LIGO-T980113-00-D

Reflective

# Report on the Tolerance Analysis of PO 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 PO 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. In addition to the tolerance requirements listed in the statement of work, some other important issues of irregularity modeling and analysis have also been addressed in this report.

## 3. Performance requirements

Beam reduction = 8X;
Clear aperture diameter >156mm (no vignetting);
Output beam quality: P-V wavefront distortion < 0.25 wave @ 1064nm for the field of view = $\pm 5 \times 10^{-4}$ rad ($\pm 0.0286°$).

## 4. Tolerance requirements

Tolerance on optical fabrication parameters:

- Surface base radii;
- Conic constant;
- Tilt, with reference to back surface;
- Center off-set;
- Diameter;
- Edge thickness.

Tolerance on mechanical alignment parameters:

- Parallelism of back surface of mirror to optical reference surface;
- Lateral displacement of mirror centerline from input optical axis;
- Rotation of mirror about the mirror centerline;
- Tilt of mirror, with respect to optical reference surface.

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

| Tolerance | Primary mirror | Secondary Mirror |
|---|---|---|
| Radius | +/- 30mm | +/- 4.0mm |
| Power | 0.12 fringe @0.633μm | 0.12 fringe @0.633μm |
| Irregularity | 0.06 fringe @0.633μm | 0.06 fringe @0.633μm |
| Conic constant | +/- 0.002 | +/- 0.002 |
| Surface tilt | +/- 0.003 degree | +/-0.003 degree |
| De-center | +/- 0.12 mm | +/- 0.01 mm |
| Diameter | -0.1/0.0 mm | -0.1/0.0 mm |
| Thickness | +/- 0.5 mm | +/- 0.5 mm |

Compensator: Distance between primary and secondary mirrors: +/- 25mm;
Tilt of the secondary mirror: +/- 0.05°;
De-center of the secondary mirror: +/- 0.2mm.

## 6. Evaluations on the existing tolerance

In the following evaluation, some of the element tolerances have been assigned with certain reasonable values because they are not available in the drawings. Those assumed tolerances are preceeded with "*".

| Tolerance | Primary mirror | Secondary Mirror |
|---|---|---|
| Radius | +/- 30mm | +/- 4.0mm |
| Irregularity | 0.06 fringe @0.633μm | 0.06 fringe @0.633μm |
| Conic constant | +/- 0.002 | +/- 0.002 |
| Surface tilt | +/- 0.003 degree | +/-0.003 degree |
| Surface de-center | +/- 0.12 mm | +/- 0.01 mm |
| *Element de-center | +/- 0.12 mm | +/- 0.04 mm |
| *Element tilt | +/- 0.01 degree | +/- 0.01 degree |

Three types of compensators have been used:
(1) distance between two mirrors: +/-25mm;
(2) tilt of the secondary mirror: +/- 0.05 degree;
(3) de-center of the secondary mirror: +/-0.2mm.

Results of the sensitivity analysis and 20 trials Monte Carlo runs are listed below:

```
Sensitivity Analysis:
Worst offenders:
Type  Sf1 Sf2       Value          MF        Change
TCON        5    0.002000     0.000473     0.000277
TCON        5   -0.002000     0.000443     0.000247
TETX    4   5   -0.010000     0.000410     0.000214
TETY    4   5   -0.010000     0.000388     0.000192
TETY    4   5    0.010000     0.000366     0.000170
TETX    4   5    0.010000     0.000343     0.000147
```

