

*Refracting*

**Report on the Tolerance Analysis of ETM Telescope for California Institute of Technology**

**1. Objective of the tolerance analysis**

To evaluate the tolerances provided by California Inst. of Tech. and to recommend optimized tolerances for the ETM telescope.

**2. Scope of the analysis**

This tolerance analysis is based on the nominal design provided by California Inst. of Tech. and system performances specified in the statement of work dated on 09/14/98. The proposed scope of work has been accomplished.

**3. Performance requirements**

Beam reduction = 8X;  
 Clear aperture diameter >156mm (no vignetting);  
 Output beam quality: P-V wavefront distortion < 1.0 wave @ 1064nm for the field of view =  $\pm 2 \times 10^{-4}$  rad ( $\pm 0.01146^\circ$ ).

**4. Tolerance requirements in the statement of work**

Tolerance on optical fabrication parameters:

- Surface radius;
- Tilt, with reference to optical axis;
- De-center;
- Diameter;
- Edge thickness.

Tolerance on mechanical alignment parameters:

- Tilt, with reference to optical axis;
- De-center;
- Lens spacing

**5. Tolerance provided by California. Inst. of Tech.**

Tolerance	Lens #1	Lens #2	Lens #3
Radius	S1: +/- 3.5 mm	S1: +/- 0.1 mm	S1: +/- 1.0 mm
	S2: +/- 9.9 mm	S2: +/- 0.2 mm	S2: +/- 1.0 mm
Power	0.5 fringe@0.633 $\mu$ m	0.5 fringe@0.633 $\mu$ m	0.5 fringe@0.633 $\mu$ m
Irregularity	0.12 fringe@0.633 $\mu$ m	0.12 fringe@0.633 $\mu$ m	0.12 fringe@0.633 $\mu$ m
<del>Surface tilt</del>	<del>+/- 0.03 degree</del>	+/-0.06 degree	+/-0.06 degree
TIR (wedge)	0.034mm	0.07mm	0.04mm
Surface de-center	+/- 0.025 mm	+/- 0.025 mm	+/- 0.025 mm

*Elem tilt*

*(~1mm spot dia)*

Element tilt	0.056 degree	0.056 degree	0.056 degree
Element de-center	+/- 0.2 mm	+/- 0.2 mm	+/- 0.2 mm
Diameter	-0.1/ 0.0 mm	-0.1/0.0 mm	-0.1/0.0 mm
Thickness	+/- 0.5 mm	+/- 0.2 mm	+/- 0.5 mm

Compensator: Spacing between lens #1 and lens #2: +/- 12mm;  
Spacing between lens #2 and lens #3: +/- 5mm.

## 6. Evaluations on the existing tolerance

In the existing tolerances, TIR, spherical surface tilt and de-center are related tolerances. TIR is the most commonly used. In the following analysis, only TIR is adopted.

The sensitivity and 20 runs Monte Carlo analysis results have shown that some of the existing tolerances are too loose to meet the specification after tolerancing, for example, the TIR and element de-center for all the three lenses. While the irregularity tolerances on the three lenses are too tight.

The top 40 worst offenders and 20 Monte Carlo run results are printed below:

