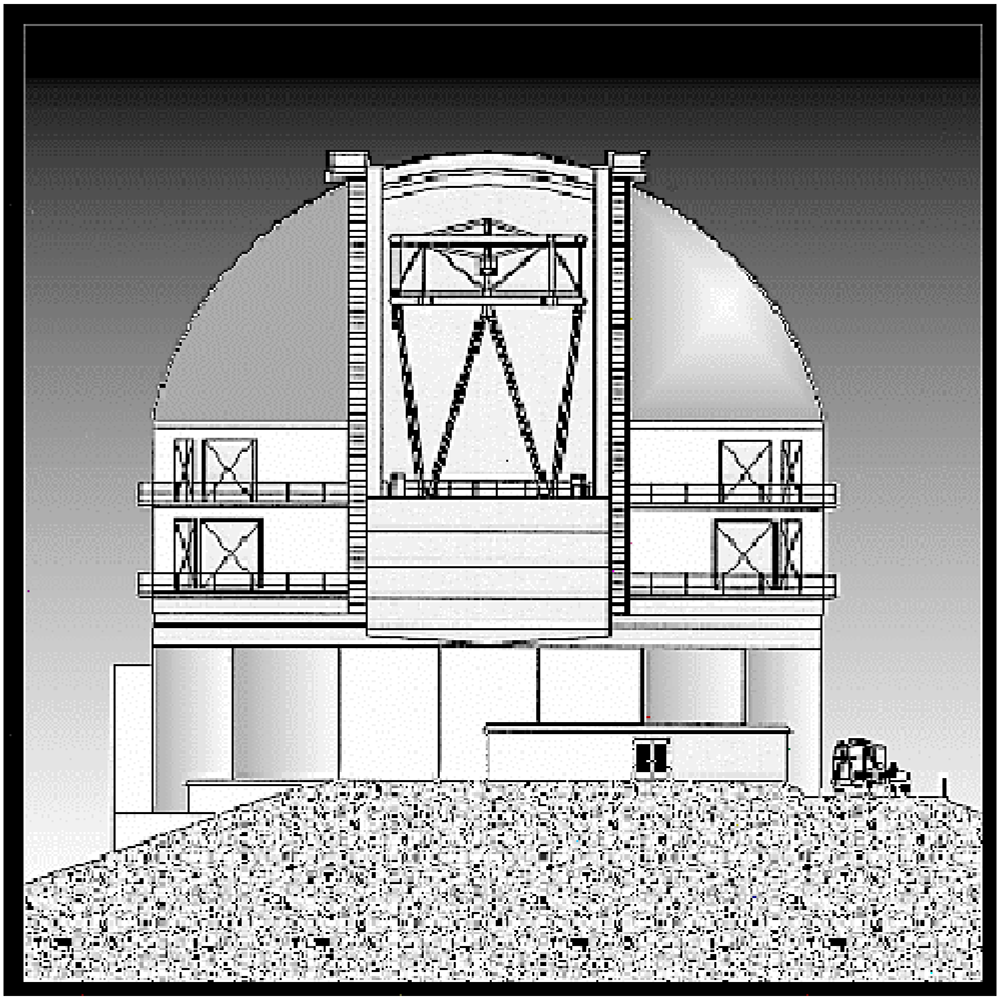
GEMINI
8-M Telescopes
Project

SPE-S-G0041
Version 3.1

Gemini System Error Budget Plan



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January 2, 1997

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Gemini System Error Budget Plan

Change Sheet

Version 2.0 dated:	November 14, 1993	Original Controlled Release
Version 2.1 dated:	February 1, 1994	Approval: ____________________
Version 3.0 dated:	February 1, 1996	Approval: ____________________
Version 3.1 dated:	January 2, 1997	Approval: ____________________

Gemini System Error Budget Plan

Summary of Changes

Version 2.1

1. Excess high wind error budget from enclosure seeing given to wind shake. Analysis shows less effect in higher wind cases.
   - Enclosure seeing changed from .043 to .03 arcseconds
   - Wind shake changed from 0.028 to 0.043 arc seconds
   - for f/16 error budgets only at this time.

2. Allocation of zenith error budget from primary mirror supports changed from 15% of zenith budget to 10%. The zenith allocation of wind shake is increased to 30%.
   - All error budgets

3. Reallocation of Pointing error budget based upon controls group analysis
   - Includes Wind effects

4. Consolidation of Dynamic Image Quality error budget items into to categories:
   - Tilt corrected errors (errors due to correction of image wander by tilt of the secondary)
   - Primary to Secondary Focus errors

   This reflects a more complete finite element model which combines the optical effects previously listed.

Version 3.0

1. Addition of AO System Error Budget.

Version 3.1

1. Revision of AO System Error Budget for 45^{o} case.
2. Addition of Near Infrared Imager top level error budget.

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1. Introduction

This document describes the Gemini system error budget as it exists and how it will evolve as the design and fabrication phases of the program progress. The initial error budget has been generated from the top down (from the science requirements). There will also be an ongoing effort to track the errors from the bottom up. This will aid in identifying critical areas of concern. The resolution of conflicts will involve a continual process of review and comparison of the top down and bottom up approaches, modifying both as needed to meet the top level requirements in the end. The areas to be covered are:

- Top-down error budget
- Non-AO System
- AO System
- Bottom-up error budget
- Resolution of discrepancies
- Monitoring of performance related subsystem errors

2. Non-AO Top-down Error Budget

The top-down error budgets flow from the Gemini Science Requirements, Version 1.0. Four top-level requirements have been identified, from which the subsystem requirements were derived. The highest priority error budget is based upon the IR f/16 Cassegrain configuration operating at 2.2 microns. It is based on system performance analysis, subsystem error analysis (estimating achievable tolerances or analysis of subsystems, in some cases from a bottoms-up sense), initial estimates of correction possible, and rough estimates of perceived difficulty relative to other tasks. As a top-down approach, this leads to some detailed budgets which do add up to meet the overall system specifications/goals, but also lead to some very tight subsystem/component specifications which may not seem practical at first glance. This will be addressed later in this document under the bottom-up error tracking and how to resolve discrepancies. The budget presented has been revised to clarify some areas and to reflect some of the current analysis being done. This budget will continually be revised as the program progresses to represent the design and to provide a mechanism for relating design and manufacturing changes to the top-level requirements.

2.1 Organization of Budget

The budget is organized into four independent categories which relate to the science requirements. The IR f/16 at 2.2 microns, 1 arcminute field (12 arcminute for track-guide and pointing) case is presented. This represents the top priority and the most stringent requirements. The top level of the budget tree contains these categories from which all other error budgets are derived. The four categories are:

Category	Requirement/Goal	Current # of Sub-categories
1. Image Size	0.1 arcsecond (50%)	32
2. Track-guide	0.02 arcsecond	13
3. Pointing	1 arcsecond rms	29
4. Emissivity	2%	7

These items will remain fixed with the exception of the track-guide requirement. The track-guide top-level requirement is derived from the residual image jitter estimates and how this relates to smearing the image over a given integration time. This is covered in the image size error budget. The separate Track-guide error budget refers only to the low frequency "bias" to tracking (involving maintaining position and alignment of the mirrors). The first imaging budget tree given is for the zenith pointing case. Immediately following, an additional error budget allowance versus zenith angle is shown with an allotment to several areas from the zenith pointing case which may change significantly with pointing angle. This is based upon the allowance of degrading the image quality requirement by the three-fifths power of the secant of the zenith angle as given in the science requirements. This relates to the longer atmospheric path involved as the telescope points down closer to the horizon. Each of the four categories is then broken down to various levels of detail with estimates based upon analysis in some areas or first-cut error budgets in others. These budgets may change during the course of the detailed design and manufacture stage of the program.

The budget presented takes the top-level requirement and breaks it down into identified contributors relating directly to that item. Each of these is subsequently broken down into a third level of contributors and so forth. The most detailed break down contains five levels. Some items are not broken down that far if it was deemed unnecessary to understand the sources.

The Emissivity category was broken down into seven categories. The various sources which contribute to this simply add together (as opposed to rss'd).

2.2 Assumptions made for corrections

Several assumptions were made in the development of this error budget based upon capabilities to manufacture and assemble the system and the corrections which may be made to account for overall system bias or repeatable functions. The assumptions made are listed on the appropriate part of the error budget tree. In general, a combination of corrections based upon analysis, calibration of the system, and real time corrections based upon instrument output or measurement sensor outputs will be needed to meet the system level requirements.

An example of a correction based upon analysis is primary mirror shape changes. This changes with telescope pointing, but may be calculated and compensated for to some degree of accuracy by controlling the primary and secondary mirror positions relative to their mounts and the shape of the primary can be brought back into its desired shape through control of its mounting structure.

Based upon analysis only, some corrections may not be good enough to bring the residual errors to within the budget. For these, calibration of repeatable functions will be needed to further reduce the system residual errors. An example of this is the possibility of measuring the actual primary mirror motion versus telescope pointing and using this to verify/update the control system correction for this motion. Both corrections made by analysis and calibrations are applied through use of look-up tables.

In some cases, residual errors may be random or difficult to calibrate. Here, final closed-loop control of the telescope or its subsystems may be needed to reduce these to an acceptable level. An example here is using closed-loop guiding on a star image to reduce the low and high frequency image motion caused by wind moving/stressing the telescope.

The budget presented does not present details of how to make these corrections, but rather makes some assumptions as to how well these corrections may be performed. The net error after corrections goals are met are the numbers given in this top down budget.

2.3 Error Budget Tree

2.3.1 Image Size

The following imaging error budgets are given in this section:

f/16	2.2 micron	50% encircled energy
		85% encircled energy
	0.5 micron	85% encircled energy
	10 micron	50% encircled energy (chopping)
f/6	0.55 micron	36% encircled energy
		50% encircled energy
		90% encircled energy

22_50P.XLS

ERROR BUDGET FOR f/16 at 50% ENCIRCLED ENERGY, 2.2 MICRONS (High Wind)

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.100 Arc Seconds				
1.1 Static Image Quality		0.088			
1.1.1 Optical Design			0.065		
1.1.1.1 Diffraction Size				0.065	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.043		
1.1.2.1 Primary				0.036	
1.1.2.1.1 Polishing Residuals					0.015
1.1.2.1.2 Support Residuals					0.010
1.1.2.1.3 Thermal Distortion					0.005
1.1.2.1.4 Wind Buffeting					0.030
1.1.2.1.5 Coating Thickness					0.004
1.1.2.2 Secondary				0.021	
1.1.2.2.1 Polishing Residuals					0.015
1.1.2.2.2 Support Residuals					0.010
1.1.2.2.3 Thermal Distortion					0.005
1.1.2.2.4 Wind Buffeting					0.010
1.1.2.2.5 Coating Thickness					0.003
1.1.2.3 Active Control				0.010	
1.1.3 Alignment of Optics			0.015		
1.1.3.1 Secondary Decenter				0.008	
1.1.3.2 Secondary Defocus				0.010	
1.1.3.3 Secondary Tilt				0.008	
1.1.4 Self Induced Seeing			0.038		
1.1.4.1 Enclosure				0.030	
1.1.4.2 Telescope (thermal seeing)				0.024	
1.1.4.2.1 Primary Mirror Delta T					0.010
1.1.4.2.2 Secondary Mirror Delta T					0.004
1.1.4.2.3 OSS Structure Delta T					0.015
1.1.4.2.4 CR/ISS Delta T					0.015
1.2 Dynamic Image Quality		0.019			
1.2.1 Dynamic Optical Alignment			0.016		
1.2.1.1 Tilt correction errors				0.012	
1.2.1.2 Primary Secondary Defocus				0.010	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.010		
1.3 Image Smear		0.044			
1.3.1 Wind Shake			0.043		
1.3.2 Measure Error			0.003		
1.3.3 Other Errors			0.011		

2.3.1.1 Error budget versus zenith angle

The tables and graphs on the following pages give the additional error budget allowance versus zenith pointing angle. Since many items on the error budget are not expected to change randomly versus pointing angle, the additional top-level allowance leads to significant additional error allowances for the few areas which may change significantly. The items presented represent a first-cut list plus a large reserve (or misc.) to be allocated as further analysis indicates other sources which present trouble versus zenith pointing angle. The preliminary list includes:

- Primary mirror support system
- Wind deformations of the primary mirror
- Secondary support system
- Wind deformations of the secondary mirror
- Primary to secondary defocus due to wind buffeting

The value shown for the zenith pointing case (0 degrees) matches the budget previously presented. A similar section follows each imaging error budget presented.

Also given in this section is a preliminary error budget for 10 micron chopping requirement. The current prediction is 0.35 arc seconds, but many items are under review. Three major areas have changed from the 2.2 micron case:

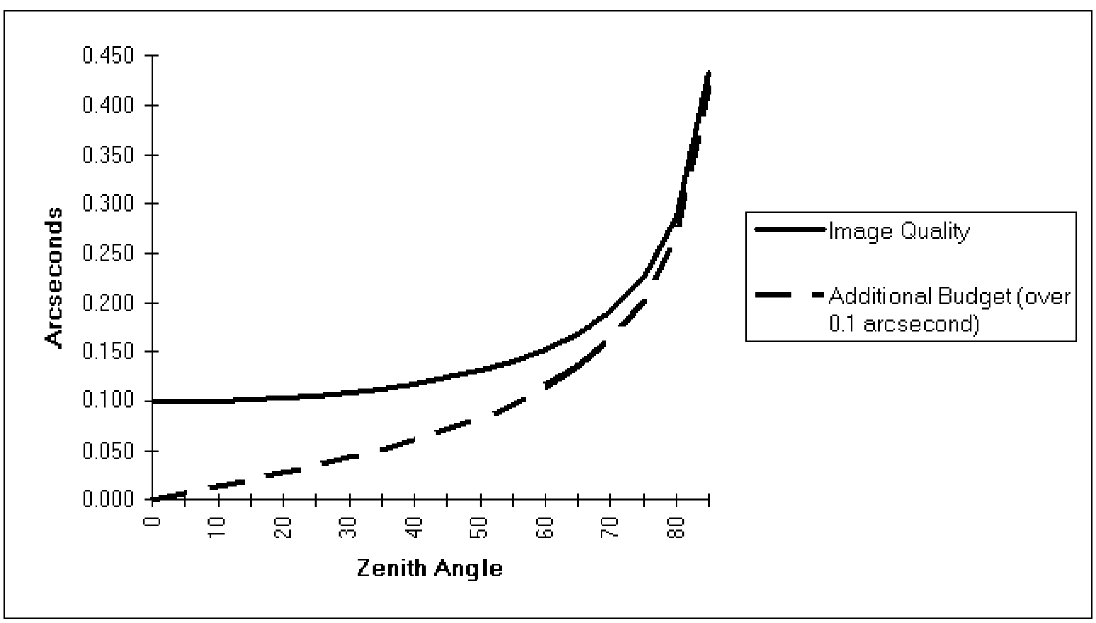
- Coma due to maximum chop angle: 0.15 arc sec contribution
- Residual image smear from primary/secondary residual tilt: .08 arc sec
- Support induced deflections in the secondary: 0.03 arc sec