decenter RMS change in RMS

| | | | | | |
|---|---|---|---|---|---|
| TEDY | 4 | 5 | -0.120000 | 0.000255 | 0.000059 |
| TEDY | 5 | 5 | -0.120000 | 0.000255 | 0.000059 |
| TEDX | 5 | 5 | 0.120000 | 0.000239 | 0.000042 |
| TEDX | 4 | 5 | 0.120000 | 0.000239 | 0.000042 |
| TETX | 5 | 5 | -0.003000 | 0.000234 | 0.000038 |
| TETY | 5 | 5 | -0.003000 | 0.000223 | 0.000027 |
| TEDX | 5 | 5 | -0.120000 | 0.000221 | 0.000025 |
| TEDX | 4 | 5 | -0.120000 | 0.000221 | 0.000025 |
| TIRR | | 9 | 0.060000 | 0.000217 | 0.000020 |
| TCON | | 9 | -0.002000 | 0.000214 | 0.000018 |
| TETY | 5 | 5 | 0.003000 | 0.000212 | 0.000016 |
| TEDY | 8 | 9 | 0.040000 | 0.000210 | 0.000014 |
| TIRR | | 5 | -0.060000 | 0.000208 | 0.000012 |
| TEDX | 8 | 9 | -0.040000 | 0.000204 | 0.000007 |
| TEDY | 5 | 5 | 0.120000 | 0.000202 | 0.000006 |
| TEDY | 4 | 5 | 0.120000 | 0.000202 | 0.000006 |
| TETX | 5 | 5 | 0.003000 | 0.000201 | 0.000005 |
| TEDY | 9 | 9 | 0.010000 | 0.000199 | 0.000003 |
| TRAD | | 9 | 4.000000 | 0.000199 | 0.000002 |
| TEDX | 9 | 9 | -0.010000 | 0.000197 | 0.000001 |
| TEDX | 8 | 9 | 0.040000 | 0.000197 | 0.000001 |
| TETX | 9 | 9 | 0.003000 | 0.000196 | 0.000000 |
| TRAD | | 5 | -30.000000 | 0.000196 | 0.000000 |

↑ 40 worst offenders

Nominal RMS Wavefront : 0.000196
Estimated change : 0.000378
Estimated RMS Wavefront : 0.000574

Merit Statistics:
Mean : 0.000232
Standard Deviation : 0.000070

Monte Carlo Analysis:
Number of trials: 20

Statistics: Normal Distribution

| | | | 0.0, 0.0 | 0.0, 1.0 | 0.0, -1.0 | 1.0, 0.0 | -1.0, 0.0 |
|---|---|---|---|---|---|---|---|
| Trial | Merit | Change | Field 1 | Field 2 | Field 3 | Field 4 | Field 5 |
| 1 | 0.000297 | 0.000101 | 0.000387 | 0.000290 | 0.000253 | 0.000267 | 0.000268 |
| 2 | 0.000295 | 0.000098 | 0.000402 | 0.000287 | 0.000228 | 0.000292 | 0.000229 |
| 3 | 0.000285 | 0.000088 | 0.000413 | 0.000265 | 0.000225 | 0.000234 | 0.000243 |
| 4 | 0.000219 | 0.000023 | 0.000379 | 0.000216 | 0.000103 | 0.000118 | 0.000161 |
| 5 | 0.000246 | 0.000050 | 0.000380 | 0.000175 | 0.000221 | 0.000185 | 0.000210 |
| 6 | 0.000399 | 0.000202 | 0.000482 | 0.000412 | 0.000343 | 0.000363 | 0.000378 |
| 7 | 0.000335 | 0.000138 | 0.000443 | 0.000279 | 0.000329 | 0.000286 | 0.000310 |
| 8 | 0.000271 | 0.000075 | 0.000376 | 0.000223 | 0.000247 | 0.000258 | 0.000218 |
| 9 | 0.000205 | 0.000009 | 0.000385 | 0.000115 | 0.000135 | 0.000116 | 0.000134 |
| 10 | 0.000422 | 0.000226 | 0.000517 | 0.000382 | 0.000403 | 0.000412 | 0.000380 |
| 11 | 0.000235 | 0.000039 | 0.000386 | 0.000169 | 0.000184 | 0.000155 | 0.000201 |
| 12 | 0.000205 | 0.000009 | 0.000380 | 0.000140 | 0.000120 | 0.000131 | 0.000127 |
| 13 | 0.000277 | 0.000080 | 0.000423 | 0.000193 | 0.000265 | 0.000191 | 0.000243 |
| 14 | 0.000324 | 0.000128 | 0.000443 | 0.000285 | 0.000291 | 0.000283 | 0.000289 |
| 15 | 0.000210 | 0.000014 | 0.000383 | 0.000114 | 0.000157 | 0.000133 | 0.000137 |
| 16 | 0.000311 | 0.000115 | 0.000430 | 0.000241 | 0.000312 | 0.000265 | 0.000270 |
| 17 | 0.000267 | 0.000071 | 0.000414 | 0.000256 | 0.000179 | 0.000190 | 0.000224 |
| 18 | 0.000269 | 0.000072 | 0.000390 | 0.000208 | 0.000251 | 0.000237 | 0.000214 |
| 19 | 0.000300 | 0.000104 | 0.000432 | 0.000232 | 0.000305 | 0.000244 | 0.000239 |
| 20 | 0.000427 | 0.000231 | 0.000513 | 0.000363 | 0.000444 | 0.000380 | 0.000417 |
| Nominal | 0.000196 | | 0.000378 | 0.000111 | 0.000112 | 0.000112 | 0.000112 |
| Best | 0.000205 | | 0.000376 | 0.000114 | 0.000103 | 0.000116 | 0.000127 |
| Worst | 0.000427 | | 0.000517 | 0.000412 | 0.000444 | 0.000412 | 0.000417 |
| Mean | 0.000290 | | 0.000418 | 0.000242 | 0.000250 | 0.000237 | 0.000245 |
| Std Dev | 0.000065 | | 0.000042 | 0.000080 | 0.000088 | 0.000084 | 0.000079 |

