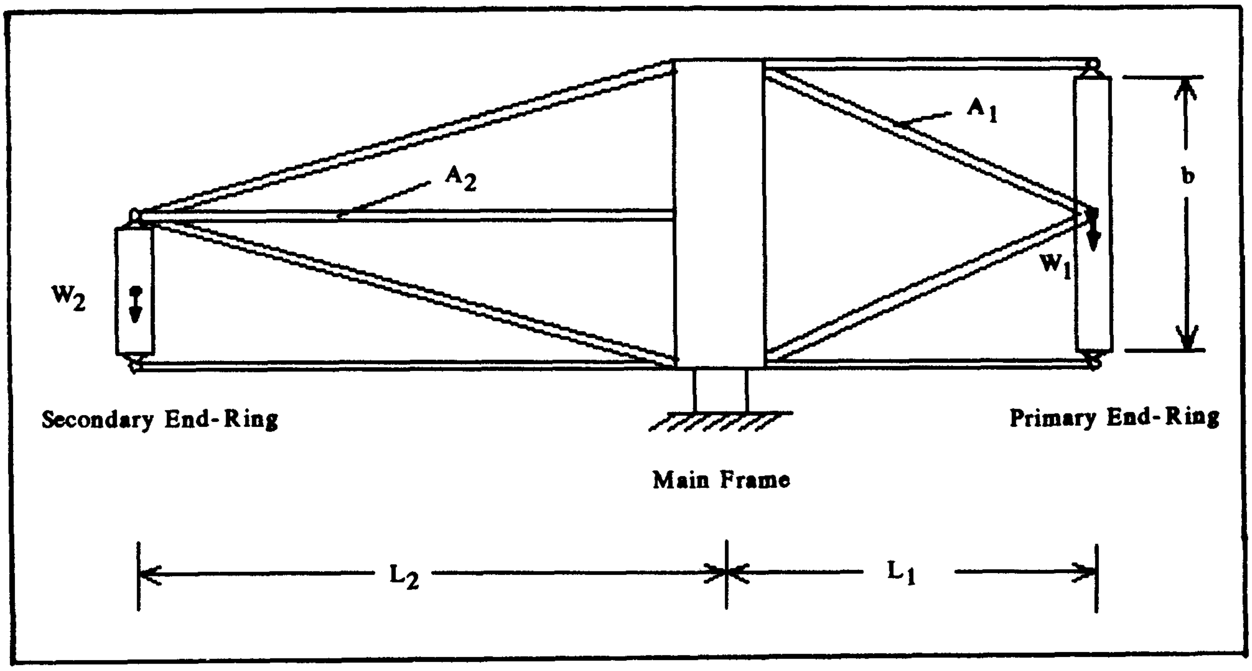

Figure 2. Modified Serrurier Truss

The Serrurier truss is not a complete solution to the gravity deflection problem in telescope structures. Stiffness to weight of the Serrurier truss is low in comparison with other types of truss structures[3]. When the ratio of truss length to width exceeds about 1.4, a multiple bay truss is stiffer than a Serrurier truss of the same weight[4]. Low fundamental frequencies, typically about 4 to 5 Hz, are common in low stiffness Serrurier truss structures. These low fundamental frequencies often lead to vibration problems[5]. Use of the Serrurier truss requires careful design to overcome these drawbacks in large optical support structures.

3.0 MODIFIED SERRURIER TRUSS DESIGN

3.1 Gravity Design

A modified Serrurier truss was designed (Figure 2) to support the secondary and primary optics of the beam collapser. The disadvantage of the standard Serrurier truss is that the secondary end-ring and the upper member of the truss at the secondary end block the field of view of the siderostat. A modified version of the Serrurier truss was therefore required. The upper part of the truss, used to keep the secondary end-ring parallel, was removed and placed lower to the side. The continuous secondary end-ring was then modified to a semi-circular end-ring. The deflection characteristics remain the same as the triangular side members of the truss, governing deflection, were not affected. This greatly improved the field of view of the siderostat.