Z1.XLS

IR f/16 Error Budget — **1 arcminute field**
Cassegrain — **vs Zenith Angle**
2.2 microns — **50% encircled energy**

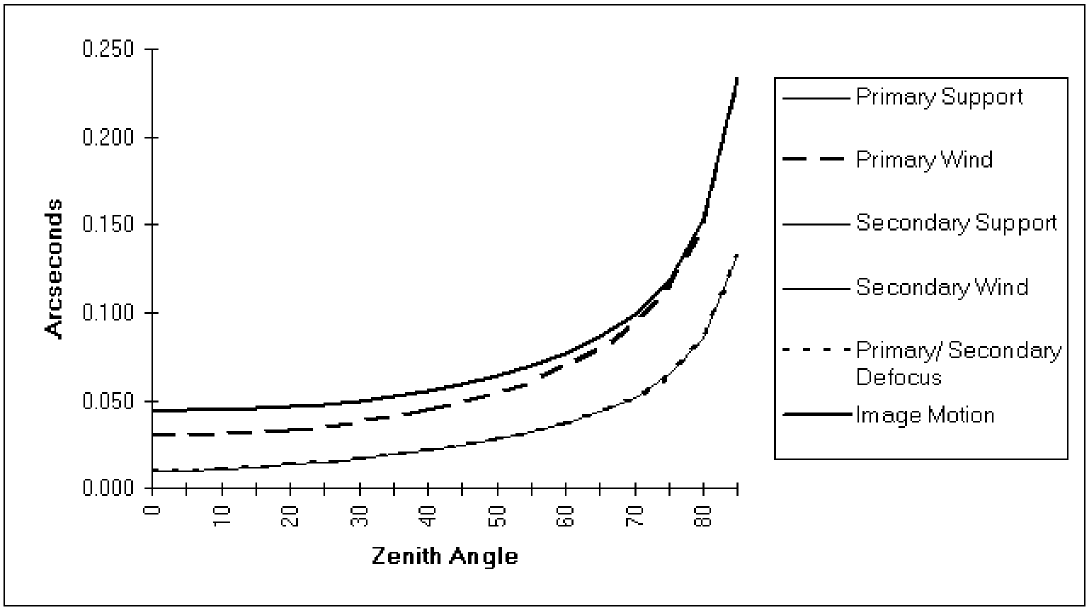
SPEC: 0.1

Degrees	Image Quality	Additional Budget (over 0.1 arcsecond)
0	0.100	0.000
5	0.100	0.007
10	0.101	0.014
15	0.102	0.021
20	0.104	0.028
25	0.106	0.035
30	0.109	0.043
35	0.113	0.052
40	0.117	0.061
45	0.123	0.072
50	0.130	0.084
55	0.140	0.097
60	0.152	0.114
65	0.168	0.135
70	0.190	0.162
75	0.225	0.202
80	0.286	0.268
85	0.432	0.421



IR f/16 Error Budget Z1.XLS **1 arcminute field**
Cassegrain **vs Zenith Angle**
2.2 microns **50% Encircled Energy**

	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.010	0.030	0.010	0.010	0.010	0.044
5	0.010	0.030	0.010	0.010	0.010	0.045
10	0.011	0.031	0.011	0.011	0.011	0.045
15	0.012	0.032	0.012	0.012	0.012	0.046
20	0.013	0.034	0.013	0.013	0.013	0.047
25	0.015	0.036	0.015	0.015	0.015	0.049
30	0.017	0.038	0.017	0.017	0.017	0.050
35	0.019	0.041	0.019	0.019	0.019	0.053
40	0.022	0.045	0.022	0.022	0.022	0.056
45	0.025	0.049	0.025	0.025	0.025	0.059
50	0.028	0.055	0.028	0.028	0.028	0.064
55	0.032	0.061	0.032	0.032	0.032	0.069
60	0.037	0.069	0.037	0.037	0.037	0.077
65	0.044	0.080	0.044	0.044	0.044	0.086
70	0.052	0.094	0.052	0.052	0.052	0.099
75	0.065	0.114	0.065	0.065	0.065	0.119
80	0.085	0.150	0.085	0.085	0.085	0.153
85	0.133	0.232	0.133	0.133	0.133	0.235



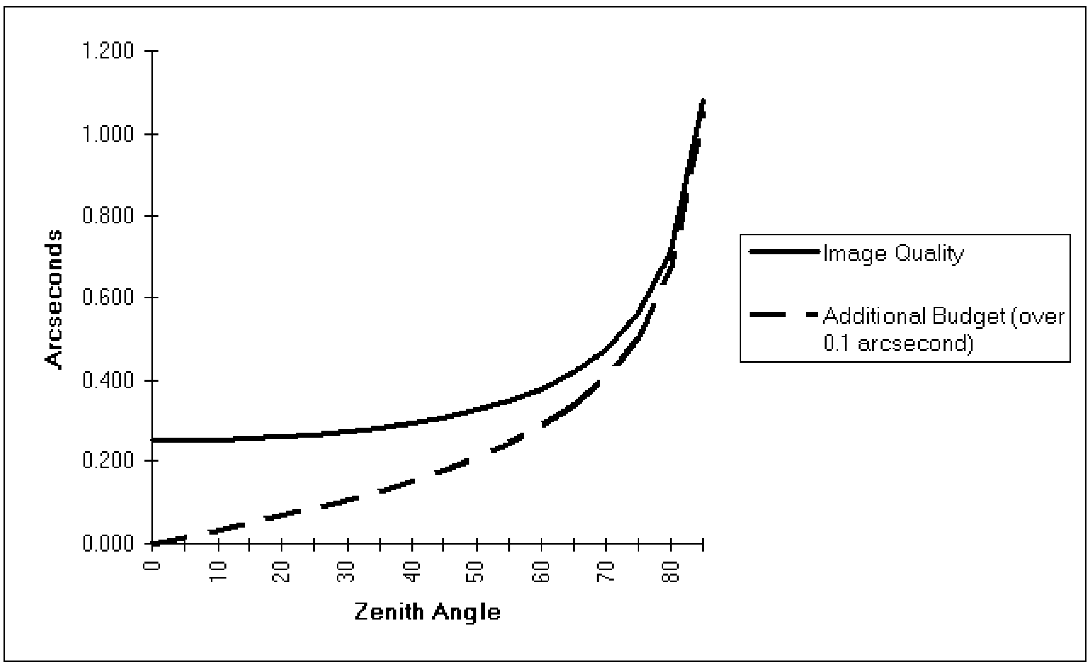
22_85P.XLS

ERROR BUDGET FOR f/16 at 85% ENCIRCLED ENERGY, 2.2 MICRONS (High Wind)

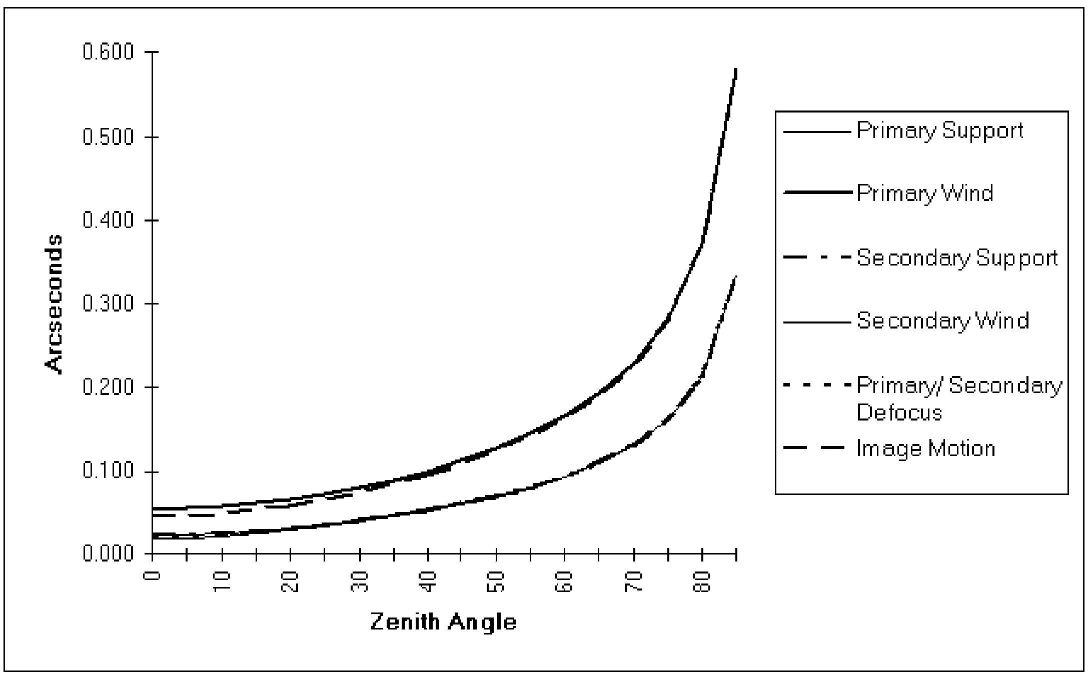
Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.250				
1.1 Static Image Quality		0.242			
1.1.1 Optical Design			0.196		
1.1.1.1 Diffraction Size				0.196	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.117		
1.1.2.1 Primary				0.090	
1.1.2.1.1 Polishing Residuals					0.067
1.1.2.1.2 Support Residuals					0.022
1.1.2.1.3 Thermal Distortion					0.009
1.1.2.1.4 Wind Buffeting					0.054
1.1.2.1.5 Coating Thickness					0.007
1.1.2.2 Secondary				0.074	
1.1.2.2.1 Polishing Residuals					0.067
1.1.2.2.2 Support Residuals					0.022
1.1.2.2.3 Thermal Distortion					0.009
1.1.2.2.4 Wind Buffeting					0.018
1.1.2.2.5 Coating Thickness					0.005
1.1.2.3 Active Control				0.018	
1.1.3 Alignment of Optics			0.038		
1.1.3.1 Secondary Decenter				0.020	
1.1.3.2 Secondary Defocus				0.025	
1.1.3.3 Secondary Tilt				0.020	
1.1.4 Self Induced Seeing			0.072		
1.1.4.1 Enclosure				0.050	
1.1.4.2 Telescope (thermal seeing)				0.052	
1.1.4.2.1 Primary Mirror Delta T					0.023
1.1.4.2.2 Secondary Mirror Delta T					0.027
1.1.4.2.3 OSS Structure Delta T					0.027
1.1.4.2.3 CR/ISS Delta T					0.027
1.2 Dynamic Image Quality		0.039			
1.2.1 Dynamic Optical Alignment			0.028		
1.2.1.1 Tilt Correction Errors				0.021	
1.2.1.2 Primary Secondary Defocus				0.018	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.027		
1.3 Image Smear		0.044			
1.3.1 Wind Shake			0.043		
1.3.2 Measurement Error			0.003		
1.3.3 Other			0.011		

IR f/16 Error Budget	Z1X.XLS	**1 arcminute field**
Cassegrain		**vs Zenith Angle**
2.2 microns		**85% Encircled Energy**

SPEC:	0.25	85% EE
Degrees	Image Quality	Additional Budget (over 0.1 arcsecond)
0	0.250	0.000
5	0.251	0.017
10	0.252	0.034
15	0.255	0.052
20	0.260	0.070
25	0.265	0.088
30	0.273	0.109
35	0.282	0.130
40	0.293	0.153
45	0.308	0.180
50	0.326	0.209
55	0.349	0.243
60	0.379	0.285
65	0.419	0.336
70	0.476	0.405
75	0.563	0.504
80	0.715	0.670
85	1.081	1.052



IR f/16 Error Budget			Z1X.XLS			**1 arcminute field**
Cassegrain						**vs Zenith Angle**
2.2 microns						**85% Encircled Energy**
	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.022	0.054	0.022	0.018	0.018	0.044
5	0.023	0.055	0.023	0.019	0.019	0.045
10	0.024	0.057	0.024	0.021	0.021	0.048
15	0.027	0.061	0.027	0.024	0.024	0.053
20	0.031	0.066	0.031	0.028	0.028	0.059
25	0.036	0.073	0.036	0.033	0.033	0.066
30	0.041	0.080	0.041	0.039	0.039	0.074
35	0.047	0.089	0.047	0.045	0.045	0.084
40	0.053	0.100	0.053	0.052	0.052	0.095
45	0.061	0.112	0.061	0.060	0.060	0.108
50	0.070	0.127	0.070	0.069	0.069	0.123
55	0.080	0.144	0.080	0.079	0.079	0.141
60	0.093	0.165	0.093	0.092	0.092	0.162
65	0.109	0.192	0.109	0.108	0.108	0.190
70	0.130	0.228	0.130	0.129	0.129	0.226
75	0.161	0.281	0.161	0.160	0.160	0.280
80	0.213	0.371	0.213	0.213	0.213	0.369
85	0.333	0.578	0.333	0.333	0.333	0.578



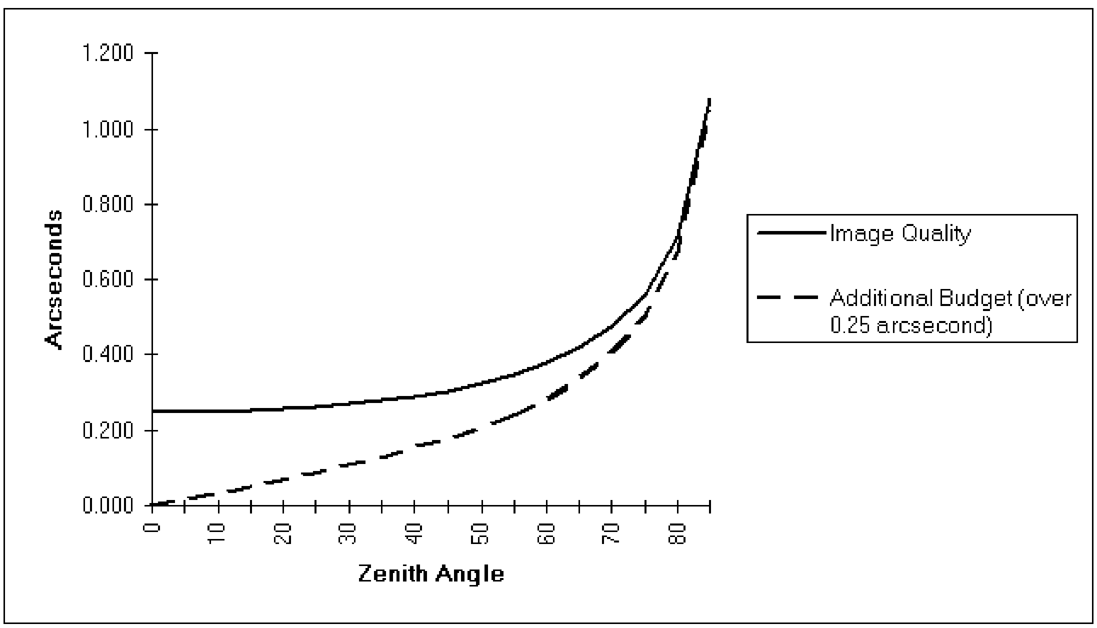
55_85P.XLS

ERROR BUDGET FOR f/16 at 85% ENCIRCLED ENERGY, 0.55 MICRONS **GOALS**

5 arc minute field (High Wind)