Worst offenders:			Value	MF	Change
Type	Sf1	Sf2			
TEDY	6	7	-0.200000	0.172975	0.139085
TEDY	6	7	0.200000	0.172975	0.139085
TEDX	6	7	-0.200000	0.172862	0.138971
TEDX	6	7	0.200000	0.172862	0.138971
TEDY	2	3	0.200000	0.116541	0.082650
TEDY	2	3	-0.200000	0.116541	0.082650
TEDX	2	3	0.200000	0.116502	0.082611
TEDX	2	3	-0.200000	0.116502	0.082611
TEDY	4	5	0.200000	0.069261	0.035370
TEDY	4	5	-0.200000	0.069261	0.035370
TEDX	4	5	0.200000	0.069214	0.035323
TEDX	4	5	-0.200000	0.069214	0.035323
TIRY		6	-0.020000	0.059584	0.025693
TIRY		6	0.020000	0.059584	0.025693
TIRX		6	0.020000	0.059564	0.025673
TIRX		6	-0.020000	0.059564	0.025673
TETX	6	7	-0.056000	0.056566	0.022676
TETX	6	7	0.056000	0.056566	0.022676
TETY	6	7	0.056000	0.056554	0.022663
TETY	6	7	-0.056000	0.056554	0.022663
TIRY		2	-0.017000	0.039738	0.005848
TIRY		2	0.017000	0.039738	0.005848
TIRX		2	-0.017000	0.039734	0.005844
TIRX		2	0.017000	0.039734	0.005844
TIRY		4	0.035000	0.039528	0.005637
TIRY		4	-0.035000	0.039528	0.005637
TIRX		4	-0.035000	0.039519	0.005628
TIRX		4	0.035000	0.039519	0.005628
TIRY		3	-0.017000	0.039418	0.005527
TIRY		3	0.017000	0.039418	0.005527
TIRX		3	-0.017000	0.039415	0.005524
TIRX		3	0.017000	0.039415	0.005524
TIRY		5	-0.035000	0.037489	0.003599
TIRY		5	0.035000	0.037489	0.003599
TIRX		5	0.035000	0.037488	0.003597

TIRX	5	-0.035000	0.037488	0.003597	
TETY	2	3	-0.056000	0.035087	0.001196
TETY	2	3	0.056000	0.035087	0.001196
TETX	2	3	-0.056000	0.035076	0.001185
TETX	2	3	0.056000	0.035076	0.001185

Nominal RMS Wavefront : 0.033891  
 Estimated change : 0.239552  
 Estimated RMS Wavefront : 0.273442

Merit Statistics:  
 Mean : 0.047861  
 Standard Deviation : 0.032028

Compensator Statistics:  
 Thickness Surf 3:  
 Nominal : 370.820000  
 Minimum : 359.514636  
 Maximum : 377.545718  
 Mean : 371.379355  
 Standard Deviation : 2.058075

Thickness Surf 5:  
 Nominal : 81.523000  
 Minimum : 79.612578  
 Maximum : 84.406983  
 Mean : 81.364511  
 Standard Deviation : 0.577984

Monte Carlo Analysis:  
 Number of trials: 20

Statistics: Normal Distribution

Trial	Merit	Change	0.000	0.700	-0.700	1.000	-1.000
			Field 1	Field 2	Field 3	Field 4	Field 5
1	0.053932	0.020041	0.040875	0.053579	0.053971	0.064286	0.064760
2	0.091992	0.058101	0.085677	0.087567	0.096054	0.092117	0.103507
3	0.141269	0.107378	0.137001	0.104802	0.169994	0.091407	0.184299
4	0.192830	0.158939	0.189505	0.155622	0.223862	0.141294	0.238706
5	0.178541	0.144650	0.175299	0.184405	0.172387	0.190014	0.173130
6	0.215348	0.181457	0.212597	0.225377	0.204751	0.232188	0.203040
7	0.151544	0.117653	0.147639	0.172722	0.126754	0.184364	0.119621
8	0.160669	0.126778	0.156908	0.187090	0.128817	0.200454	0.117767
9	0.238351	0.204460	0.235792	0.262983	0.210784	0.275170	0.200908
10	0.068921	0.035030	0.059223	0.093956	0.025269	0.108919	0.012492
11	0.081710	0.047819	0.074594	0.082063	0.081169	0.088933	0.087743
12	0.181365	0.147474	0.178005	0.168704	0.193112	0.166748	0.201070
13	0.189970	0.156080	0.186834	0.213214	0.163356	0.225176	0.154497
14	0.129298	0.095407	0.124784	0.132548	0.125841	0.138273	0.129002
15	0.196903	0.163012	0.193946	0.191652	0.201940	0.192484	0.206965
16	0.087008	0.053117	0.080012	0.046552	0.113762	0.032462	0.128279
17	0.074722	0.040831	0.066428	0.082134	0.066249	0.091949	0.071311
18	0.200094	0.166204	0.197088	0.175056	0.222258	0.166862	0.233781
19	0.253788	0.219898	0.251264	0.232672	0.273214	0.225923	0.283480
20	0.109773	0.075882	0.104319	0.092005	0.124914	0.090168	0.135414
Nominal	0.033891		0.000648	0.033659	0.033659	0.048087	0.048087
Best	0.053932		0.040875	0.046552	0.025269	0.032462	0.012492
Worst	0.253788		0.251264	0.262983	0.273214	0.275170	0.283480
Mean	0.149901		0.144889	0.147235	0.148923	0.149960	0.152489
Std Dev	0.058521		0.060951	0.062014	0.063687	0.064055	0.065978