A closed-form solution for the design of the truss members was developed under gravity loading. The design equations produce a truss with equal end-ring deflections and a structure balanced about its center support points with gravity acting perpendicular to the optical axis. These equations take into account the weight of the truss members which are carried half by the main frame and half by the end-rings. The effect of sag of the members under their own weight was neglected. The design equations require the input of the total length of the truss and the position of the main frame relative to the end-rings. The areas of the primary and secondary truss members may then be determined along with the end-ring deflection. The design equations are expressed below:

Secondary Truss Area:
$$A_2 = \frac{-\beta \pm \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha} \tag{1}$$

Primary Truss Area:
$$A_1 = \frac{W_2 L_2 - W_1 L_1 + 2\rho A_2 X_2 L_2}{2\rho X_1 L_1} \tag{2}$$

Primary end-ring deflection:
$$\Delta_1 = \frac{W_1' X_1^3}{8EA_1 b^2} \tag{3}$$

Secondary end-ring deflection:
$$\Delta_2 = \frac{W_2' X_2^3}{8EA_2 b^2} \tag{4}$$

(Note: A positve value for the area of the secondary truss members must result from the quadratic equation to provide a realistic truss design.)

where:

$\alpha = 4\rho^2 EL_2 (X_2^5 - X_2 X_1^4)$

$\beta = 2\rho E [W_2 L_2 (2X_2^4 - X_1^4) - W_1 L_1 X_2^4]$

$\gamma = EW_2 X_2^3 (W_2 L_2 - W_1 L_1)$

$X_1 = \sqrt{4L_1^2 + b^2}$

$X_2 = \sqrt{4L_2^2 + b^2}$

$W_{1'} = W_1 + 2\rho A_1 X_1$

$W_{2'} = W_2 + 2\rho A_2 X_2$

ρ = the mass density of the truss material
E = modulus of elasticity
W_1 = weight of the primary end-ring including mirror and cell
W_2 = weight of the secondary end-ring including mirror and cell
b = height of the structure

Example:

E = 28E6 psi (steel)
ρ = 7.87E-4 lb_m
W_1 = 600 lbs.
W_2 = 200 lbs.
L_1 = 35.5 in.
L_2 = 56.5 in.
b = 50 in.

Design equations yield:

A_1 = 3.12 in.^{2}
A_2 = 1.72 in.^{2}
$\Delta_1 = \Delta_2$ = 4.69E-4 in.

NASTRAN finite element model yields:

Δ_1 = 4.70E-4 in.
Δ_2 = 4.73E-4 in.

The closed-form equations provided an initial truss design. A primary end-ring position of 35.5 in. relative to the main frame was selected. The design equations yielded an area of 3.12 in.^{2} for the secondary truss members and an area of 1.72 in.^{2} for the primary truss members.

The pipe selected for the truss structure was a 3.5" nominal diameter (3.17 in.^{2}) for the secondary members and 2.0" nominal diameter (1.70 in.^{2}) for the primary members.

A NASTRAN finite element model of the modified Serrurier truss was developed. The design of the truss was modified to account for the 10-degree rotation of the structure with respect to gravity. The distance from the main frame to the primary end-ring was adjusted to 32.25 in. with the truss member areas remaining unchanged. The box beam members of the end-rings and main frame are 4"x4"x1/2" and 5"x5"x1/2", respectively.

The beam collapser is to be assembled and aligned in the zero-degree orientation with respect to gravity. It will then be rotated to its final 10-degree position upon installation at the site. The truss structure was found to rotate about the main frame as the truss was oriented to its final 10-degree position. This effect is due to the gravity vector component acting along the optical axis. The common Serrurier truss used in telescope designs is mounted on trunions located at the center of gravity which eliminate this rotation effect. The modified Serrurier truss required two A-braces (5"x2"x5/16" box sections) extending out from the main frame to maintain the optics within the decenter tolerance (Figure 3). The axial separation of the optics exceeded the tolerance from the rotation but the structure will be re-focused on site. The finite element deflections of the optics due to gravity were found by subtracting out the deflection due to gravity in the zero-degree orientation from the deflection of the optics in the 10-degree orientation.