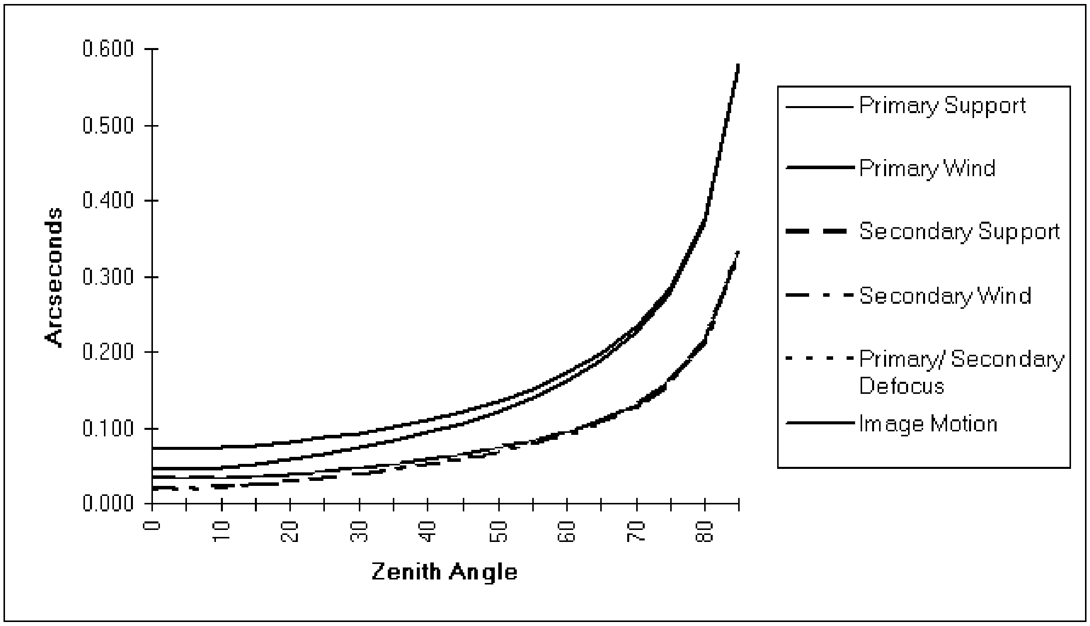
Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.250 Arc Seconds				
1.1 Static Image Quality		0.243			
1.1.1 Optical Design			0.120		
1.1.1.1 Diffraction Size				0.049	
1.1.1.2 Field Angle Position				0.110	
1.1.2 Surface Errors			0.182		
1.1.2.1 Primary				0.137	
1.1.2.1.1 Polishing Residuals					0.110
1.1.2.1.2 Support Residuals					0.033
1.1.2.1.3 Thermal Distortion					0.013
1.1.2.1.4 Wind Buffeting					0.073
1.1.2.1.5 Coating Thickness					0.010
1.1.2.2 Secondary				0.118	
1.1.2.2.1 Polishing Residuals					0.110
1.1.2.2.2 Support Residuals					0.033
1.1.2.2.3 Thermal Distortion					0.013
1.1.2.2.4 Wind Buffeting					0.020
1.1.2.2.5 Coating Thickness					0.010
1.1.2.3 Active Control				0.025	
1.1.3 Alignment of Optics			0.029		
1.1.3.1 Secondary Decenter				0.015	
1.1.3.2 Secondary Defocus				0.020	
1.1.3.3 Secondary Tilt				0.015	
1.1.4 Self Induced Seeing			0.102		
1.1.4.1 Enclosure				0.075	
1.1.4.2 Telescope (thermal seeing)				0.069	
1.1.4.2.1 Primary Mirror Delta T					0.040
1.1.4.2.2 Secondary Mirror Delta T					0.020
1.1.4.2.3 OSS Structure Delta T					0.037
1.1.4.2.4 CR/ISS Delta T					0.037
1.2 Dynamic Image Quality		0.039			
1.2.1 Dynamic Optical Alignment			0.028		
1.2.1.1 Pointing				0.021	
1.2.1.4 Primary Secondary Defocus				0.018	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.027		
1.3 Image Smear		0.044			
1.3.1 Wind Shake			0.043		
1.3.2 Measurement Error			0.003		
1.3.3 Other			0.011		

Optical f/16 Error Budget GOALS Cassegrain 0.55 microns	Z4.XLS	**10 arcminute field vs Zenith Angle 85% Encircled Energy**
SPEC:	0.25	
Degrees	Image Quality	Additional Budget (over 0.25 arcsecond)
0	0.250	0.000
5	0.251	0.017
10	0.252	0.034
15	0.255	0.052
20	0.260	0.070
25	0.265	0.088
30	0.273	0.109
35	0.282	0.130
40	0.293	0.153
45	0.308	0.180
50	0.326	0.209
55	0.349	0.243
60	0.379	0.285
65	0.419	0.336
70	0.476	0.405
75	0.563	0.504
80	0.715	0.670
85	1.081	1.052



Optical f/16 Error Budget Z4.XLS **10 arcminute field**
GOALS **vs Zenith Angle**
Cassegrain **85% Encircled Energy**
0.55 microns

	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.033	0.073	0.033	0.020	0.018	0.044
5	0.033	0.074	0.033	0.021	0.019	0.045
10	0.035	0.075	0.035	0.023	0.021	0.048
15	0.037	0.078	0.037	0.026	0.024	0.053
20	0.040	0.082	0.040	0.030	0.028	0.059
25	0.043	0.088	0.043	0.034	0.033	0.066
30	0.048	0.094	0.048	0.040	0.039	0.074
35	0.053	0.102	0.053	0.046	0.045	0.084
40	0.059	0.111	0.059	0.052	0.052	0.095
45	0.066	0.122	0.066	0.060	0.060	0.108
50	0.074	0.136	0.074	0.069	0.069	0.123
55	0.084	0.152	0.084	0.080	0.079	0.141
60	0.096	0.172	0.096	0.092	0.092	0.162
65	0.111	0.198	0.111	0.108	0.108	0.190
70	0.132	0.233	0.132	0.130	0.129	0.226
75	0.163	0.285	0.163	0.161	0.160	0.280
80	0.214	0.374	0.214	0.213	0.213	0.369
85	0.334	0.581	0.334	0.333	0.333	0.578



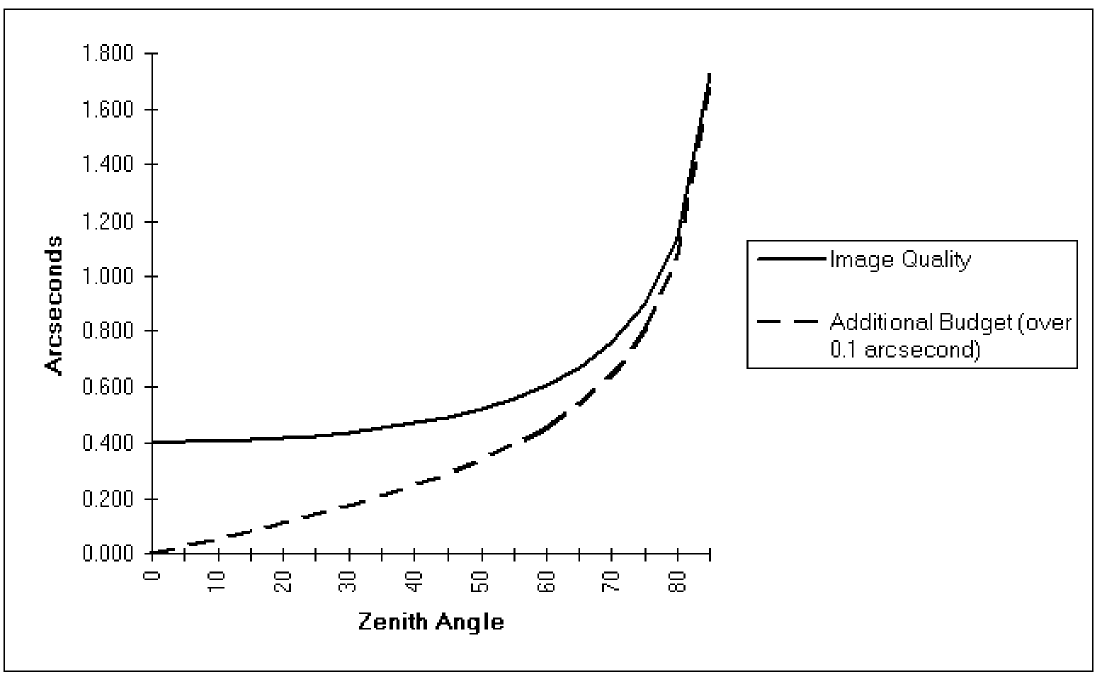
10_50P.XLS

ERROR BUDGET FOR f/16 at 50% ENCIRCLED ENERGY, 10 MICRONS (High Wind)

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.400 Arc Seconds				
1.1 Static Image Quality		0.309			
1.1.1 Optical Design			0.300		
1.1.1.1 Diffraction Size				0.300	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.051		
1.1.2.1 Primary				0.036	
1.1.2.1.1 Polishing Residuals					0.015
1.1.2.1.2 Support Residuals					0.010
1.1.2.1.3 Thermal Distortion					0.005
1.1.2.1.4 Wind Buffeting					0.030
1.1.2.1.5 Coating Thickness					0.004
1.1.2.2 Secondary				0.035	
1.1.2.2.1 Polishing Residuals					0.015
1.1.2.2.2 Support Residuals					0.030
1.1.2.2.3 Thermal Distortion					0.005
1.1.2.2.4 Wind Buffeting					0.010
1.1.2.2.5 Coating Thickness					0.003
1.1.2.3 Active Control				0.010	
1.1.3 Alignment of Optics			0.015		
1.1.3.1 Secondary Decenter				0.008	
1.1.3.2 Secondary Defocus				0.010	
1.1.3.3 Secondary Tilt				0.008	
1.1.4 Self Induced Seeing			0.051		
1.1.4.1 Enclosure				0.045	
1.1.4.2 Telescope (thermal seeing)				0.024	
1.1.4.2.1 Primary Mirror Delta T					0.010
1.1.4.2.2 Secondary Mirror Delta T					0.004
1.1.4.2.3 OSS Structure Delta T					0.015
1.1.4.2.4 CR/ISS Delta T					0.015
1.2 Dynamic Image Quality		0.166			
1.2.1 Dynamic Optical Alignment			0.165		
1.2.1.1 Tilt Correction Errors				0.160	
1.2.1.2 Primary Seondary Defocus				0.040	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.015		
1.3 Image Smear		0.192			
1.3.1 Wind Shake			0.140		
1.3.2 Measurement Error			0.003		
1.3.3 Other			0.131		
1.3.3.1 Residual Top End Tilt				0.100	
1.3.3.2 Residual Articulation System Tilt				0.050	
1.3.3.3 Residual Mirror Tilt				0.050	
1.3.3.4 Other				0.047	

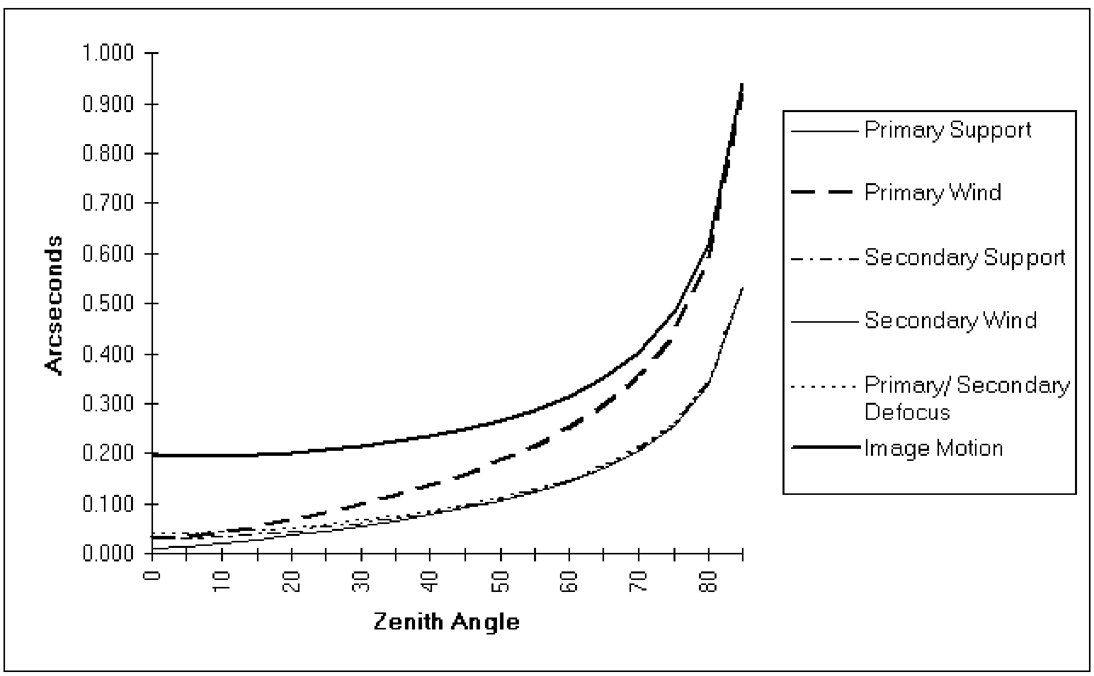
IR f/16 Error Budget Cassegrain 10 microns	Z2.XLS	**1 arcminute field vs Zenith Angle Chopping 50% Encircled Energy**
SPEC:	0.4	

Degrees	Image Quality	Additional Budget (over 0.1 arcsecond)
0	0.400	0.000
5	0.401	0.027
10	0.404	0.054
15	0.408	0.082
20	0.415	0.111
25	0.424	0.142
30	0.436	0.174
35	0.451	0.208
40	0.469	0.246
45	0.492	0.287
50	0.521	0.335
55	0.558	0.390
60	0.606	0.456
65	0.671	0.538
70	0.761	0.648
75	0.900	0.806
80	1.144	1.071
85	1.729	1.682



IR f/16 Error Budget Z2.XLS **1 arcminute field**
Cassegrain **vs Zenith Angle**
10 microns **Chopping**
50% Encircled Energy

	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.010	0.030	0.030	0.010	0.040	0.192
5	0.013	0.033	0.031	0.013	0.041	0.192
10	0.020	0.042	0.035	0.020	0.044	0.194
15	0.028	0.054	0.040	0.028	0.048	0.197
20	0.037	0.068	0.046	0.037	0.053	0.201
25	0.046	0.083	0.054	0.046	0.060	0.207
30	0.056	0.100	0.063	0.056	0.068	0.214
35	0.067	0.118	0.072	0.067	0.077	0.223
40	0.078	0.138	0.083	0.078	0.087	0.234
45	0.091	0.160	0.096	0.091	0.099	0.248
50	0.106	0.186	0.110	0.106	0.113	0.265
55	0.124	0.215	0.127	0.124	0.130	0.287
60	0.144	0.251	0.147	0.144	0.150	0.315
65	0.171	0.296	0.173	0.171	0.175	0.352
70	0.205	0.356	0.207	0.205	0.209	0.403
75	0.255	0.443	0.257	0.255	0.258	0.481
80	0.339	0.588	0.340	0.339	0.341	0.617
85	0.532	0.922	0.533	0.532	0.534	0.941