The sensitivity analysis results show that some of the existing tolerances are unnecessarily tight. For example, the tolerances on the primary and secondary mirror surface tilt = +/-0.003°; the de-center of the secondary mirror = +/- 0.01mm; the surface irregularity on both the primary and secondary surfaces = +/-0.006 fringe, etc.

Due to the tight tolerances, some of the compensator ranges are not fully utilized. The existing and the calculated compensator ranges are listed in the following table.

| Compensator ranges | Existing | Calculated |
|---|---|---|
| Distance between two mirrors | +/- 25mm | +/-15mm |
| Element tilt of the secondary | +/-0.05degree | +/-0.025degree |
| De-center of the secondary | +/-0.2mm | +/-0.2mm |

Based on the Monte Carlo analysis with 20 trials, the maximum P-V wavefront error is 0.0056 wave, which is much smaller than the 0.25 wave. This means that some of the exiting tolerances can be loosened.

## 7. Recommended tolerances

The following tolerances are recommended for the PO telescope:

| Tolerance | Primary mirror | Recommended /existing | Secondary Mirror | Recommended /existing |
|---|---|---|---|---|
| Radius(mm) | +/- 30 | 1 | +/- 4.0 | 1 |
| Irregularity(fringe@0.633μm) | 0.25 | 4.2 | 0.25 | 4.2 |
| Conic constant | +/- 0.002 | 1 | +/- 0.02 | 10 |
| Surface tilt(degree) | +/- 0.03 | 10 | +/-0.05 | 16.67 |
| Surface de-center(mm) | +/- 0.12 | 1 | +/- 0.1 | 10 |
| Element de-center(mm) | +/-0.12 | N.A. | +/- 0.1 | N.A. |
| Element tilt(degree) | +/-0.05 | N.A. | +/-0.05 | N.A. |

The recommended compensator ranges:

- distance between the two mirrors: +/-15mm;
- de-center of the secondary: +/-0.2mm;
- tilt of the secondary: +/-0.055degree;

The compensator is at the secondary mirror. Theoretical speaking, one can perfectly compensate the element tilt and de-center of the both mirrors. However, practically, there are always some residual errors. Contributors to residual errors in secondary adjustment include absolute accuracy of the test setup and finite precision in the actual adjustment mechanism(s) for the secondary. An assumption that has been made for the recommended tolerance calculation is that: the residual error is equal to 20% of the total compensation range.

With the recommended tolerances, the results of the sensitivity analysis and 20 trials Monte Carlo runs are shown below:

```
Mode                : Sensitivities
Sampling            : 3
Optimization Cycles : Automatic mode
```

Merit: RMS Wavefront Error in waves

Nominal Merit Function (MF) is 0.00018891

Test wavelength: 0.6330

Fields: User Defined Angle in degrees

| # | X-Field | Y-Field | Weight | VDX | VDY | VCX | VCY |
|---|---|---|---|---|---|---|---|
| 1 | 0.000E+000 | 0.000E+000 | 1.000E+000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2 | 0.000E+000 | 2.860E-002 | 1.000E+000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3 | 0.000E+000 | -2.860E-002 | 1.000E+000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | 2.860E-002 | 0.000E+000 | 1.000E+000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 5 | -2.860E-002 | 0.000E+000 | 1.000E+000 | 0.000 | 0.000 | 0.000 | 0.000 |