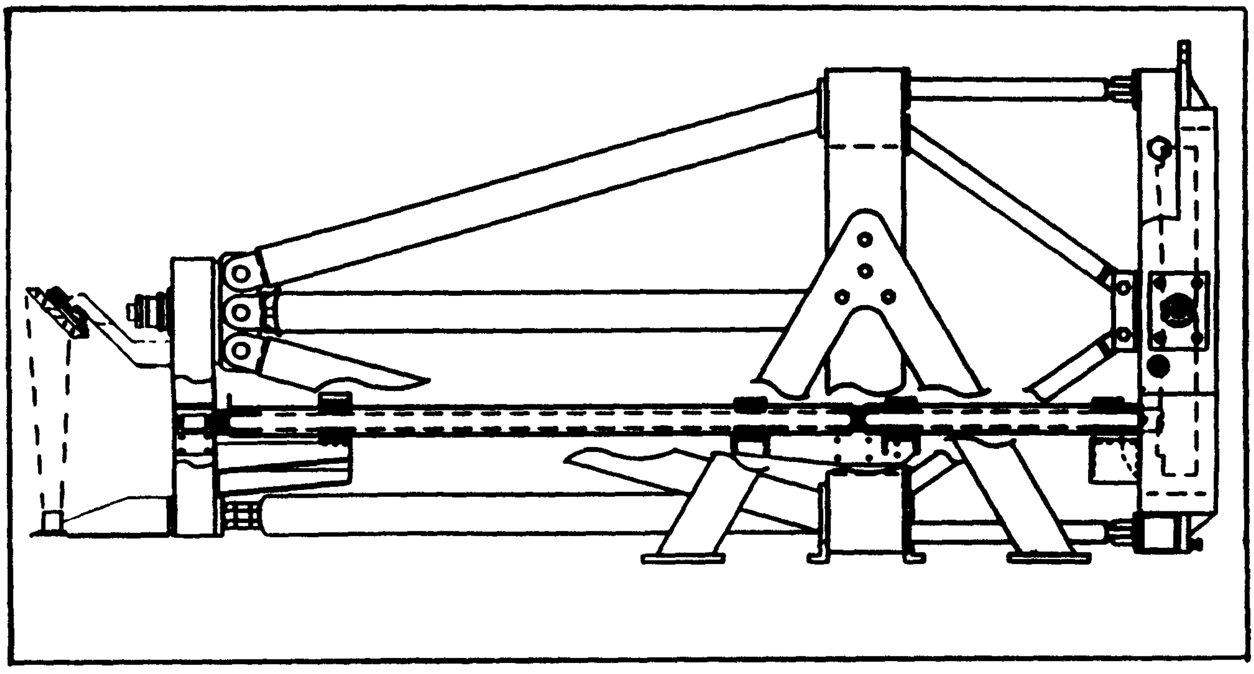

Figure 3. Modified Serrurier Truss with A-brace

A study was done, once the main frame was adequately braced against rotation, to verify the theoretical prediction that a Serrurier truss will maintain the decenter of the optics within tolerance at any angle with respect to gravity. The results showed that the secondary and the primary optics maintained a relative decenter according to theory.

3.2 Dynamic Analysis

The fundamental frequency of the support structure was computed to be 35.1 Hz using NASTRAN. This satisfies the structural requirement that the fundamental frequency be greater than 10 Hz.

3.3 Wind Design

The beam collapser was analyzed for deflection characteristics under a steady 9 m/s wind. The analysis showed that the structure maintained the optics within the observation tolerances with the wind loading acting in the lateral and optical axis directions.

The wind loading was applied as static pressure loads using the finite element model. A coefficient of drag of 1.20 and 2.05 was used for the round truss members and the rectangular structural members, respectively. A coefficient of drag of 1.20 was used for the mirrors for the wind acting in both the lateral and optical axis directions.

The structural integrity of the truss was verified under a 100 MPH wind applied in the two orthogonal directions. The maximum stress produced in the structure was well below the design limit. The allowable stress was taken to be half the microyield of steel.

3.4 Thermal Effects

A thermal analysis was conducted on the beam collapser support structure. The effects of a unit linear temperature gradient acting through the depth of the structure, and in the transverse (lateral), and longitudinal (optical axis) directions was modeled using NASTRAN. A thermal soak of 20 degrees celsius was also applied.

The results of the thermal analysis show that the axial separation of the optics exceeds the tolerance due to a unit linear gradient in the x,y, and z axes and due to the thermal soak. Decenter in the y and z direction and rotation of the optics was within the specified tolerance.

The problem of maintaining the axial separation of the optics under the thermal loading will be solved by the use of metering rods. These rods will be made of the same material as the optics and will maintain the axial spacing between the secondary and the primary mirror.