55_36P.XLS

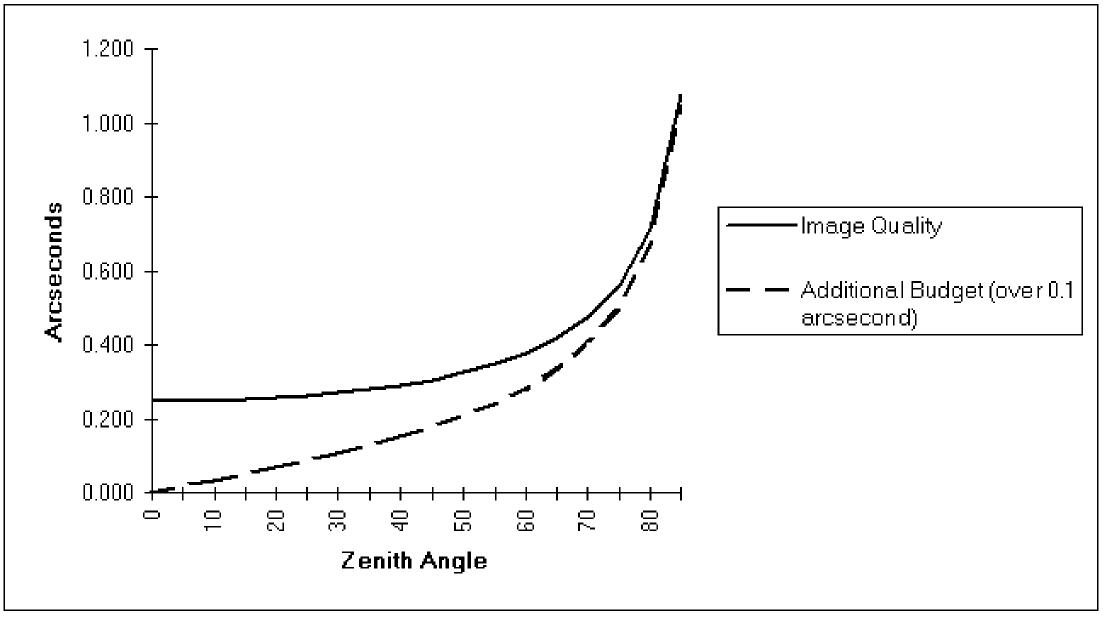
ERROR BUDGET FOR f/6 at 36% ENCIRCLED ENERGY, 0.55 MICRONS

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.250				
1.1 Static Image Quality		0.138			
1.1.1 Optical Design			0.115		
1.1.1.1 Diffraction Size				0.115	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.057		
1.1.2.1 Primary				0.044	
1.1.2.1.1 Polishing Residuals					0.030
1.1.2.1.2 Support Residuals					0.010
1.1.2.1.3 Thermal Distortion					0.005
1.1.2.1.4 Wind Buffeting					0.030
1.1.2.1.5 Coating Thickness					0.004
1.1.2.2 Secondary				0.035	
1.1.2.2.1 Polishing Residuals					0.030
1.1.2.2.2 Support Residuals					0.010
1.1.2.2.3 Thermal Distortion					0.010
1.1.2.2.4 Wind Buffeting					0.010
1.1.2.2.5 Coating Thickness					0.004
1.1.2.3 Active Control				0.010	
1.1.3 Alignment of Optics			0.017		
1.1.3.1 Secondary Decenter				0.010	
1.1.3.2 Secondary Defocus				0.010	
1.1.3.3 Secondary Tilt				0.010	
1.1.4 Self Induced Seeing			0.049		
1.1.4.1 Enclosure				0.045	
1.1.4.2 Telescope (thermal seeing)				0.018	
1.1.4.2.1 Primary Mirror Delta T					0.010
1.1.4.2.2 Decondary Mirror Delta T					0.004
1.1.4.2.3 OSS Structure Delta T					0.015
1.2 Dynamic Image Quality		0.023			
1.2.1 Dynamic Optical Alignment			0.023		
1.2.1.1 Pointing				0.000	
1.2.1.2 Primary Seondary Decenter				0.010	
1.2.1.3 Primary Secondary Tilt				0.005	
1.2.1.4 Primary Secondary Defocus				0.020	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.000		
1.3 Image Smear		0.207			
1.3.1 Wind Shake			0.200		
1.3.2 Measurement Error			0.020		
1.3.3 Other			0.050		

Optical f/6 Error Budget Z3.XLS **45 arcminute field**
Cassegrain **vs Zenith Angle**
0.55 microns **36% Encircled Energy**

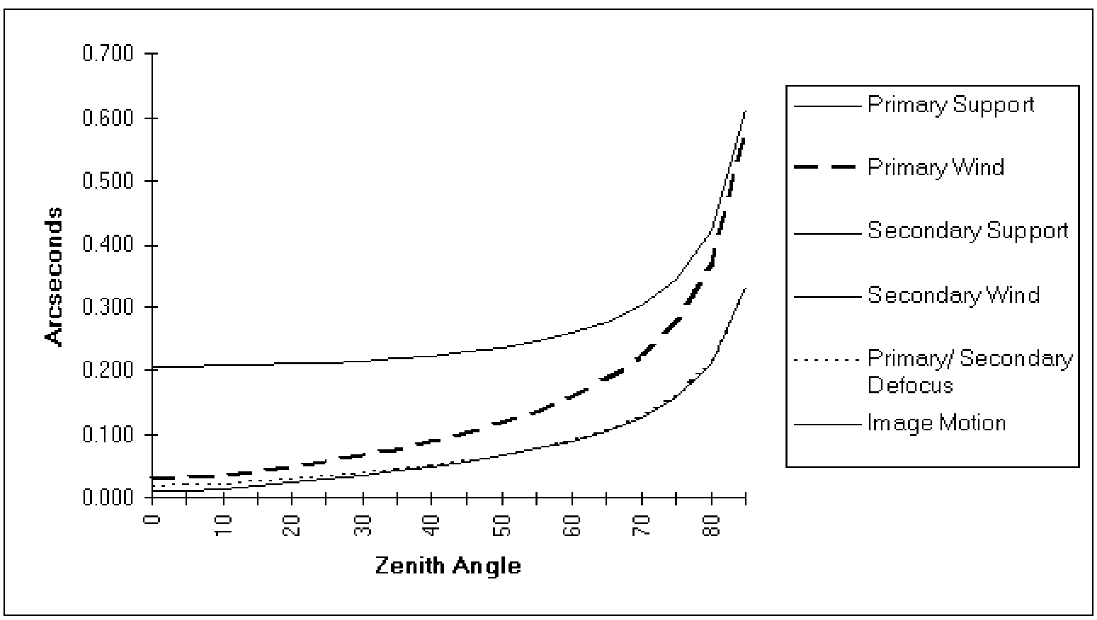
SPEC: 0.25

Degrees	Image Quality	Additional Budget (over 0.1 arcsecond)
0	0.250	0.000
5	0.251	0.017
10	0.252	0.034
15	0.255	0.052
20	0.260	0.070
25	0.265	0.088
30	0.273	0.109
35	0.282	0.130
40	0.293	0.153
45	0.308	0.180
50	0.326	0.209
55	0.349	0.243
60	0.379	0.285
65	0.419	0.336
70	0.476	0.405
75	0.563	0.504
80	0.715	0.670
85	1.081	1.052



Optical f/6 Error Budget Z3.XLS **45 arcminute field**
Cassegrain **vs Zenith Angle**
0.55 microns **36% Encircled Energy**

	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.010	0.030	0.010	0.010	0.020	0.207
5	0.011	0.031	0.011	0.011	0.021	0.207
10	0.015	0.035	0.015	0.015	0.023	0.208
15	0.019	0.041	0.019	0.019	0.026	0.209
20	0.024	0.049	0.024	0.024	0.030	0.211
25	0.030	0.057	0.030	0.030	0.034	0.213
30	0.036	0.067	0.036	0.036	0.040	0.215
35	0.042	0.077	0.042	0.042	0.046	0.219
40	0.050	0.089	0.050	0.050	0.052	0.224
45	0.058	0.103	0.058	0.058	0.060	0.229
50	0.067	0.118	0.067	0.067	0.069	0.237
55	0.078	0.137	0.078	0.078	0.080	0.246
60	0.091	0.159	0.091	0.091	0.092	0.259
65	0.107	0.187	0.107	0.107	0.108	0.277
70	0.128	0.224	0.128	0.128	0.130	0.303
75	0.160	0.278	0.160	0.160	0.161	0.345
80	0.212	0.368	0.212	0.212	0.213	0.421
85	0.333	0.577	0.333	0.333	0.333	0.612



55_50P.XLS

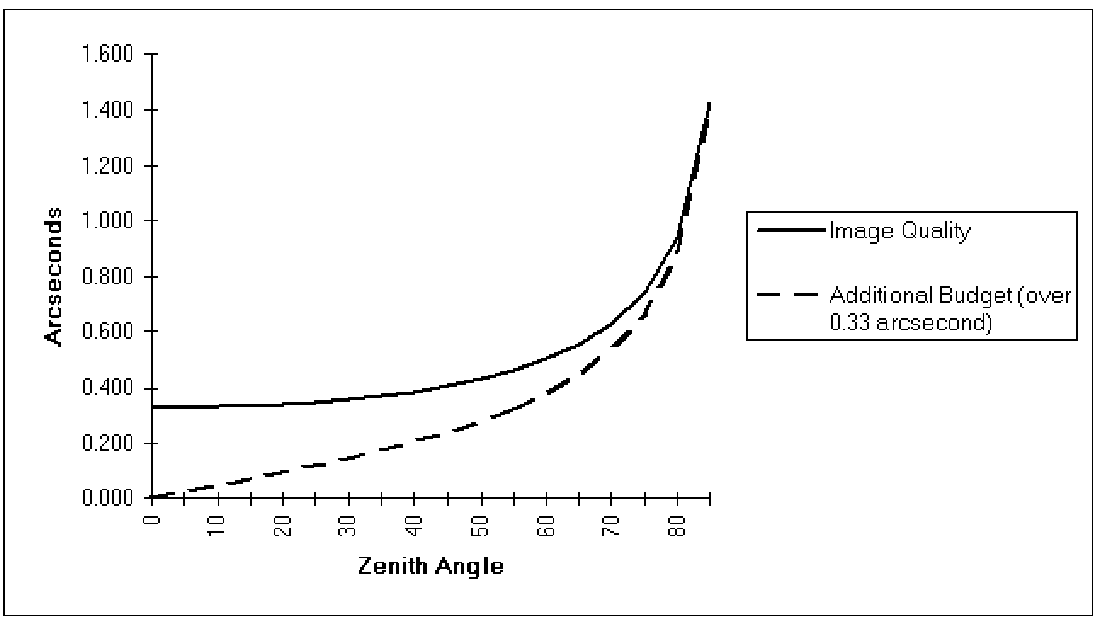
ERROR BUDGET FOR f/6 at 50% ENCIRCLED ENERGY, 0.55 MICRONS

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.333				
1.1 Static Image Quality		0.208			
1.1.1 Optical Design			0.176		
1.1.2 Surface Errors			0.093		
1.1.2.1 Primary				0.076	
1.1.2.1.1 Polishing Residuals					0.04
1.1.2.1.2 Support Residuals					0.02
1.1.2.1.3 Thermal Distortion					0.01
1.1.2.1.4 Wind Buffeting					0.06
1.1.2.1.5 Coating Thickness					0.008
1.1.2.2 Secondary				0.054	
1.1.2.2.1 Polishing Residuals					0.040
1.1.2.2.2 Support Residuals					0.020
1.1.2.2.3 Thermal Distortion					0.020
1.1.2.2.4 Wind Buffeting					0.020
1.1.2.2.5 Coating Thickness					0.008
1.1.2.3 Active Control				0.010	
1.1.3 Alignment of Optics			0.035		
1.1.3.1 Secondary Decenter				0.020	
1.1.3.2 Secondary Defocus				0.020	
1.1.3.3 Secondary Tilt				0.020	
1.1.4 Self Induced Seeing			0.049		
1.1.4.1 Enclosure				0.045	
1.1.4.2 Telescope (thermal seeing)				0.018	
1.1.4.2.1 Primary Mirror Delta T					0.010
1.1.4.2.2 Decondary Mirror Delta T					0.004
1.1.4.2.3 OSS Structure Delta T					0.015
1.2 Dynamic Image Quality		0.046			
1.2.1 Dynamic Optical Alignment			0.046		
1.2.1.1 Pointing				0.000	
1.2.1.2 Primary Seondary Decenter				0.020	
1.2.1.3 Primary Secondary Tilt				0.010	
1.2.1.4 Primary Secondary Defocus				0.040	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.000		
1.3 Image Smear		0.256			
1.3.1 Wind Shake			0.250		
1.3.2 Measurement Error			0.020		
1.3.3 Other			0.050		

Optical f/6 Error Budget Z3X.XLS **45 arcminute field**
Cassegrain **vs Zenith Angle**
0.55 microns **50% Encircled Energy**

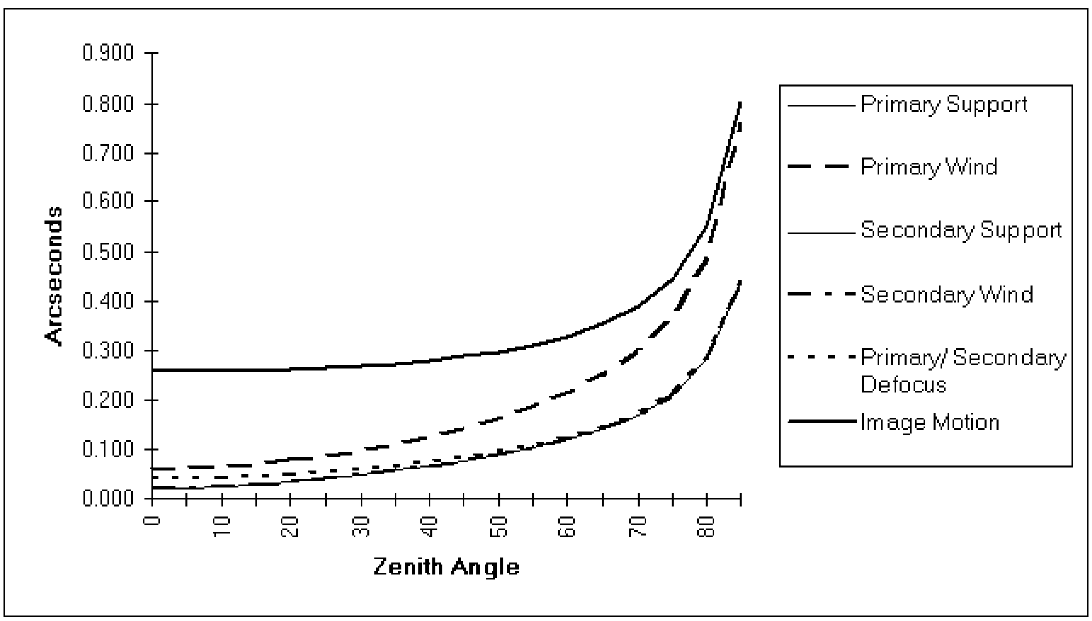
SPEC: 0.33

Degrees	Image Quality	Additional Budget (over 0.33 arcsecond)
0	0.330	0.000
5	0.331	0.022
10	0.333	0.045
15	0.337	0.068
20	0.343	0.092
25	0.350	0.117
30	0.360	0.143
35	0.372	0.172
40	0.387	0.203
45	0.406	0.237
50	0.430	0.276
55	0.461	0.321
60	0.500	0.376
65	0.553	0.444
70	0.628	0.535
75	0.743	0.665
80	0.943	0.884
85	1.427	1.388