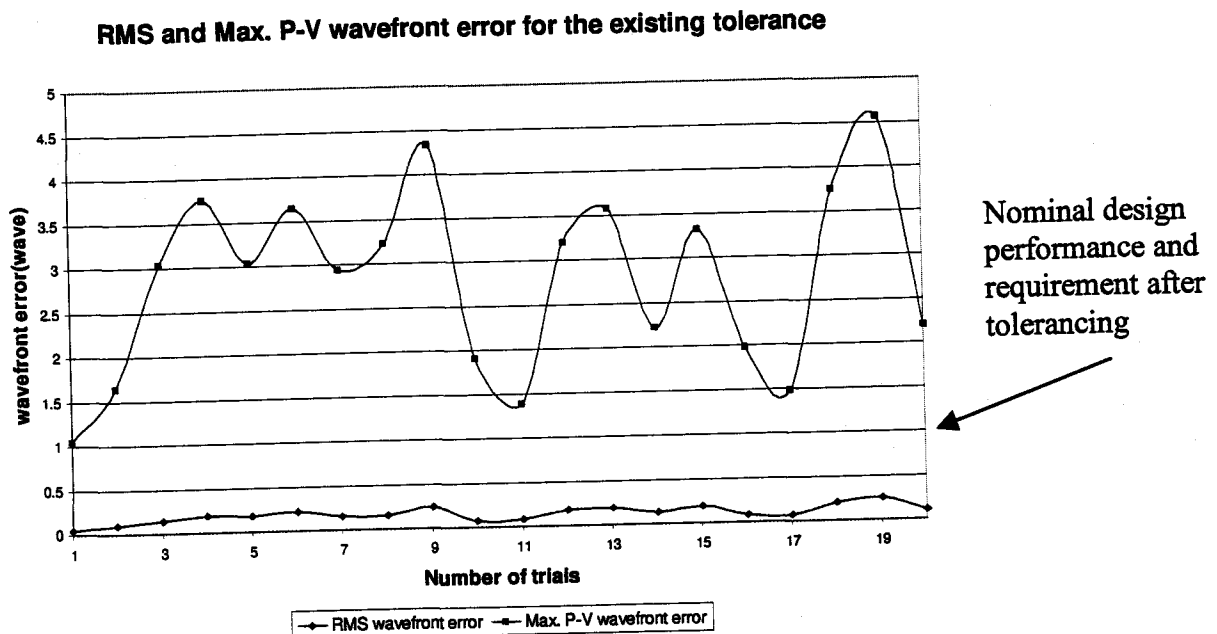
Compensator Statistics:  
 Thickness Surf 3:  
 Nominal : 370.820000  
 Minimum : 365.887679  
 Maximum : 380.921316  
 Mean : 376.308935

Standard Deviation : 3.349394

Thickness Surf 5:  
Nominal : 81.523000  
Minimum : 78.599195  
Maximum : 82.763208  
Mean : 80.067793  
Standard Deviation : 1.047019

90% of Monte Carlo lenses have a merit function below 0.233781.  
50% of Monte Carlo lenses have a merit function below 0.135414.  
10% of Monte Carlo lenses have a merit function below 0.064760.

The following figure shows the RMS wavefront error and maximum P-V wavefront error of the 20 Monte Carlo runs based on the existing tolerances. The maximum P-V wavefront error is 4.5666 wave.



It shows that the P-V wavefront error with the existing tolerances is far larger than 1 wave which is specified in the statement of work.