Sensitivity Analysis:

Worst offenders:

| Type | Sf1 | Sf2 | Value | MF | Change |
|---|---|---|---|---|---|
| TETX | 4 | 5 | 0.050000 | 0.035574 | 0.035386 |
| TETX | 4 | 5 | -0.050000 | 0.035292 | 0.035103 |
| TETY | 4 | 5 | 0.050000 | 0.034136 | 0.033947 |
| TETY | 4 | 5 | -0.050000 | 0.034136 | 0.033947 |
| TETX | 5 | 5 | -0.030000 | 0.015631 | 0.015442 |
| TETX | 5 | 5 | 0.030000 | 0.015478 | 0.015289 |
| TETY | 5 | 5 | 0.030000 | 0.014942 | 0.014753 |
| TETY | 5 | 5 | -0.030000 | 0.014942 | 0.014753 |
| TCON | | 10 | 0.020000 | 0.000553 | 0.000364 |
| TCON | | 10 | -0.020000 | 0.000551 | 0.000362 |
| TCON | | 5 | 0.002000 | 0.000439 | 0.000250 |
| TCON | | 5 | -0.002000 | 0.000439 | 0.000250 |
| TIRR | | 5 | -0.250000 | 0.000247 | 0.000058 |
| TIRR | | 5 | 0.250000 | 0.000246 | 0.000057 |
| TIRR | | 10 | 0.250000 | 0.000227 | 0.000038 |
| TIRR | | 10 | -0.250000 | 0.000227 | 0.000038 |
| TRAD | | 10 | 4.000000 | 0.000191 | 0.000002 |
| TRAD | | 5 | -30.000000 | 0.000189 | 0.000000 |
| TETY | 10 | 10 | -0.050000 | 0.000189 | 0.000000 |
| TEDX | 9 | 10 | 0.040000 | 0.000189 | 0.000000 |
| TEDY | 5 | 5 | -0.120000 | 0.000189 | 0.000000 |
| TEDY | 4 | 5 | 0.120000 | 0.000189 | 0.000000 |
| TEDX | 5 | 5 | 0.120000 | 0.000189 | 0.000000 |
| TEDX | 5 | 5 | -0.120000 | 0.000189 | 0.000000 |
| TEDY | 5 | 5 | 0.120000 | 0.000189 | 0.000000 |
| TEDX | 4 | 5 | -0.120000 | 0.000189 | 0.000000 |
| TEDY | 4 | 5 | -0.120000 | 0.000189 | 0.000000 |
| TETY | 8 | 10 | -0.050000 | 0.000189 | 0.000000 |
| TEDX | 4 | 5 | 0.120000 | 0.000189 | 0.000000 |
| TEDY | 10 | 10 | 0.100000 | 0.000189 | 0.000000 |
| TEDX | 10 | 10 | 0.100000 | 0.000189 | -0.000000 |
| TETY | 8 | 10 | 0.050000 | 0.000189 | -0.000000 |
| TEDX | 8 | 10 | 0.100000 | 0.000189 | -0.000000 |
| TETX | 10 | 10 | -0.050000 | 0.000189 | -0.000000 |
| TETX | 8 | 10 | -0.050000 | 0.000189 | -0.000000 |

Nominal RMS Wavefront : 0.000189
Estimated change : 0.053372
Estimated RMS Wavefront : 0.053561