Optical f/6 Error Budget Z3X.XLS **45 arcminute field**
Cassegrain **vs Zenith Angle**
0.55 microns **50% Encircled Energy**

	0.1	0.3	0.1	0.1	0.1	0.3
Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
0	0.020	0.060	0.020	0.020	0.040	0.256
5	0.021	0.061	0.021	0.021	0.041	0.256
10	0.025	0.065	0.025	0.025	0.042	0.257
15	0.029	0.071	0.029	0.029	0.045	0.258
20	0.035	0.078	0.035	0.035	0.049	0.261
25	0.042	0.088	0.042	0.042	0.054	0.264
30	0.050	0.099	0.050	0.050	0.060	0.267
35	0.058	0.112	0.058	0.058	0.067	0.272
40	0.067	0.126	0.067	0.067	0.076	0.279
45	0.078	0.143	0.078	0.078	0.085	0.287
50	0.090	0.163	0.090	0.090	0.096	0.297
55	0.104	0.186	0.104	0.104	0.109	0.310
60	0.121	0.214	0.121	0.121	0.125	0.328
65	0.142	0.251	0.142	0.142	0.146	0.353
70	0.170	0.299	0.170	0.170	0.174	0.389
75	0.211	0.369	0.211	0.211	0.214	0.445
80	0.280	0.488	0.280	0.280	0.282	0.547
85	0.439	0.763	0.439	0.439	0.441	0.802



55_90P.XLS

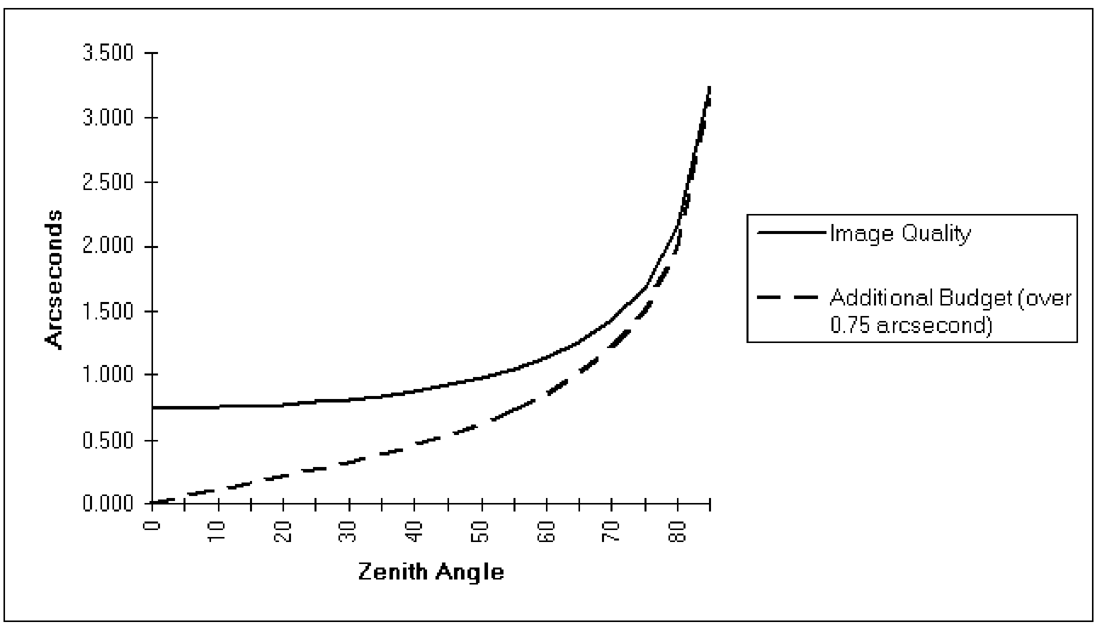
ERROR BUDGET FOR f/6 at 90% ENCIRCLED ENERGY, 0.55 MICRONS

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Image Quality	0.750				
1.1 Static Image Quality		0.566			
1.1.1 Optical Design			0.240		
1.1.1.1 Diffraction Size				0.240	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.439		
1.1.2.1 Primary				0.326	
1.1.2.1.1 Polishing Residuals					0.200
1.1.2.1.2 Support Residuals					0.100
1.1.2.1.3 Thermal Distortion					0.100
1.1.2.1.4 Wind Buffeting					0.200
1.1.2.1.5 Coating Thickness					0.080
1.1.2.2 Secondary				0.276	
1.1.2.2.1 Polishing Residuals					0.200
1.1.2.2.2 Support Residuals					0.100
1.1.2.2.3 Thermal Distortion					0.100
1.1.2.2.4 Wind Buffeting					0.100
1.1.2.2.5 Coating Thickness					0.080
1.1.2.3 Active Control				0.100	
1.1.3 Alignment of Optics			0.173		
1.1.3.1 Secondary Decenter				0.100	
1.1.3.2 Secondary Defocus				0.100	
1.1.3.3 Secondary Tilt				0.100	
1.1.4 Self Induced Seeing			0.200		
1.1.4.1 Enclosure				0.100	
1.1.4.2 Telescope (thermal seeing)				0.173	
1.1.4.2.1 Primary Mirror Delta T					0.100
1.1.4.2.2 Secondary Mirror Delta T					0.100
1.1.4.2.3 OSS Structure Delta T					0.100
1.2 Dynamic Image Quality		0.265			
1.2.1 Dynamic Optical Alignment			0.265		
1.2.1.1 Pointing				0.100	
1.2.1.2 Primary Secondary Decenter				0.100	
1.2.1.3 Primary Secondary Tilt				0.100	
1.2.1.4 Primary Secondary Defocus				0.200	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.000		
1.3 Image Smear		0.415			
1.3.1 Wind Shake			0.400		
1.3.2 Measurement Error			0.050		
1.3.3 Other			0.100		

Optical f/6 Error Budget	Z3Y.XLS	**45 arcminute field**
Cassegrain		**vs Zenith Angle**
0.55 microns		**90% Encircled Energy**

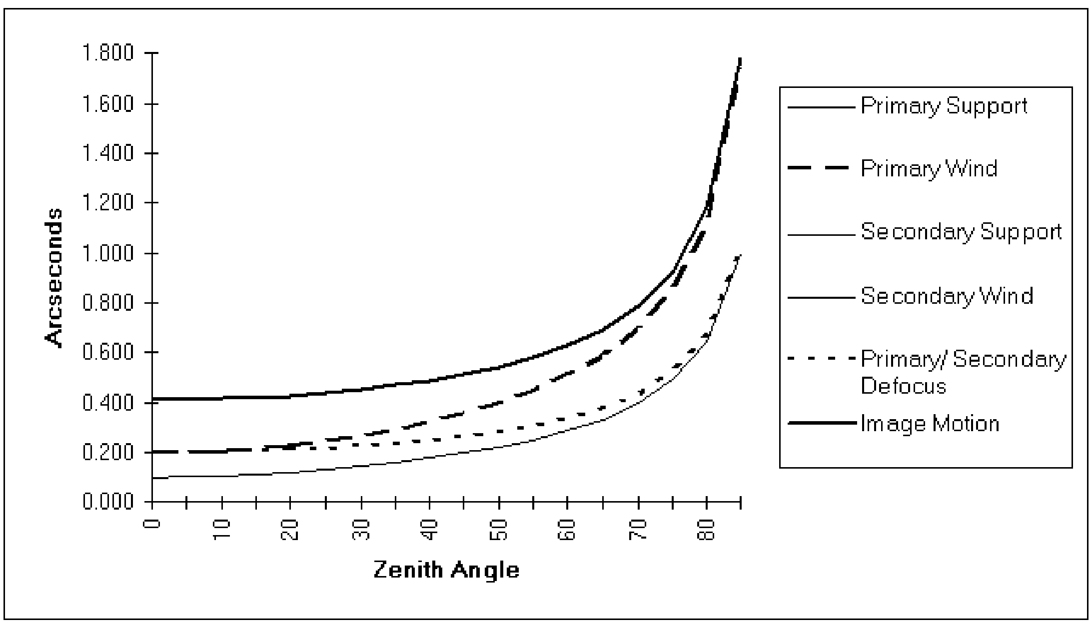
SPEC: 0.75

Degrees	Image Quality	Additional Budget (over 0.75 arcsecond)
0	0.750	0.000
5	0.752	0.051
10	0.757	0.102
15	0.766	0.155
20	0.779	0.209
25	0.796	0.265
30	0.818	0.326
35	0.845	0.390
40	0.880	0.460
45	0.923	0.539
50	0.978	0.627
55	1.047	0.730
60	1.137	0.854
65	1.257	1.009
70	1.428	1.215
75	1.688	1.512
80	2.144	2.009
85	3.243	3.155



Optical f/6 Error Budget Z3Y.XLS **45 arcminute field**
Cassegrain **vs Zenith Angle**
0.55 microns **90% Encircled Energy**

Degrees	Primary Support	Primary Wind	Secondary Support	Secondary Wind	Primary/ Secondary Defocus	Image Motion
	0.1	0.3	0.1	0.1	0.1	0.3
0	0.100	0.200	0.100	0.100	0.200	0.415
5	0.101	0.202	0.101	0.101	0.201	0.416
10	0.105	0.208	0.105	0.105	0.203	0.419
15	0.111	0.217	0.111	0.111	0.206	0.424
20	0.120	0.230	0.120	0.120	0.211	0.431
25	0.131	0.247	0.131	0.131	0.217	0.440
30	0.144	0.268	0.144	0.144	0.225	0.452
35	0.159	0.293	0.159	0.159	0.235	0.467
40	0.177	0.322	0.177	0.177	0.247	0.486
45	0.198	0.356	0.198	0.198	0.263	0.509
50	0.222	0.398	0.222	0.222	0.282	0.539
55	0.252	0.447	0.252	0.252	0.306	0.577
60	0.288	0.509	0.288	0.288	0.336	0.626
65	0.334	0.588	0.334	0.334	0.377	0.691
70	0.397	0.695	0.397	0.397	0.433	0.784
75	0.488	0.852	0.488	0.488	0.518	0.926
80	0.643	1.118	0.643	0.643	0.666	1.176
85	1.003	1.739	1.003	1.003	1.017	1.777



2.3.2 Tracking

TRACKING.XLS

ERROR BUDGET FOR f/16 TRACKING

Title	***Error Budget***			
Level	1	2	3	4
1.0 Track-Guide	0.020			
1.1 Optic Axis w.r.t. CR		0.016		
1.1.1 Primary Mirror			0.010	
1.1.1.1 X Displacement				0.005
1.1.1.2 Y Displacement				0.005
1.1.1.3 X Rotation				0.005
1.1.1.4 Y Rotation				0.005
1.1.2 Secondary Mirror			0.012	
1.1.2.1 X Displacement				0.005
1.1.2.2 Y Displacement				0.005
1.1.2.3 X Rotation				0.007
1.1.2.4 Y Rotation				0.007
1.2 Field Rotation		0.010		
1.2.1 A, E Position			0.003	
1.2.2 Calculated Field Rate			0.003	
1.2.3 Drive Servo Rate Error			0.009	
1.3 Detector		0.005		
1.4 Guide Detector Position w.r.t. Science Detector		0.005		

The Tracking error budget presented above refers to the relative alignment sensitivities needed to maintain alignment and average tracking over a slow time constant. The higher frequency tracking errors for such things as wind shake errors are included in the image quality error budget under the title "Image Smear". This refers to the image motion over the detector integration time which blurs the resultant image.

2.3.3 Pointing

POINTING.XLS

ERROR BUDGET FOR f/16 POINTING

Title	***Error Budget***				
Level	1	2	3	4	5
1.0 Pointing	3.000 Arc Seconds RMS				
1.1 Calibration Star Positions		0.100			
1.1.1 Catalog Position			0.045		
1.1.2 Calculated Motion Since Catalog			0.044		
1.1.3 Time Base			0.045		
1.1.4 Uncalculated Random Motion			0.064		
1.2 Interpolation Function ^A, ^E		0.500			
1.3 Encoder Readability		0.150			
1.4 Optic Axis w.r.t. CR		2.674			
1.4.1 Primary w.r.t. CR			1.171		
1.4.2 Secondary w.r.t. Primary			1.960		
1.4.3 Instrument or A&G Detector			1.391		
1.4.4 Atmospheric Dispersion Compensator (TBD)			0.000		
1.4.5 Out of Balance (TBD)			0.000		
1.5 Calculable Functions		1.254			
1.5.1 Atmospheric Correction (apparent pos.)			0.273		
1.5.1.1 Temperature				0.032	
1.5.1.2 Pressure				0.032	
1.5.1.3 Humidity				0.013	
1.5.1.4 Elevation Angle Algorithm				0.100	
1.5.1.5 Atmospheric Wedge				0.250	
1.5.2 Pier and Coordinate Transform			0.173		
1.5.2.1 Position Transform				0.100	
1.5.2.2 Low Frequency Variations				0.100	
1.5.2.3 High Frequency Variations				0.100	
1.5.3 Mount CR w.t. Pier			1.211		
1.5.3.1 Azimuth Position				0.648	
1.5.3.2 Elevation Position				0.909	
1.5.3.3 Field Position				0.000	
1.5.3.4 Mechanical Structural Hysteresis				0.470	

2.3.4 Emissivity Error Budget

The proposed emissivity error budget comes from a memo tilted "Emissivity Error Budget" from Fred Gillett to J. Oschmann dated March 8 1993. The following is quoted from this memo:

The performance requirement for Telescope Emissivity is the following:

"The fully optimized IR configuration will have a telescope emissivity, including scattering and diffraction, of 2% immediately after coating or recoating optics, with 0.5% maximum degradation during operations, at any single wavelength beyond 2.2 microns."

The fully optimized IR configuration includes a primary mirror of 8.1 m diameter reflecting surface, 8.0 m diameter for imaging, and a central obscuration of 1.2 meters or less. The secondary mirror is the telescope pupil stop and includes a central hole such that the IR instruments view a minimal amount of non-reflecting surfaces either directly or in reflection off the primary mirror and/or secondary mirror.

In evaluating the telescope emissivity, it is assumed that the IR instrumentation occupies the entire 3-arcmin diameter science FOV and incorporates and internal Lyot stop that is 10% oversized compared to the secondary mirror. The emissivity contribution is taken to be the calculated (or observed) emission from the source in question in the focal plane within the solid angle defined by the cold Lyot stop, divided by the emission from the secondary mirror coated with a perfect black body radiator with unit emissivity.