3.5 Earthquake Analysis

The structural integrity of the beam collapser was investigated under earthquake loadings. An equivalent lateral load was applied to the finite element model using the UBC/1990 SEAOC design code for a seismic zone 4 earthquake. The stresses resulting from this 1.1 G lateral load on the beam collapser truss structure were below the microyield of the steel.

4.0 Summary

A results summary of the mechanical deflections of the primary and secondary optics due to the examined load cases is listed in Table 1. The table lists the translation and rotation of each of the optical elements under gravity at a 10-degree orientation (zero-degree gravity deflection subtracted out), 9 m/s wind acting along the lateral and optical axis directions, 20-degree thermal soak, and unit linear gradients in the x,y,z directions. The relative translations of the primary and secondary optics are listed and the totals of the rotations and relative translations are listed in the totals column. The totals column reveals that under the extreme unrealistic condition that all load cases act at once the optical elements of the beam collapser will be within the specified tolerance. The quantities with an asterisk indicate that they initially exceed the tolerance. The use of metering rods and re-focusing the instrument on site will bring the relative translation in the x-dir to a total of 1.54 μm. Figure 4 illustrates the configuration of the siderostat and beam collapser.

The final structural configuration of the beam collapser support structure maintains the relative separation, centration, and tilt of the primary and secondary mirrors within the allowed tolerances. The structure has been designed to withstand gravity, wind, earthquake, and thermal effects. The secondary and the primary end-rings consists of 4"x4"x1/2" steel tubing and the main frame uses 5"x5"x1/2" steel tubing. Two A-braces supporting the main frame use 5"x2"x5/16" box beams. The truss members consist of 3.5" and 2.0" nominal diameter steel pipe for the secondary and primary members, respectively. The main frame is 32.25 inches from the primary end-ring with the total distance between end-rings of 100.25 inches. Metering rods will be used to maintain the axial separation of the optics within the allowed tolerance under the thermal load conditions.

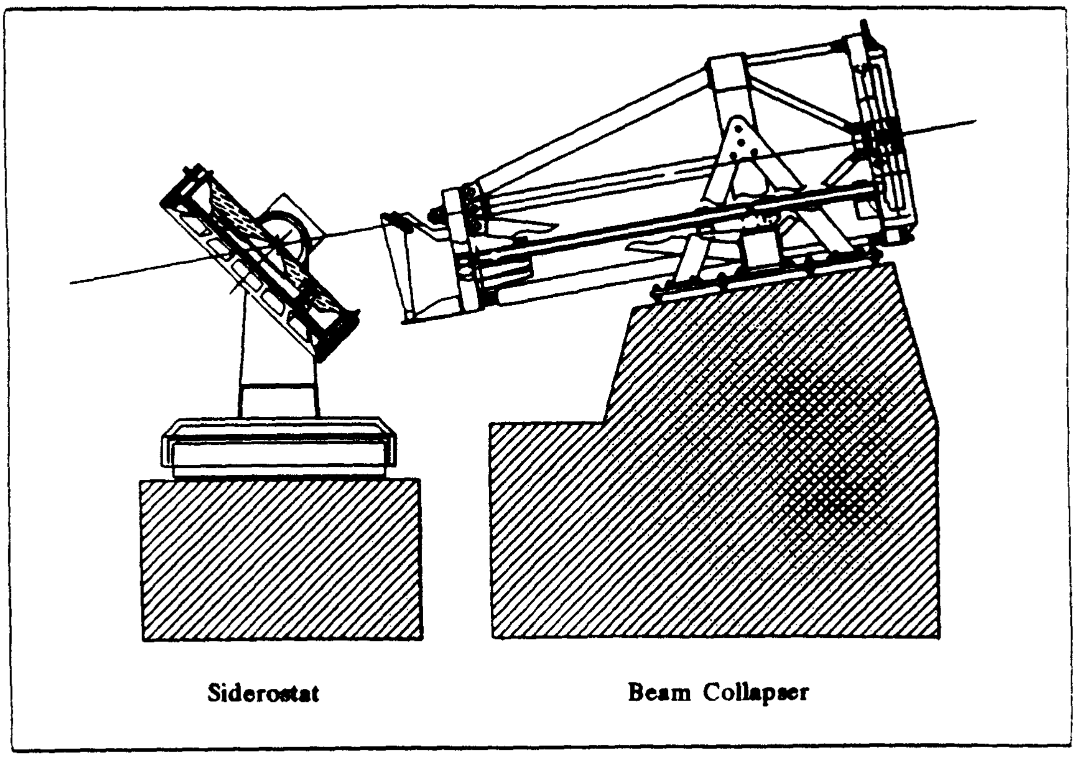

Figure 4.