Merit Statistics:
Mean : 0.003638
Standard Deviation : 0.009291

Monte Carlo Analysis:
Number of trials: 20

Statistics: Normal Distribution

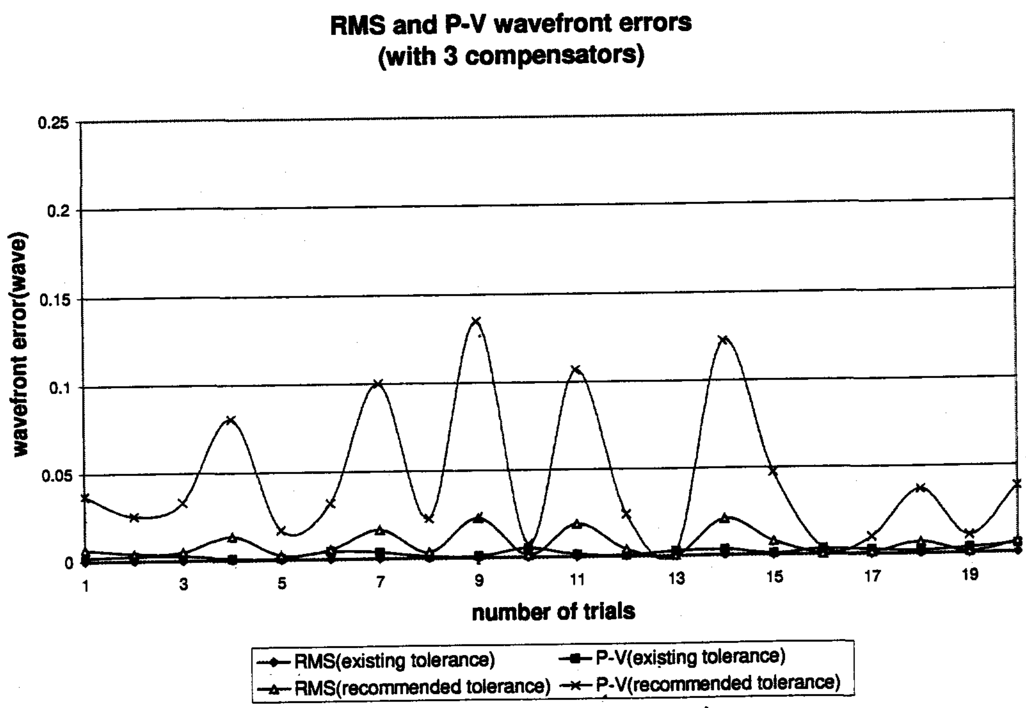
| | | | 0.0, 0.0 | 0.0, 1.0 | 0.0, -1.0 | 1.0, 0.0 | -1.0, 0.0 |
|---|---|---|---|---|---|---|---|
| Trial | Merit | Change | Field 1 | Field 2 | Field 3 | Field 4 | Field 5 |
| 1 | 0.006524 | 0.006335 | 0.006346 | 0.006651 | 0.006435 | 0.006747 | 0.006430 |
| 2 | 0.004313 | 0.004124 | 0.004240 | 0.004164 | 0.004360 | 0.004184 | 0.004601 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 | 0.004973 | 0.004784 | 0.004947 | 0.004749 | 0.005254 | 0.005019 | 0.004884 |
| 4 | 0.013472 | 0.013283 | 0.013409 | 0.013511 | 0.013300 | 0.013608 | 0.013530 |
| 5 | 0.002794 | 0.002605 | 0.002693 | 0.002795 | 0.002997 | 0.002499 | 0.002954 |
| 6 | 0.005739 | 0.005550 | 0.005683 | 0.005580 | 0.005888 | 0.005715 | 0.005823 |
| 7 | 0.016624 | 0.016435 | 0.016590 | 0.016671 | 0.016556 | 0.016790 | 0.016508 |
| 8 | 0.003700 | 0.003511 | 0.003677 | 0.003710 | 0.003639 | 0.003784 | 0.003688 |
| 9 | 0.022721 | 0.022532 | 0.022660 | 0.022658 | 0.022676 | 0.023221 | 0.022383 |
| 10 | 0.001531 | 0.001342 | 0.001446 | 0.001293 | 0.001689 | 0.001672 | 0.001517 |
| 11 | 0.018865 | 0.018676 | 0.018814 | 0.018800 | 0.019022 | 0.018883 | 0.018805 |
| 12 | 0.004044 | 0.003855 | 0.004043 | 0.003977 | 0.004116 | 0.003999 | 0.004083 |
| 13 | 0.000328 | 0.000139 | 0.000406 | 0.000271 | 0.000432 | 0.000289 | 0.000169 |
| 14 | 0.020925 | 0.020736 | 0.020877 | 0.020920 | 0.020842 | 0.020866 | 0.021117 |
| 15 | 0.007910 | 0.007722 | 0.007867 | 0.007833 | 0.007965 | 0.008166 | 0.007714 |
| 16 | 0.000531 | 0.000342 | 0.000390 | 0.000864 | 0.000675 | 0.000205 | 0.000113 |
| 17 | 0.001245 | 0.001056 | 0.000702 | 0.001869 | 0.001693 | 0.000704 | 0.000639 |
| 18 | 0.006729 | 0.006540 | 0.006715 | 0.006403 | 0.007014 | 0.006909 | 0.006584 |
| 19 | 0.001145 | 0.000956 | 0.000740 | 0.001304 | 0.001454 | 0.000973 | 0.001114 |
| 20 | 0.006422 | 0.006233 | 0.006275 | 0.006272 | 0.006272 | 0.006846 | 0.006424 |
| Nominal | 0.000189 | | 0.000378 | 0.000095 | 0.000094 | 0.000095 | 0.000095 |
| Best | 0.000328 | | 0.000390 | 0.000271 | 0.000432 | 0.000205 | 0.000113 |
| Worst | 0.022721 | | 0.022660 | 0.022658 | 0.022676 | 0.023221 | 0.022383 |
| Mean | 0.007527 | | 0.007426 | 0.007515 | 0.007614 | 0.007554 | 0.007454 |
| Std Dev | 0.006878 | | 0.006919 | 0.006847 | 0.006798 | 0.007000 | 0.006900 |