The proposed initial allocation of emissivity contributions immediately after coating or recoating optics, is as follows:

Source	**Contribution (% emissivity)**
Primary mirror surface	0.80
Secondary mirror surface	0.70
Secondary outer bevel	0.16
Secondary inner bevel	0.03
Secondary support struts in reflection	0.20
Secondary support struts in direct emission	0.06
All other sources	0.05
Total	2.00

3. AO System Error Budget

3.1 Introduction

The Gemini 8-meter telescopes, when using adaptive optics, are to deliver superb images under median seeing conditions. The specification for performance is given in the Gemini Science Requirements Document and is interpreted as delivered image quality. It is widely understood that use of AO will also correct for some of the telescope system imperfections. It cannot be assumed that all errors will be corrected. To this end, the Gemini telescopes have been designed to deliver superb image quality without AO and have made a concerted attempt where practical, to consider AO needs in specifying critical components such as the primary mirror polishing specifications. The goal is to build the best possible telescope, without any assumptions for correction of errors by AO. For AO use, we still must consider these residual aberrations and the effects of the optical quality of the scientific instruments using AO upon the final delivered images. This is what directly effects the science to be attained. As will be shown, an additional 'margin' or degradation due to the telescope and instruments will be in the 20-30% range and must be accounted for in a complete systems error budget.

3.2 Error Budget Considerations

When considering the addition of an adaptive optics system, one must still consider the telescope aberrations and the effect the AO system will have on them and the final scientific instrument errors, most of which will not be effected by the AO system. As shown later, we begin by developing an overall error budget consisting of three main items:

1.0 Telescope System
2.0 Scientific Instruments
3.0 Adaptive Optics System

The following is a discussion in each of these areas giving some level of background and details where possible on how the error budget items given later were derived. This represents my own first cut at a system level AO error budget with some estimates of bottoms up performance included. Comments and suggestions are encouraged so that we may come up with an understandable and agreed error budget in the near term. The derivation of errors will be in terms of time varying rms tilt for any tracking errors and rms wavefront errors (spatially) for any higher order terms. These are converted to phase variance values which are related to Strehl ratio by the following approximation:

$$Strehl\_Ratio =$$

where: δ^2 = phase variance = $(2\pi\sigma/\lambda)^2$ for higher order spatial wavefront variations
σ = rms wavefront error in nm
λ = wavelength of interest

This relationship is widely used and considered to be valid for Strehl ratios in excess of about 0.2.

Most Strehls given are given at 1.6 microns. Strehls at other wavelengths are given in the error budget listing for the complete system. Many of the errors are derived from the Gemini Systems Error Budget Plan, version 2.1. Specifically, the 2.2 micron, 50% encircled energy error budget is used as a starting point to derive various telescope errors. Only on axis correction is considered at this time. Correction with off axis guide stars will further degrade the results presented here.

3.2.1 Telescope System Errors

As will be done for all three areas, the errors of tilt and higher order effects are considered separately. First, we consider the tilt error contributions of the telescope.

When operating as a system, the tilt errors are measured by the AO Facility Wavefront Sensor (AO FWFS) or the On Instrument Wavefront Sensor (OIWFS) and feed back to a fast tilt mirror (and/or M2) for correction of tilt errors from any source within the system. The only exception is that there will be some slow flexure type errors which occur between the OIWFS (sensing slow variations) and the actual science focal plane of interest. For error budgeting purposes here, we will consider the major sources of tilt error from the telescope in this category, not including atmospheric tilt, measurement error, servo response (within the AO subsystem error budget allocation) and flexure between the OIWFS and science focal plane (within the science instrument focal plane). These will be considered in the AO subsystem error budget with the exception of flexure, which is accounted for in the scientific instrument error section.

The major source of tilt error in the telescope system that may not be negligible is residual windshake under median to 70th percentile winds. All gravity sag effects, misalignments causing tilt, and such will be negligible after AO correction and are assumed to be zero for this purpose. The detailed analysis of the residual wind shake error source has been analyzed for the non-AO case where the WFS's are used at up to 200 Hz to correct the tilt errors induced by windshake (could be OIWFS or PWFS for correction of wind shake). This analysis was done for 70th percentile winds at MK (11 m/s). For AO use, this may not be adequate. There is an outstanding action to model this in detail to determine what sampling frequency the wavefront sensor must have to bring this down to a reasonable level. For a start, we approximate the residual error by assuming a 1000 Hz sampling (roughly 4 times the expected sampling needed for atmospheric tilt correction - based upon modeling by Brent Ellerbroek to date) as a starting guess. The error allocations derived may have to be re-allocated when the complete analysis is done. Since the measurement errors are considered separately, we will assume a very high signal to noise and no latency other than that inherent to the integration time consistent with the sampling rate. Under median wind conditions, this effect would be further reduced (about 2 times less based upon CFHT wind data).

The estimate of this is scaled from a wind shake prediction at 200 Hz sampling of 0.034 arc sec 50% encircled energy. When scaled to 1000 Hz sampling, this amount is roughly reduced by the percentage increase in sampling rate, giving 0.0068 arc sec 50% encircled energy residual. In terms of rms wavefront variation, this is equivalent to 34 nm rms. This estimate comes from a conversation with Mike Burns on how to roughly scale this effect. This should be checked/ modified.

For higher order effects, the following higher level items are considered from the nominal Gemini Systems Error Budget:

3.2.1.1 Primary Mirror Surface Errors
3.2.1.2 Secondary Mirror Surface Errors
3.2.1.3 Alignment Errors
3.2.1.4 Self Induced Seeing Errors
3.2.1.5 A&G : AO fold and Science Fold Errors

There are many more detailed items in the nominal Gemini error budget for the telescope, but they are either considered negligible for this purpose (a small contingency category should be considered for these) or are considered as a subset of the items listed above.

3.2.1.1 First, we will walk through a description of the detailed analysis which exists for the primary mirror surface errors to determine its contributions to the AO system error budget. This will be used as the basis for estimation of the secondary mirror contribution.

From other sections in this document, we can use the allocations given as the basis of the system performance without AO correction. For the primary mirror surface errors, we have an allocation of 0.036 arc sec, 50% encircled energy at 2.2 microns. Analysis to date shows slightly better performance predicted. Following the primary mirror PDR, several cases of surface error performance were modeled in detail. The cases modeled in detail each had about 20 specific detailed error sources including simulated polishing errors, many types of support system errors (axial and lateral), and thermal effects. For these cases, secondary mirror gravity sag was also included, but it did not effect the results after active optics correction. The results of one of these cases is shown in Figure 1.

The 3D plot on the left is before closed loop active optics correction (but with look-up table correction). It has a value of about 130 nm rms surface error. After aO correction, the plot on the right shows a residual surface error of 21 nm rms. This is the fitting error after correction with a 10 x 10 SH and correcting 15 to 20 mirror modes, using a support system consisting of 120 active elements. There is little difference in correcting more modes as the residual shown is simply the simulated high spatial frequency polishing errors used on the input file. This holds true for correction of up to 80 modes of correction. An adaptive optics system of low to medium order will also not be able to reduce this error source any further. It would take a high order system, capable of correcting on small spatial scales (as possible with a high degree of freedom stacked actuator mirror). We have made no assumptions of scaling of the residuals versus number of actuators for this first cut, based upon our aO analysis referred to above. If high order systems are envisioned, this should be revisited. We can expect other error sources which produce low spatial frequency errors such as those corrected well with the aO system to be very

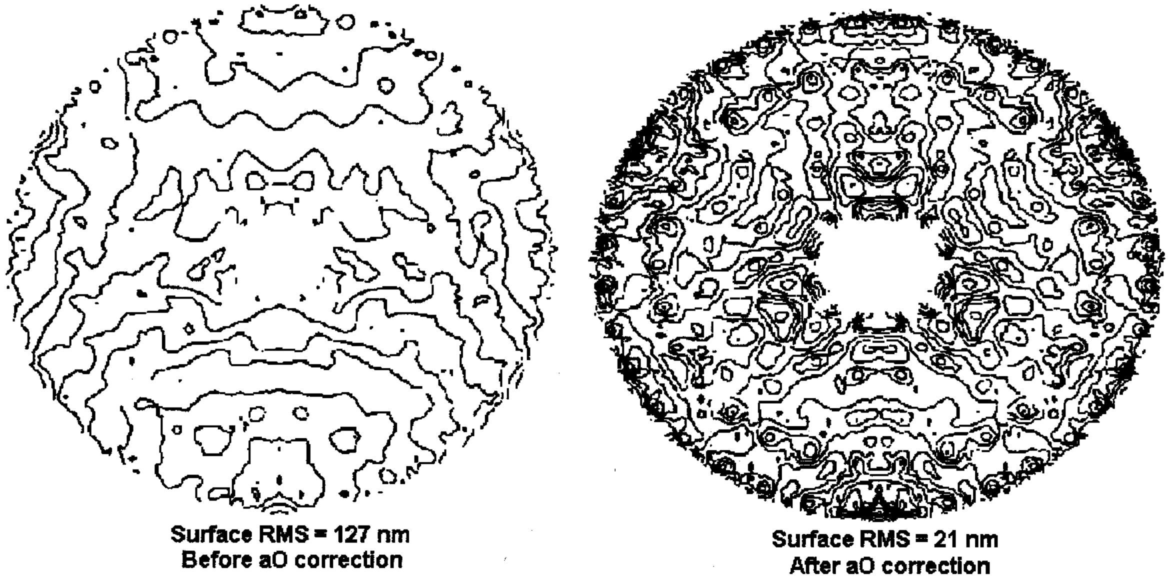


Figure 1. Example of aO correction analysis performed by IGPO optics group and Brent Ellerbroek of SOR. Contour levels were adjusted between plots.

well corrected by the faster AO system. This would cover error budget items such as "dynamic image quality" listed in the Gemini Systems Error Budget Plan which produce small amounts of time varying coma. These items, on axis would essentially be zero for operation with bright guide stars. We leave a small amount under the "alignment" section here to cover the small residuals (20nm rms which gives a Strehl of 0.99).

Now that we have determined that high spatial frequency polishing errors will not be corrected (especially for low to medium order systems), we can use this to determine an AO allocation for the primary mirror surface allocations. It should be noted that the simulated polishing errors used here came from scaling actual surface measurements attained on the WIYN mirror. We may get better (or worse) results than this in the end, but we will not know until final polishing and testing of our first mirror. For error budgeting purposes, we will scale these results further from WIYN to the limit allowed by our polishing specifications with REOSC. The case run in the analysis shown above was a point about half way between our requirement and a goal specified. The value to use to just meet our specification is about 30 nm rms. This value already assumes a reasonable level (up to 100 newtons force out of +/-386 newtons total) of aO correction.

For the error budget entry, this value is doubled to 60 nm rms to represent the effect of the surface figure on the reflected wavefront (defects on the surface effect the reflected wavefront a factor of two larger than the defect as the light travels through this ’defect’ twice). This corresponds to a Strehl of 0.95.

3.2.1.2 For the secondary mirror, we have not simulated polishing errors. We have modeled a similar level of support, gravity and thermal error sources. All of these lead to fairly low order effects which are corrected well with either aO or AO. As noted above, secondary gravity sag was included in the modeling performed. For purposes here, we have essentially the same limits and specification as on the primary mirror polishing. Experience with polishing of convex secondary mirrors suggest that it is not unreasonable to expect high spatial frequency zonal errors (especially for large, steep aspheric mirrors). For this reason, we will allocate the same value of 60 nms rms wavefront to the AO error contribution of the secondary mirror.

3.2.1.3 For alignment effects (and dynamic image quality referred to earlier) we expect that, on axis, the residual errors to be very small. In the non-AO error budget, 0.026 arc sec, 50% ee @ 2.2 microns is allocated. This corresponds to an rms wavefront error of about 130 nm rms (approximation of 0.01 arc sec equals 50 nm rms wavefront). Though all of this is very low order, we want to keep a small residual error here of 20 nm rms when operating with AO. This is an 85% reduction of these errors and represents a Strehl of 0.99 as stated above (at 1.6 microns).

3.2.1.4 Self induced seeing is much harder to quantify. We do not have accurate models of the spatial content of this effect. The amount of correction, even if the effect is of low spatial order, will vary as one tracks off-axis if conjugating to altitude. For limiting purposes here, we are assuming tracking and correcting on the object of interest and assume that the AO system will correct some level of this self induced seeing. The specific amount is subject to interpretation and comments are welcomed.

To start out with, we will take the non-AO case of self induced seeing as a starting point. From elsewhere in this document, the self-induced seeing error allocation for high wind is 0.035 arc sec 50% encircled energy at 2.2 microns. This corresponds to about 175 nm rms wavefront error. Without spatial frequency information, we can only guess as to the amount of correction on axis. As one goes off axis, less and less of this will be corrected if conjugating to altitude.

My "guess" for the on axis case, with relatively low order correction is a residual of 50 nm rms (0.01 arc sec 50% ee). It will certainly scale with the order of correction in some manner, but for this first pass, we will assume a fixed number. This should be revisited if building a higher order AO system. For now, this is my guess for a 36 -54 degree of freedom system. This will have an effective Strehl contribution of 0.96 for now (from 50nm rms wavefront at 1.6 microns).

3.2.1.5 A&G errors:

Residual errors within the A&G system when using AO also fall with in the two categories of tilt and higher order effects. The tilt terms associated with ISS flexure and fold mirror flexure are considered as a negligible contribution since they are slow and within the system 'loop' which takes out these effects very well. For this reason, only the higher order effects are covered here. These come from the optical quality of the upper AO fold mirror and the science fold flat.

Some detailed analysis of these mirrors was performed as part of the A&G PDR and in subsequent designs by RGO, the project office, and in one case for the science fold, Eastman Kodak. These did not include any assumptions for polishing errors.

For the AO fold mirror, which sends the telescope science beam into the AO subsystem, low order effects due to gravity sag (for example) will be well corrected when guiding on axis. The residual error is also assumed here to be higher order polishing errors. Since in the loop, my estimate for the residual higher order effects is about 1/40th wave rms in the visible (considered a very good mirror by commercial standards). Remember that this level of correction is only valid on axis if conjugating to altitude. The wavefront effect is double this to 1/20th wave rms (not exactly doubled since at 45 degree, but close enough and on the conservative side for error budgeting purposes). This is in the visible (normally specified at 0.6238 microns). This gives about 30 nm rms wavefront error. It certainly is possible to a bit better here, but recognizing that this contributes a Strehl of 0.986, it is not worth the cost of doing better for this small effect (in my opinion - there are bigger fish to catch!).

For the science fold flat, the considerations are a bit different. The mirror is after the higher order correction loop and hence should not be considered as correctable by AO. We should make this mirror as good as we can afford to. Having higher order wavefront sensing after this mirror (i.e. in the instruments) would help here, but when one considers all of the elements before the final science detector plane which also cannot be corrected in the AO loop, this is still a small effect (i.e. look at the system effects!). This optic is not specifically covered in our nominal non-AO error budget (this covers the direct up-look port only) but a specification has been derived as part of the A&G functional design requirements (still under revision). The specification for the science fold called out is a 0.01 arc sec degradation at 2.2 microns, 50% encircled energy (over a 1 arc minute field). This came directly from AO considerations and represents about a 50 nm rms wavefront (Strehl of 0.96 @ 1.6 microns).