## 7. Recommended tolerances

The nominal design has a P-V wavefront error of 0.6185 wave on axis and 1.0125 wave @ 0.01146 degree. But, in the statement of the work, the output beam quality after tolerancing is required <1 wave P-V for all the field view. In this report, some recommended tolerances are proposed based on a P-V wavefront error < 1.2 – 1.3 wave after tolerancing.

The following tolerances are recommended for the ETM telescope:

Tolerance	Lens #1		Lens #2		Lens #3	
	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing
Radius(mm) S1:	+/- 3.5	1	+/- 0.1	1	+/- 1.0	1
S2:	+/- 9.9	1	+/- 0.2	1	+/- 1.0	1
Irregularity fringe@0.633μm	0.5	4.2	0.5	4.2	0.25	2.1
TIR(mm)	0.02	0.59	0.05	0.71	0.015	0.375
Element tilt(degree)	+/-0.05	0.89	+/-0.05	0.89	+/-0.015	0.268
Element de-center(mm)	+/- 0.025	0.125	+/- 0.025	0.125	+/- 0.02	0.1
Center thickness(mm)	+/- 0.5	1	+/- 0.2	1	+/- 0.5	1

Compensator: Spacing between lens #1 and lens #2: +/- 12mm;  
Spacing between lens #2 and lens #3: +/- 5mm.

Based on the recommended tolerances, some sensitivity and Monte Carlo analysis have been conducted. Here listed part of the results.

Sensitivity Analysis:  
Worst offenders:

Type	Sf1	Sf2	Value	MF	Change
TIRY	6		-0.007500	0.038571	0.004680
TIRY	6		0.007500	0.038571	0.004680
TIRX	6		0.007500	0.038566	0.004675
TIRX	6		-0.007500	0.038566	0.004675
TEDY	6	7	0.020000	0.038072	0.004181
TEDY	6	7	-0.020000	0.038072	0.004181
TEDX	6	7	-0.020000	0.038067	0.004176
TEDX	6	7	0.020000	0.038067	0.004176
TIRY		4	-0.025000	0.036880	0.002990
TIRY		4	0.025000	0.036880	0.002990
TIRX		4	-0.025000	0.036876	0.002985
TIRX		4	0.025000	0.036876	0.002985
TEDY	2	3	-0.025000	0.036645	0.002754
TEDY	2	3	0.025000	0.036645	0.002754
TEDX	2	3	-0.025000	0.036643	0.002752
TEDX	2	3	0.025000	0.036643	0.002752
TIRY		2	0.010000	0.036022	0.002131
TIRY		2	-0.010000	0.036022	0.002131
TIRX		2	0.010000	0.036020	0.002129
TIRX		2	-0.010000	0.036020	0.002129
TETX	6	7	-0.015000	0.036004	0.002113
TETX	6	7	0.015000	0.036004	0.002113
TETY	6	7	-0.015000	0.036003	0.002112
TETY	6	7	0.015000	0.036003	0.002112
TIRY		3	-0.010000	0.035900	0.002009
TIRY		3	0.010000	0.035900	0.002009
TIRX		3	-0.010000	0.035899	0.002008
TIRX		3	0.010000	0.035899	0.002008
TIRY		5	-0.025000	0.035773	0.001882
TIRY		5	0.025000	0.035773	0.001882
TIRX		5	-0.025000	0.035772	0.001881
TIRX		5	0.025000	0.035772	0.001881
TIRR		3	0.500000	0.034874	0.000983
TIRR		5	0.500000	0.034869	0.000978
TIRR		2	-0.500000	0.034860	0.000969
TETY	2	3	-0.050000	0.034846	0.000955
TETY	2	3	0.050000	0.034846	0.000955
TETX	2	3	0.050000	0.034838	0.000947
TETX	2	3	-0.050000	0.034838	0.000947
TIRR		4	-0.500000	0.034820	0.000929

Nominal RMS Wavefront : 0.033891  
Estimated change : 0.012465  
Estimated RMS Wavefront : 0.046356

Merit Statistics:  
Mean : 0.035051  
Standard Deviation : 0.001400

Compensator Statistics:

Thickness Surf 3:  
 Nominal : 370.820000  
 Minimum : 359.514636  
 Maximum : 377.545718  
 Mean : 370.977887  
 Standard Deviation : 1.560849

Thickness Surf 5:  
 Nominal : 81.523000  
 Minimum : 79.612578  
 Maximum : 84.406983  
 Mean : 81.461519  
 Standard Deviation : 0.478351

Monte Carlo Analysis:

Number of trials: 20

Statistics: Normal Distribution

Trial	Merit	Change	0.000 Field 1	0.700 Field 2	-0.700 Field 3	1.000 Field 4	-1.000 Field 5
1	0.053677	0.019787	0.041639	0.074339	0.014319	0.088585	0.015534
2	0.045193	0.011302	0.029324	0.015292	0.061796	0.026054	0.076178
3	0.040764	0.006873	0.022105	0.040769	0.040365	0.053609	0.053174
4	0.038126	0.004236	0.016710	0.035360	0.040310	0.048745	0.053962
5	0.046035	0.012144	0.030666	0.033740	0.055389	0.043990	0.068506
6	0.055371	0.021480	0.044520	0.071561	0.031325	0.084401	0.034721
7	0.046108	0.012217	0.031410	0.005336	0.064748	0.017448	0.079102
8	0.043288	0.009398	0.025981	0.029837	0.053150	0.041302	0.066876
9	0.039272	0.005382	0.020094	0.024111	0.049722	0.036674	0.063622
10	0.034926	0.001035	0.008542	0.041639	0.025973	0.056026	0.040318
11	0.035985	0.002094	0.013547	0.028576	0.041749	0.041942	0.055531
12	0.037327	0.003436	0.014346	0.035167	0.038956	0.048958	0.052888
13	0.045591	0.011700	0.029878	0.024412	0.059404	0.034414	0.073325
14	0.041198	0.007307	0.024251	0.047333	0.033526	0.060158	0.044991
15	0.041304	0.007413	0.022563	0.056413	0.014037	0.071085	0.028024
16	0.035740	0.001849	0.009685	0.034960	0.036059	0.049207	0.050327
17	0.038348	0.004457	0.021466	0.028990	0.045532	0.040160	0.058098
18	0.041547	0.007657	0.024138	0.057168	0.012371	0.071498	0.025663
19	0.048137	0.014246	0.034415	0.012489	0.066690	0.019943	0.080827
20	0.037359	0.003468	0.021208	0.029362	0.043630	0.040128	0.055666
Nominal	0.033891		0.000648	0.033659	0.033659	0.048087	0.048087
Best	0.034926		0.008542	0.005336	0.012371	0.017448	0.015534
Worst	0.055371		0.044520	0.074339	0.066690	0.088585	0.080827
Mean	0.042265		0.024324	0.036343	0.041453	0.048716	0.053867
Std Dev	0.005553		0.009326	0.017566	0.015989	0.018748	0.017774

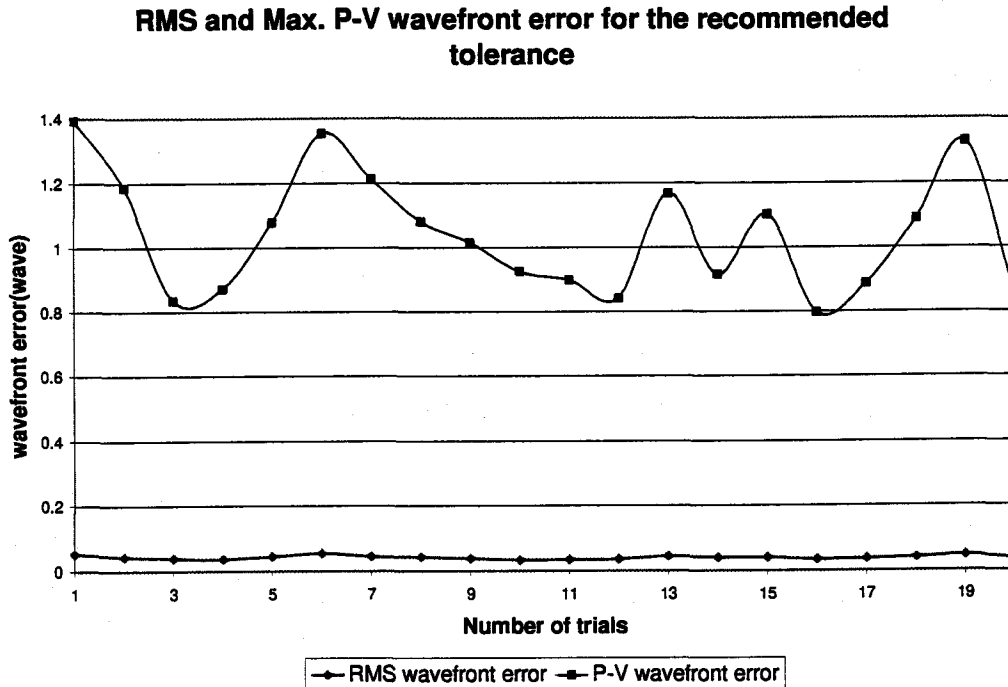
Compensator Statistics:

Thickness Surf 3:  
 Nominal : 370.820000  
 Minimum : 358.819938  
 Maximum : 376.903292  
 Mean : 370.575686  
 Standard Deviation : 5.079136

Thickness Surf 5:  
 Nominal : 81.523000  
 Minimum : 79.896299  
 Maximum : 86.239662  
 Mean : 81.682793  
 Standard Deviation : 1.557858

90% of Monte Carlo lenses have a merit function below 0.076178.  
 50% of Monte Carlo lenses have a merit function below 0.053962.  
 10% of Monte Carlo lenses have a merit function below 0.025663.

The following figure shows the RMS and maximum P-V wavefront error of the 20 Monte Carlo runs with the recommended tolerances. The maximum P-V wavefront error is 1.3949 wave.



## 8. Summary

a) The existing tolerances have been evaluated. It has been found that the existing tolerances are not appropriate to meet the requirements listed in the statement of work. The following tolerances are recommended to ETM.

The recommended tolerances on optical fabrication parameters:

Tolerance	Lens #1		Lens #2		Lens #3	
	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing
Radius(mm) S1:	+/- 3.5	1	+/- 0.1	1	+/- 1.0	1
S2:	+/- 9.9	1	+/- 0.2	1	+/- 1.0	1
Irregularity fringe@0.633μm	0.5	4.2	0.5	4.2	0.25	2.1
TIR(mm) (1.32λ)	0.02	0.59	0.05	0.71	0.015	0.375
Center thickness(mm)	+/- 0.5	1	+/- 0.2	1	+/- 0.5	1

The recommended tolerances on mechanical alignment parameters:

Tolerance	Lens #1		Lens #2		Lens #3	
	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing	Recommended tolerances	Recommended /existing
Element tilt(degree)	+/- 0.05	0.89	+/- 0.05	0.89	+/- 0.015	0.268
Element de-center(mm)	+/- 0.025	0.125	+/- 0.025	0.125	+/- 0.02	0.1

Compensator: Spacing between lens #1 and lens #2: +/- 12mm; *focus*  
 Spacing between lens #2 and lens #3: +/- 5mm.

*preset to nominal*

b) The tolerances on diameter should be determined together with mechanical housing. It is not allowed to cause the resultant error larger than what are specified in the recommended tolerances on mechanical alignment parameters.

c) It is advisable to fit vendor test plates for all the lens radii.

## 9. Discussion

The relationship among surface tilt, surface de-center and TIR

For a spherical lens, surface tilt, surface de-center and TIR are three related fabrication errors. The relationship can be shown using a simple plano-convex lens. Assuming surface radius = R, lens aperture = D and surface de-center = d. When d is quite small compared with the surface radius. The surface tilt  $\alpha$  can be obtained as:

$$\alpha = d/R$$

The TIR can be found as:

$$\text{TIR} = [R^2 - (D/2 - d)]^{1/2} - [R^2 - (D/2 + d)]^{1/2}$$

Therefore, only one of the three needs to be specified for a spherical lens.