90% of Monte Carlo lenses have a merit function below 0.018805.
50% of Monte Carlo lenses have a merit function below 0.004884.
10% of Monte Carlo lenses have a merit function below 0.000169.

Based on the above 20 trials results, the maximum RMS wavefront error and P-V wavefront error are 0.022721 wave and 0.1349 wave respectively.

The following figure presents the RMS and P-V wavefront error for both existing tolerances and recommended tolerances with 20 Monte Carlo trails.



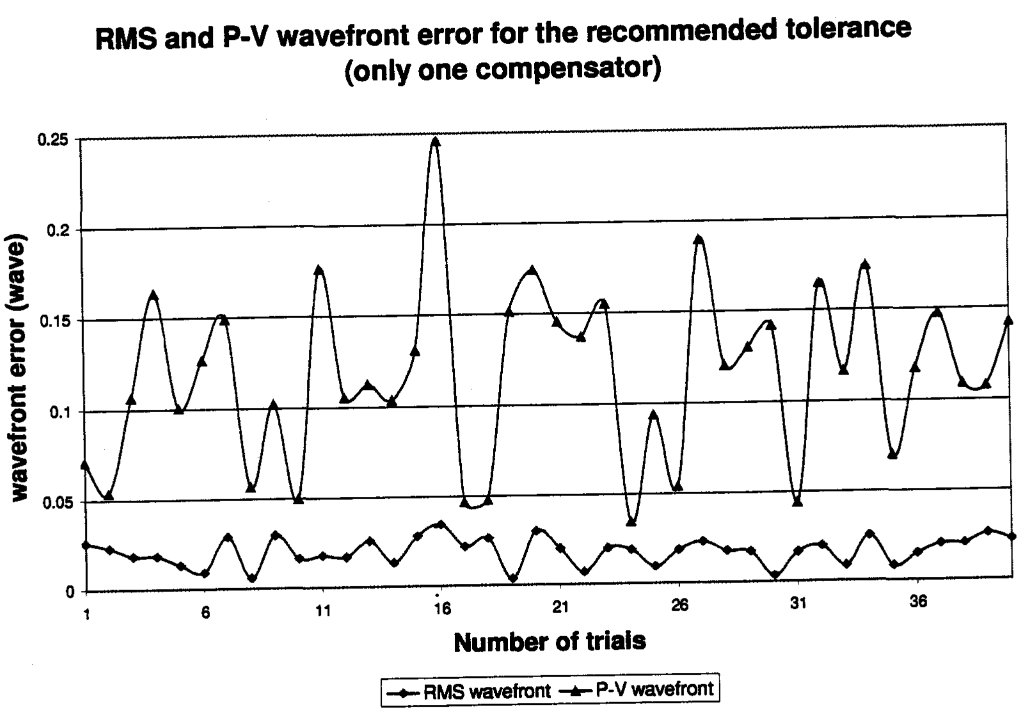
As the maximum P-V wavefront error is still far below 0.25 wave, it shows that some tolerances on optical elements can be further loosened if there are enough compensation ranges.