As a check on this, a point source would see a little less than a 3 inch by 4 inch 'patch' of the science fold. This comes from the fact that the beam is at f/16 and is located 1100 mm from focus (and at 45 degrees). A 50nm rms wavefront is a 25 nm surface which is about 1/25th wave rms. This is a reasonable number from my experience (manufacturing considerations) and shouldn't drive the costs. We may end up a bit better here, but this is the spec which will be given to the vendor and is reasonable for a mirror which is 0.5 meters in diameter (for the patch size given). We may in fact do better here, but my preference is to leave as is until we see measured results of these various optics. Note that it is less than a factor of two worse than the AO fold mirror which is within the AO correction loop.

3.2.2 Scientific Instrument Errors

Differences exist here for each instrument. Spectrographs with minimal optics before the slit focal plane may perform a bit better than imagers with a relatively large number of elements before the final imaging focal plane. This is necessary in the case of the infrared instruments due to the necessity of reimaging and having an internal cold Lyot stop. To bound the problem, one would like to use what might be one of the more difficult cases and one would like to use one of the primary instruments being considered for AO use. For now, I have chosen the case of the 1-5 micron imager to derive a first cut at an AO allocation. This section may be expanded for other cases in the future, and comments are welcome on the assumptions and derivation given here. Once a complete tolerance analysis is performed on any of the instruments (using realizable manufacturing tolerances) this can easily be updated. Most lens design software such as ZEMAX and CodeV calculate the rms wavefront performance (with a given probability) for the design. The user must take care to put reasonable or typical manufacturing tolerances for this to be representative. This is usually done in conjunction with manufacturers in the final stages of design (and the beginning of the procurement process). For now, I estimate manufacturing tolerances from my experience as a first cut. In practice, several errors due to directly and easily measured errors such as center thickness variation, centering data, etc. can be compensated for by re-running the optical design code with the numbers to re-adjust final element spacing and location to minimize wavefront error. For the best performance, some vendors will measure the quality of a system as it goes together in terms of measured wavefront quality (interferometrically) and adjust the figure on the later elements to compensate. This is a very time consuming and expensive process not typically done on these types of systems (vendor is not responsible for integration of elements into the instrument). My estimates are based upon my experience using simple compensators such as focus adjustments during assembly - not manufacture of final elements to specifically correct measured wavefront error.

To build this estimate (prior to any tolerance analysis), consider transmissive elements separately from reflective elements. For reflective elements, consider similar specifications as given for the science fold, but scaled down somewhat due to the smaller sizes of elements used. Here, if the average element is in the range of 2 inch-4 inches, a very good mirror would be 1/40th wave rms surface in the visible. Thus use 1/20th wave rms wavefront, visible (30 nm rms). This is about twice as good as the large science fold mirror. None of these errors should be considered correctable by AO.

For transmissive elements, things get a bit easier for most. From my experience, a typical high quality optic will have an rms wavefront quality (not including the basic design wavefront) in the neighbor hood of 1/50th wave in the visible for one element (12 nm rms). This is also for optics in the range of up to a few inches. Some elements will be better (such as filters), some are likely to be a bit worse (such as the larger field lens and LiF type materials). For material such as LiF (one in current design), we estimate 1/10th wave rms transmitted wavefront quality. Much smaller elements are easy to get better results than this on. For the entire optical system, the basic designed wavefront quality is added to this for actual performance.

For the 1-5 micron imager, the following make up the optical path for the fine plate scale case:

Number of reflections:	7 (6 mirrors, 1 dichroic beamsplitter)
Number of transmissive elements:	9 (7 powered elements, 2 filters)

- Window, field lens, collimator, final imaging path for 0.02 arc sec plate scale, filters (2)

In addition to the contributions from manufacturing of individual elements, how well they are aligned as a sub system is to be considered. My estimate for this is roughly 1/10th wave in the visible, rms (60nm rms).

From the number of elements and flats given above, the estimates of performance on a per element basis, and alignment considerations, the following performance is estimated (individual contributions are rss'd):

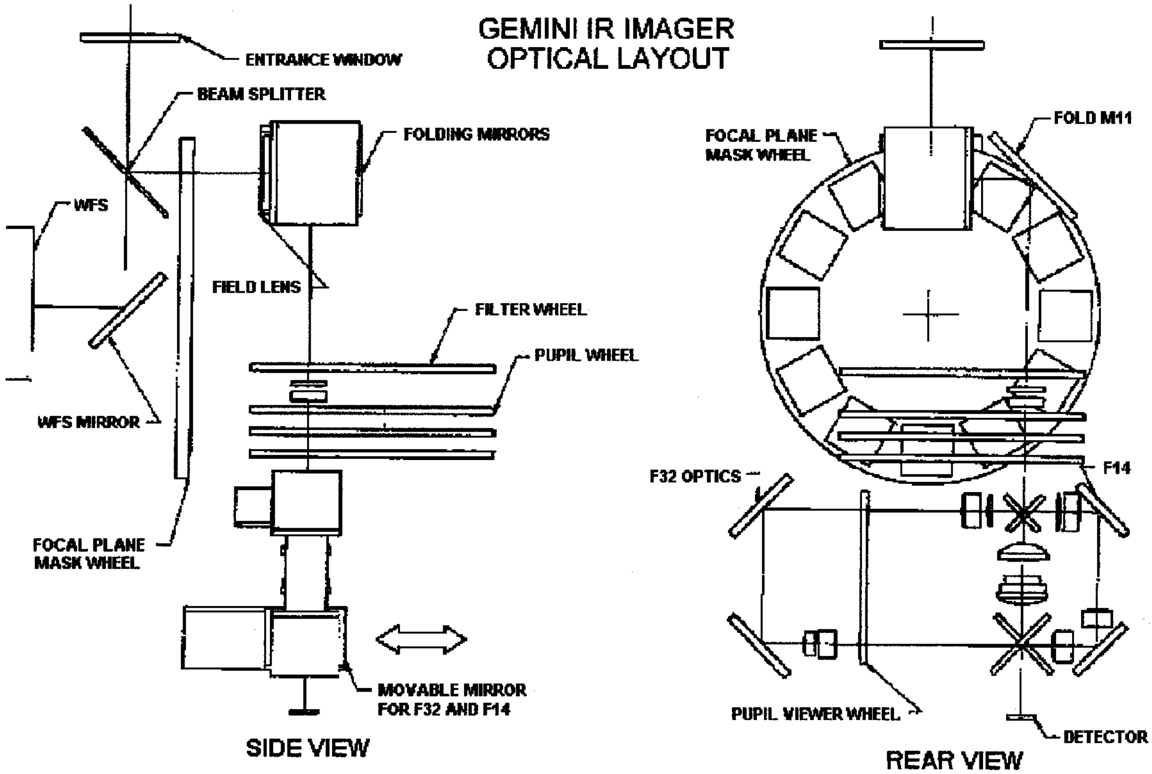


Figure 2. Near IR Imager Conceptual Design Layout. The high resolution plate scale is shown as the "F/32 Optics" on the rear view. A total of 7 folds, 1 window, nominally 1 filter, and 7 transmissive powered elements make up the path to the science detector.

Reflective elements:	79.4 nm rms
Transmissive elements (normal):	33.9 nm rms
LiF transmissive element (one element):	60 nm rms
Alignment of instrument:	60 nm rms
Total	121.1 nm rms (Strehl of 0.80 @ 1.6 microns)

None of this is to be considered as corrected with the AO system

For now, a 'sanity check' on this number might be to consider the specifications to date on the IR imager. For optical design, it is stated that > 90% of the geometric rays are to fall within one pixel. Manufacturing tolerances will degrade this, but if one assumes that this would give the rms spread of rays to be within one pixel, sized at 0.02 arc sec for this case, then the rough contribution to image quality degradation for the instrument is 0.02 arc sec, 50% ee at 2.2 microns (from previously derived relations, outside of this document - it is a rough approximation). Using our general scaling of 0.01 arc sec 50% ee at 2.2 microns gives a 100 nm rms wavefront quality, which is lightly better than the above derivation.

Again, complete tolerancing should be done to update these numbers. For now, consider it a reasonable starting point.

There is also one specific tilt term to consider here. Any relative flexure between the OIWFS and the science plane of interest, will 'smear' the image over long integration times. Great effort is being spent to insure that this motion is small. As a rough estimate, most instrument builders are trying to maintain focal plane stability on the order of a few microns over an hour. Taking this as a very rough estimate of achievable flexure between the guide probe and the focal plane, a smearing of 0.005 arc sec is obtained. The averaged Strehl may be somewhat better, but for now, we'll use the equivalent wavefront error that would give such a degradation in image quality. This is 25 nm rms (Strehl of 0.99 @ 1.6 microns). This assumes an effective 6 micron smear (trying to be reasonable but conservative) with a focal plane scale of 1200 microns per arc sec (fine plate scale), over one hour.

3.2.3 AO Subsystem Errors

The AO subsystem error contributions are broken down into the following categories. This is not a detailed and exhaustive list. The details within this breakdown are the responsibility of the AO team. Hence, little explanation of the numbers presented is given at this time. The total effect of this category must be consistent with the telescope and instrument categories discussed earlier so that the desired delivered quality is attained. It should be noted that some choices here will effect the achievable contributions in the other areas (specifically telescope contributions). Examples are the choice of order of correction (thus correcting more or less telescope aberrations) and tilt loop sampling and latency, effecting the amount of tilt correction from sources such as telescope wind shake.

3.2.3.1 Fitting error (DM/WFS to atmosphere)
3.2.3.2 Tilt response
3.2.3.3 High order WFS measurement error
3.2.3.4 Servo response errors (bandwidth limitations)
3.2.3.5 Uncorrected internal optical errors
3.2.3.6 Calibration errors

3.2.3.1 For this exercise, the rms wavefront error allowed to still produce the desired Strehl ratio is input. It is the last number to be filled in for this first cut. The combination of this and the seeing conditions will determine the order of correction needed (or number of actuators). The trades are not quite so simple as indicated above, but this represents a starting point. Once an order of correction is determined, some of the other residual errors should be revisited to see if they are consistent with this order. If not, re-iterate! The value is given in the spread sheet which follows. The required number of degrees of freedom are calculated based upon this number and is discussed following the error budget.

3.2.3.2 For tilt response, we consider the residual tilt performance assuming no additional lag time in the servo (considered elsewhere). Wind shake is not considered as it was counted under the telescope contributions. For a bright star, this should be a very small contribution. From a Keck document (call it roughly equal!), a 12th magnitude star would give roughly a 5 nRad rms tilt error. This is 1 milliarc sec or about 10 nms rms.

3.2.3.3 High order measurement error comes from a Keck estimate, dominated by photon noise. The value they assign is 30 nm rms. We probably have better numbers for this based upon analysis by Brent and Rene, but I do not have this handy at this time.

3.2.3.4 Servo response error also comes from a Keck estimate. I know we are working on this, but again, I do not have the correct numbers handy and would be glad to update this as the AO team sees fit. The value here is 18 nm rms for their assumptions.

3.2.3.5 Uncorrected optical errors are estimated as a series of reflective optics with similar correctable errors as used for the AO fold mirror in the A&G. Seven reflective surfaces are assumed, each contributing 1/20th wave rms at 0.6 microns to the wavefront after AO correction (1/40th wave rms surface). Some will no doubt be better, and some will be worse. The DM is considered to be one of these 7 elements. Assuming these 7 mirrors, the rss'd total is 79 nm rms (Strehl contribution of 0.92 @ 1.6 microns).

A full tolerance analysis may help here, but the AO correctable portion may be hard to predict (not impossible though!). It will be much more difficult to predict off axis, but that is to be considered at a later time.

3.2.3.6 Calibration errors are estimated to be 1/20th wave rms in the optical (0.6 microns). This is the same estimate made by Keck. This is 30 nm rms or a Strehl of 0.986 at 1.6 microns.

3.2.4 Zenith Dependence

The most direct effect on zenith related performance is atmospheric fitting. Accordingly, most of the zenith degradation is given to the AO subsystem to reach a delivered performance goal of 0.4 Strehl at 45^{o}.

The one other area given some allocation is the primary and secondary performance. This is consistent with the telescope error budget. It accounts for some zenith gravity effects (interaction with lateral supports) and wind buffeting predictions.

All items that do not have an explicit gravity allocation are expected to meet the stated error budget at any orientation. Within the AO subsystem, the workpackage team is free to make any trades among the sub-items listed as they see fit to better account for this effect.

3.3 Error Budget Producing 0.5 Strehl at 1.6 microns

Adaptive Optics Error Budget Spreadsheet								
Errors allocated in terms of rms wavefront error (or surface if noted)						non-AO limits		0.64
Rms errors added in quadrature								
Strehls calculated from following approx:				Strehl = S = exp[-2*PI*fractional rms wavefront]^2				
	(considered good for strehls above 0.2)					AO		
						Zenith		45 deg
						on axis rms wavefront (nm)		
1.0 Telescope Limitations						116		130
				Strehl @ 1.6 microns:		0.81		0.77
	Tilt/image smear effects							
		Tilt loop performance				0		0
	Higher order image quality effects							
		Primary mirror				60		75
		Secondary mirror				60		70
		Alignment				20		20
		Self induced seeing				50		50
		A&G				58		58
			AO fold			*30*		30
			Science fold (uncorrected)			*50*		50
2.0 Instrument Limitations						124		124
				Strehl @ 1.6 microns:		0.79		0.79
	Tilt/image smear effects							
		Flexure relative to OIWFS				25		25
	Higher order image quality effects					121		121
3.0 AO System						147		165
				Strehl @ 1.6 microns:		0.72		0.66
	Fitting errors (DM/WFS to atmosphere)					109		133
	- Strehl @ 1.6 microns from atm. fitting:				0.83		0.76	
	Tilt response					10		10
	Wind shake					34		34
	Servo response errors (bandwidth limitations)					18		18
	High order WFS measurement error					30		30
	Uncorrected internal optics					79		79
	Calbration errors					30		30
Totals:						224		244
				Wavelength (microns)		Strehl		
Strehl Totals:				0.7		0.02		0.01
				1		0.14		0.10
				1.2		0.25		0.20
				1.6		0.46		0.40
				2.2		0.66		0.62

3.4 Derivation of Required Degrees of Freedom

From the error budget item labeled "Fitting Errors (DM/WFS to atmosphere), we next derive the required number of degrees of freedom to achieve this residual error (for given atmospheric assumptions, to be stated below). Taken from the Keck "book" on AO, the following is a relationship for atmospheric variance and number of degrees of freedom for a DM (and WFS). The equation is their number 4.3-13.

$$\delta_{dm}^2 = \mu_N \left(D \Big/ \sqrt{N_{dof}}\, r_0 \right)^{5/3}$$

Where: D = 8 meters
r_0 = 25 cm for median seeing in the visible, 41 cm for 10% best seeing
μ_N= 0.221 for continuous facesheet DM
δ_{dm} = phase variance = 2μ rms σ/λ
σ = wavefront in nm rms
λ = 0.5 microns (or same as used in r_0 above)

Reworking this equation to solve for the number of degrees of freedom needed to attain a certain residual variance gives:

$$N_{dof} = \left[\frac{D/r_0}{\left(\delta^2/\mu_N\right)^{3/5}} \right]^2$$

For the median seeing (r_0 = 0.25 m) and a desired residual of 80.9 nm rms wavefront, this leads to a variance of 1.034 and 160 degrees of freedom needed on the DM (and wavefront sensor).