Table 1.

Modified Serrurier Truss Results Summary (μm, arcsec)										
Loading			Gravity	Wind		Thermal (soak, gradient)				Totals
				Lateral	OA	20°	X	Y	Z	
SECONDARY	Translation	X	14.63	-----	1.90	-375.92	-7.90	-8.15	-5.16	-----
		Y	-----	1.51	0.0065	-----	-----	-12.14	-----	-----
		Z	6.43	-----	0.78	161.80	-9.27	1.25	3.61	-----
	Rotation	R_Y	0.97	-----	0.11	0.37	0.29	0.057	0.45	2.25
		R_Z	-----	-----	-----	-----	-----	0.30	-----	0.30
PRIMARY	Translation	X	3.33	-----	0.36	185.67	3.84	4.52	8.08	-----
		Y	-----	1.20	-----	-----	-----	-6.58	-----	-----
		Z	-2.59	-----	-0.38	164.34	-0.54	-----	5.33	-----
	Rotation	R_Y	0.085	-----	-----	1.25	0.14	0.057	0.062	1.59
		R_Z	-----	-----	-----	-----	-----	0.15	-----	0.15
RELATIVE DEFLECTION	Translation	X	11.30*	-----	1.54	561.34*	11.73*	12.67*	13.24*	585.91
		Y	-----	0.31	0.007	-----	-----	5.56	-----	5.88
		Z	9.02	-----	1.18	2.54	8.74	1.23	1.73	24.44

*Exceeds Tolerances

Allowed Tolerances:

Axial separation X: 4μm
Decenter Y,Z: 25μm
Rotation Y,Z (primary): 3 arcsec
Rotation Y,Z (secondary): 6 arcsec

References

[1] R. Dowson, "The Static Deflection of the Telescope of the 74" Reflector for Pretoria", *Heaton Works Journal*, Vol. 3, No. 13, pp. 111-119 (Summer, 1938.

[2] M. Serrurier, "Structural Features of the 200-inch telescope for Mt. Palomar Observatory", *Civil Engineering*, Vol.8, No.8, pp. 524-526 (Aug., 1938)

[3] A.B. Meinel and M.P. Meinel, "Wind Deflection Compensated, Zero-Coma Telescope Truss Geometries", *Proc. SPIE 628*, pp. 403-411 (1986)

[4] J. Lubliner, *Preliminary Design of Tube for TMT*, Keck Observatory Report No. 50 (Jan. 5, 1981).

[5] B. H. Thomas, W. Neville and J. Snodgrass, "Assessment and Control of Vibrations Affecting Large Astronomical Telescopes", *Proc. SPIE 732*, pp. 130-156 (1987).

General References

Pope, J.D., "Optical Performance Criteria for Telescope Tube Design", Anglo-Australian Telescope Project.

Hughes, Dr. James A. and Donald J. Hutter, "Astrometry with Optical Interferometers", Technical Report, U.S. Naval Observatory, Washington D.C. May, 1990.

Vukobratovich, "Preliminary Design Study of the Beam Collapser and Certain Optomechanical Aspects of the Siderostat," USNO Progress report, 1991.

American Institute of Steel Construction, Inc., "Manual of Steel Construction," Allowable Stress Design, USA, 1989.

Committee on Wind Effects, "Wind Loading and Wind-Induced Structural Response", ASCE, Chapt. 6, Trussed Frameworks, Pg. 125., New York, 1987.

Hoerner, Sighard F., "Fluid-Dynamic Drag", Published by author, 1958. Chapter 3.

Fox, Robert W. and Alan T. McDonald, "Introduction to Fluid Mechanics", John Wiley and Sons, Cananda, 1985, pp. 454-469.

Harris, Cyril M., "Shock and Vibration Handbook", 3rd edition, McGraw-Hill Book Company, New York, 1988. Chpt. 29.

Zago, Lorenzo, "Design and Performance of Large Telescopes Operated in Open Air", SPIE Vol. 628, 1986. pp. 350-359.