In addition to the analysis based on full compensators, some calculations have been carried out based on the recommended tolerances with only one compensator, which is the distance between the two mirrors. A result of Monte Carlo analysis with 40 trials is printed below:

```
Monte Carlo Analysis:
Number of trials: 40
Statistics: Normal Distribution
Nominal     0.000189              0.000378   0.000095   0.000095   0.000095   0.000095
Best        0.003555              0.003513   0.003609   0.003492   0.003589   0.003544
Worst       0.034532              0.034472   0.034870   0.034096   0.034757   0.034462
Mean        0.018736              0.018699   0.018950   0.018528   0.018737   0.018758
Std Dev     0.007519              0.007513   0.007592   0.007437   0.007560   0.007502

90% of Monte Carlo lenses have a merit function below 0.028022.
50% of Monte Carlo lenses have a merit function below 0.018658.
10% of Monte Carlo lenses have a merit function below 0.007382.
```

The maximum RMS wavefront error is 0.034532 wave and the maximum P-V wavefront error is 0.2462 wave. The following figure shows the relationship between the RMS wavefront and P-V wavefront for the 40 Monte Carlo runs.



Based on the recommended tolerance setting, a Monte Carlo analysis with 500 trials has been conducted. Only the spacing between the two mirrors has been used as compensator. Here below is the summary of the results:

```
Monte Carlo Analysis:
Number of trials: 500

Nominal    0.000189         0.000378   0.000095   0.000095   0.000095   0.000095
Best       0.000814         0.000612   0.000967   0.000729   0.000575   0.000850
Worst      0.047736         0.047672   0.048332   0.047101   0.047935   0.047631
Mean       0.017555         0.017525   0.017724   0.017396   0.017565   0.017559
Std Dev    0.008988         0.008986   0.009099   0.008881   0.008979   0.009002

98% of Monte Carlo lenses have a merit function below 0.041036.
90% of Monte Carlo lenses have a merit function below 0.029818.
50% of Monte Carlo lenses have a merit function below 0.016985.
10% of Monte Carlo lenses have a merit function below 0.005998.
 2% of Monte Carlo lenses have a merit function below 0.002740.
```

Among the 500 trials, the top 9 cases with the largest RMS wavefront error and P-V wavefront error are listed in the following table:

| No. | RMS (wave) | P-V (wave) |
|---|---|---|
| 1 | 0.047736 | 0.2829 |
| 2 | 0.045276 | 0.27 |
| 3 | 0.045179 | 0.2696 |
| 4 | 0.043096 | 0.2581 |
| 5 | 0.042438 | 0.2561 |
| 6 | 0.042177 | 0.2532 |
| 7 | 0.042129 | 0.2427 |
| 8 | 0.041517 | 0.2480 |
| 9 | 0.041148 | 0.2499 |

These results have shown that the above-recommended tolerances would ensure the PO telescope has a P-V wavefront error less than 0.25 wave with about 99% confidence level even with one compensator, which is the spacing between the two mirrors.

## 8. Summary

a) In this tolerance analysis, the exiting tolerances provided by California Inst. of Tech. have been evaluated. The analysis results have shown that some of the existing tolerances are unnecessarily tight and the specified compensation rages are not fully utilized.

b) With the following recommended tolerances and compensator ranges, the existing tolerances have been loosened.

Recommended tolerance on optical fabrication parameters:

| | Primary mirror | Recommended /existing | Secondary mirror | Recommended /existing |
|---|---|---|---|---|
| Radius(mm) | +/-30 | 1 | +/4 | 1 |
| Conic constant | -1+/-0.002 | 1 | -1+/-0.02 | 10 |
| Tilt, with reference to back surface(degree) | +/-0.03 | 10 | +/-0.05 | 16.67 |
| Center off-set(mm) | +/-0.12 | 1 | +/-0.1 | 1 |

Recommended tolerance on mechanical alignment parameters:

| | Primary mirror | Secondary mirror |
|---|---|---|
| Lateral displacement of mirror centerline from input optical axis | +/-0.12mm | +/-0.1mm |
| Rotation of mirror about the mirror centerline | +/-0.2degree | +/-0.2degree |
| Tilt of mirror with respect to optical reference surface (caused by parallelism of back surface of mirror and any other factors) | +/-0.05degree | +/-0.05degree |

Recommended compensator ranges:

distance between the two mirrors: +/-15mm;
de-center of the secondary :+/-0.2mm;
tilt of the secondary: +/-0.055degree.

c) An analysis has also been conducted based on only one compensator, which is the spacing between the two mirrors. The analysis results have shown that the recommended tolerances have 99% probability to meet P-V wavefront error less than 0.25 wave @1.06μm.

d) Rotation about both mirror aperture center and curvature center has been considered. The sensitivity analysis results have shown that it is a very insensitive error.

e) If the telescope assembly tilts with reference to the optical axis, it will also introduce wavefront error. The following table provides the sensitivity of the assembly tilt.

| Assembly tilt about X or Y (degree) | 0 | +/-0.1 | +/-0.2 | +/-0.3 |
|---|---|---|---|---|
| Max. wavefront error (wave) | 0.0016 | 0.033 | 0.1049 | 0.217 |

worst

f) The diameter and edge thickness tolerances only affect the system performance when they are combined with certain mechanical housing. They are very much related to how the two mirrors are mounted. The bottom line to decide these tolerances is that they should not cause the resultant errors larger than what are specified in the above table of the recommended tolerance on mechanical alignment parameters.

## 9. Discussion

a) Surface irregularity modeling and analysis

Fabrication tolerances on a non-spherical system like the PO telescope generally consists of three parts - mirror surface error, null lens or correction optics error and other test equipment uncertainty.

For the case of classic conic sections, correction optics are simple spheres. In fact, for a paraboloid, the spherical corrector has infinite radius (flat). Given a high quality flat mirror, the residual test errors for a paraboloid are expected to be small.

In analyzing the surface irregularity, one must consider the spatial frequency and distribution of the errors. Low frequency errors are generally recognized as classic low-order aberrations such as astigmatism, spherical aberration, etc. The effect of low frequency error may be partially or completely compensated by similar errors in other mirror or by alignment. Middle frequency errors are referred as "waviness" or slope error and have several periods per diameter. High frequency errors are associated with surface scatter characteristics. An example of this error is found in typical diamond-machined surface. Given both mirror surfaces are to be polished, one would expect little contribution from high frequency error. Middle and high frequency error normally cannot be compensated. They are very difficult to model and characterize and are most damaging errors to system performance.

Much research has been conducted on how to model and evaluate the effects of high frequency surface error. The basic intent of this research is to establish a statistical relationship between surface error and MTF degradation or maximum angular blur size. Some researchers have used surface correlation length, while others have used surface slope error or RMS error. A very widely used equation, which was developed by Hufnagel, relates the MTF degradation to a RMS wavefront error. The equation is:

$$T(v)=\exp[-(2\pi W)^2(1-\exp(-2H^2v^2))]$$

Where: $T(v)$ is the MTF degradation factor at spatial frequency $v$;
$W$ is the RMS wavefront error;
$H$ is the Hufnagel constant deccribing the frequency of the error in cycles/diameter of the test piece.

This equation has shown that the MTF reaches a stationary value, for a given RMS wavefront error, at surface spatial frequency greater than 15cycles/diameter.

Some researchers have suggested to use a sinusoidally varying wavefront to represent a surface error. The equation is given below:

$$W(d)=0.5A\lambda \mathrm{Sin}(\pi n d/D)$$

Where: A = Peak-valley amplitude;
$\lambda$ = Wavelength;
n = Number of bumps or highs and lows across wavefront;
D = Extent of wavefront.

The maximum slope of the wavefront can be expressed as:

$$S_{max} = \pi A\lambda n/(2D)$$

The total maximum angular blur size can be obtained as:

$$\alpha= \pi A\lambda n/D$$

If assuming n=3, $\lambda$=1.06 and an uniform distribution of the energy, the total maximum angular blur size becomes:

$$\alpha= \pi A\lambda n/D=10.03A/D$$

If further assuming RMS $\approx$ A/5, an approximative relationship between the total angular blur size and the RMS wavefront error can be established as:

$$\alpha \approx 10.03A/D \approx 50.15RMS/D$$

Conclusion:

- Continuum of surface error frequency, generally categorized as low, middle and high frequency;
- Polished part expected low frequency contributions to dominate;
- Analysis done to date considers low frequency only.