For best seeing (r_0 = 0.41 m) and the above conditions, 60 degrees of freedom are needed. To show more of the range of possibilities, Figure 3 plots required number of degrees of freedom versus rms wavefront error (in nm rms).

3.5 Summary and Future Work

This represents a first cut estimate of telescope, instrument, and AO subsystem contribution to delivered AO performance. The numbers should be reviewed, discussed, and appropriately modified. Some areas are fairly well defined at this time (such as primary and secondary mirror contributions). Others may change quite a bit. The key feature derived from this is what type of margin one must design for in the AO system to achieve delivered images of a given quality. The example shown suggests as much as a 30% margin is to be allowed for items not directly under the AO subsystem control. If one looks carefully at the numbers and rationale, one will quickly see that under the most optimistic conditions, this margin will not be substantially reduced without major and costly impacts upon the rest of the telescope system. We should all work to reduce this margin as much as reasonable, but we must be practical as some areas will cost quite a bit to improve substantially over the levels estimated here. My personal guess is that the best we will be able to do is in the range of a 20% margin to account for the telescope and instrument (as opposed to the 30% shown here).

Specific cases of analysis were described in the discussions presented. They include:

- Tolerance analysis of instrumentation (including surface quality effects)
- Tilt loop performance in the presence of wind (70th percentile wind was used and roughly scaled)
- AO subsystem optical tolerance analysis including correctable errors

These are only a few current examples. Also, as actual performance of various key items becomes available, this breakdown can be modified (and should!). For now, we can only estimate the effects based upon analysis done to date and some judgment. This will have to form the basis of any near term decisions to be made regarding AO subsystem implementation (along with any cost trades!)

4. Near Infrared Imager (NIRI) image quality error budget

4.1 Introduction

To date the specifications for the optical performance of NIRI have been set at 90% encircled geometric energy falling in a single pixel across the entire 1k^2 array for all modes. This specification was set well before the optical design of NIRI had taken shape, its plate scales defined, or even its science drivers well established in the context of Gemini's IRISWG. It also obviously ignores diffraction and seeing effects. It is therefore prudent to reevaluate the NIRI optical design specifications as the optical prescription for NIRI approaches its final form.

There are different science objectives for each of the 3 NIRI plate scales and each of these use the telescope and Gemini facilities differently. As a result it's important that we distinguish what is needed from each plate scale in defining useful design constraints. Over constraining in some areas can, for example, lead to inadequate exploration of design parameter space within the NIRI team. Under constraining optical specifications can lead to NIRI not meeting baseline Gemini science goals. In broad terms the 3 NIRI plate scales have different requirements pinned to use with either Gemini's AO or tip/tilt compensation systems. This short memo attempts to explain the driver behind each of the plate scales to offer guidance as design options are investigated.

4.2 NIRI image plate scale considerations

Narrow Field - 0.02" per pixel, 20" FOV

This mode is destined to be primarily used for adaptive optics applications and, as such, high Strehl is important to avoid degrading the wavefront passed by the telescope and AO unit. A NIRI intrinsic Strehl at J-K of >80% is desired to balance the NIRI, AO, and telescope error budgets. Note that this Strehl includes nominal decenters, tilts, surface irregularities, etc. of elements, as derived from the NIRI optical tolerancing analysis. This is not the "perfect" optical model specification which does not include fabrication error estimates. It should be noted that the specification for Gemini-N's AO system is pinned to H-band performance. Also, as NIRI's intrinsic optical Strehl effectively acts like a multiplier in the Strehl of final delivered images, pushing NIRI's f/32 mode to the highest possible intrinsic Strehl will be beneficial scientifically.

Image quality specifications should be held across the entire field of view (out to the corners) as the size of the AO corrected field in the near-infrared is large compared to NIRI's field of view in this mode. L and M imaging, where the diffraction limited PSF core is well sampled (nearly 6 pixels at L), and where the scientific motivation is not as strong as J-K for AO applications and AO may not be used in preference to the 0.05" mode, should not drive image quality as strongly as imaging at J-K.

Critically sampling the PSF will not be possible at J with the AO/NIRI combination. Nyquist sampling of the delivered AO PSF can be achieved in this mode though at H and longer wavelengths. While single integrations can in principle significantly degrade the Strehl in an image (e.g., by having the PSF fall on the intersection of pixels), with dithered image sequences, which should be the typical AO acquisition mode, it will be possible to recover high Strehl images at H and beyond to fully exploit high Strehl optics in NIRI (see TN-PS-G0027).

Middle Field - 0.05" per pixel, 51" FOV
This mode is driven primarily by tip/tilt imaging applications and is intended to properly sample Gemini's tip/tilt corrected delivered image across the entire J-M range. This is arguably the "work horse" mode among all those possible with NIRI. It may also have AO applications since sampling at L and M (2.3 pixels across the diffraction core at L) will be adequate and better utilization of the AO corrected field, where the isoplanatic patch size is large, will be achieved than the narrow field mode. Brent Ellerbroek's calculations indicate Strehls as high as ~70-80% can be achieved at L and M with a moderate order AO system on Gemini under median seeing, hence maintaining high intrinsic Strehl in NIRI at these wavelengths is important. Note that use of AO at L and M is designated as a goal in the current AO science requirements (see SWG-I-G0037).

Accordingly, specifications should be driven by the tip/tilt image quality delivered by Gemini at J-K and AO image quality at L and M, all under good seeing conditions. NIRI's intrinsic image quality should not degrade across the entire field in this mode.

Wide Field - 0.12" pixels - 123 arcsec FOV
NIRI's wide field mode will be used to image extended targets in which the utmost in spatial resolution and/or photometric accuracy is not required. This mode will also likely be used to generate mosaics of objects which otherwise greatly exceed NIRI's field of view. Due to the poor PSF sampling in this mode, AO is not a design driver and it should be assumed that tip/tilt compensation is all that is used.

The field of view is sufficiently large that the size of the tip/tilt corrected field needs consideration in defining specifications. Typically a few percent degradation in 50% encircled energy occurs between stars imaged on-axis and those imaged at a corner-pixel in this mode and this degradation should be factored into NIRI's optical specifications.

4.3 Error budget spreadsheet

The NIRI top level image quality error budget is given in the attached table. This gives the error budget in terms of 50% encircled energy for each of the plate scales used in NIRI and for each of the relevant wavelength bands. In addition to this table of 50% encircled energies, the finest platescale for NIRI (f/32) should conform to the Strehl based error budget given in the Adaptive Optics System error budget in the previous chapter.

To briefly explain this table, the top section starts with the expected atmospheric effect on 50% encircled energy and derives the telescope error budget (not including instruments). A more detailed breakdown of the telescope error budget is given in the first part of this document. It is pinned on the 50% encircled energy case at 2.2 microns, but some other cases are given.

In short the telescope error budget is that which allows a 15% degradation of the predicted atmospheric 50% ee value under the 10% best seeing conditions, assuming perfect tilt correction of the atmosphere (on axis). The combination of the atmosphere and telescope errors is assumed to follow a 5/3 squared dependence rather than an RSS'd combination. Diffraction is added back into the derived telescope errors to form the numbers to be used as the top level telescope error budget. Note the allowed telescope error budget at 2.2 microns, with diffraction, equals 0.1 arc sec 50% encircled energy.

From here, the additional allocations for the NIRI are derived for each image plate scale. Each is an on axis case and is to be used throughout the field for the f/32 and f/14 cases. An additional case is derived for the f/6 case which takes into account the larger field and the anisoplanatic effects. For each case, a percentage degradation in terms of delivered image quality is assumed based upon the above scientific rational and pinning the f/32 case 50% encircled energy case to be compatible with the Strehl based AO error budget (given previously). This leads to an additional 1% degradation (over the atmosphere and telescope) for the f/32 case (.02-.03 arc sec 50% ee without diffraction - this is roughly compatible with the Strehl allocation of about 80% in the AO error budget as this is in the range of 100 to 150 nm rms wavefront (depending upon type of error). The instrument error budget is also combined with diffraction and is scaled in terms of the physical size of the 50% encircled energy circle in the focal plane in use (labeled 'plate scale').

For the f/14 case, the allocation given is a 5% degradation on top of the atmosphere and telescope. This is consistent with taking advantage of the best seeing conditions with minimal impact on delivered images for this case when not using adaptive optics. It should be noted that the values derived (and sampling) are also consistent with diffraction limited performance in the L and M bands if used with AO.

For the f/6 case, where the wide field is the emphasis (and appropriately large plate scale and pixels are used), a much larger degradation of 20% is allowed. This 20% roughly accounts for the pixel plate scale changes in terms of encircled energy effects (scaling as the area) as compared to the finer plate scales. If one considered the pixel plate scale effect, this 20% degradation will not be seen under best seeing as the plate scale is not capable of resolving very well. Under median seeing, this is effect is not seen.

Table 1. Near Infrared Imager image quality error budget (delivered images)

Telescope error budget						
Wavelength	1.200	1.600	2.200	3.700	4.800	
Onboard WFS use						
On-axis, tilt corrected atmosphere	0.193	0.183	0.176	0.154	0.169	
With 15% degradation	0.222	0.210	0.202	0.177	0.194	
Allowable telescope errors	0.086	0.082	0.079	0.069	0.076	
Top-line error budget (w/diffraction)	0.093	0.095	0.102	0.129	0.161	
Instrument additions						
On axis case						
Imaging f ratio	*32*		*1% degradation allowed*			
Instrum. Allocation to Delivered Images - Non AO case, 50% encircled energy diameters						
Delivered images	0.224	0.212	0.204	0.179	0.196	
Allowable Telescope & Inst. errors	0.091	0.086	0.082	0.072	0.079	
Instrumentation errors	0.027	0.026	0.025	0.022	0.024	arcsec
plate scale w/o diff.	33	31	30	26	29	microns
Instrument with Diffraction	0.045	0.054	0.069	0.104	0.144	arcsec
plate scale w. diff.	55	66	85	128	176	microns
Imaging f ratio	*14*		*5% degradation allowed*			
Instrum. Allocation to Delivered Images - Non AO case, 50% encircled energy diameters						
Delivered images	0.233	0.221	0.212	0.186	0.204	
Allowable Telescope & Inst. errors	0.106	0.100	0.097	0.085	0.093	
Instrumentation errors	0.062	0.058	0.056	0.049	0.054	arcsec
plate scale w/o diff.	33	31	30	26	29	microns
Instrument with Diffraction	0.071	0.075	0.086	0.113	0.152	arcsec
plate scale w. diff.	38	40	46	61	81	microns
Imaging f ratio	*6*		*20% degradation allowed*			
Instrum. Allocation to Delivered Images - Non AO case, 50% encircled energy diameters						
Delivered images	0.266	0.252	0.242	0.212	0.233	
Allowable Telescope & Inst. errors	0.157	0.149	0.143	0.125	0.138	
Instrumentation errors	0.311	0.124	0.119	0.105	0.115	arcsec
plate scale w/o diff.	30	29	27	24	26	microns
Instrument with Diffraction	0.136	0.133	0.136	0.146	0.183	arcsec
plate scale w. diff.	31	31	31	34	42	microns
Off axis Telescope						
Off axis use - f/6 case only	1.200	1.600	2.200	3.700	4.800	

Off axis tilt corrected atmosphere	0.199	0.189	0.182	0.169	0.181
With 15% degradation	0.229	0.218	0.209	0.194	0.208
Allowable telescope errors	0.089	0.085	0.081	0.076	0.081
Top-line error budget (w diffraction)	0.096	0.097	0.104	0.133	0.163

Imaging f ratio 6 20% degradation allowed

Instrum. Allocation to Delivered Images - Non AO case, 50% encircled energy

Delivered images	0.275	0.261	0.251	0.233	0.250	
Allowable Telescope & Inst. errors	0.162	0.145	0.148	0.138	0.148	
Instrumentation errors	0.137	0.131	0.125	0.119	0.127	arcsec
plate scale w/o diff.	32	30	29	27	29	microns
Instrument with Diffraction	0.142	0.139	0.141	0.157	0.190	arcsec
plate scale w. diff.	33	32	32	36	44	microns

Note that 85% ee numbers would be about 2-2.5 times larger than the above numbers.

5. Bottom-up error budget development

5.1 Relation of detailed error budget items to design/manufacture specifications

The bottom-up error budget will be evolving throughout the design process. This is necessary to relate the manufacturing and assembly tolerances believed to be achievable to the system performance at some reasonable level of detail. The top-down budget presented is in terms of arcseconds of resolution, tracking capability, etc. This budget tree would become extremely large and complex if it were taken down to the component level design specification. A complete top-down approach will usually lead to completely unrealistic specifications on individual components. At some point, when the tree reasonably represents the detailed areas of concern, a bottoms-up approach is adopted. The engineers doing the detailed design of subsystems and components must specify achievable manufacturing tolerances.

5.2 Manufacturing tolerances

From these manufacturing tolerances, judgments must be made as to how various tolerances or specifications may affect or relate to the system top-down error budget. Often this will involve working up from the most detailed parts of the design, combining the effects of other related subsystems, to compare with the appropriate level in the top-down error budget.

An example to consider might be the surface figure error on the primary mirror. An assumption has been made in the top-down error budget that some of the error in the mirror figure will be taken out by active control of the mirror. This is necessary since it is not believed that a mirror of this size may be made accurately enough on its own. Since the mirror is also expected to move and sag differently as the telescope pointing changes, the telescope system already has in place a method which may be used to back out some of the manufacturing errors. Keeping this in mind will allow placing a more realistic specification on final figure polishing of the mirror since some of the low spatial frequency errors may be corrected. Final mirror polishing specifications will evolve during the design along with expected limits on the amount of control available to change the shape of the mirror, how much shape correction will be needed to correct for sag changes as the telescope pointing changes, and reasonable margins of safety.

5.3 List/prioritize manufacturing/error budget discrepancies

As this bottoms-up process continues throughout the design, there will be several areas where there are large initial discrepancies between the bottoms-up estimates and the top-down error budget. These items will be listed and prioritized as to the importance to the overall system level goal. In other areas, it may be found that the error budget for that item is easily met with some margin. The list of error budget discrepancies may be compared with areas where improvements are made to see if a straightforward change in the budget tree allocations between two or more areas will solve the problem. Those which are not easily resolved with simple tradeoffs with other areas should remain on an overall error budget discrepancy list.

6. Plans for resolving discrepancies

Though it is usually best to correct discrepancies in performance at the source of the error, it may not be practical. If the problem can not be easily traded off in its error budget against another area (loosening the troublesome error budget and tightening another error budget item to compensate at the system level), then there are several other courses of action to take.

In all cases, the appropriate engineering managers concerned with these trades or corrections will be involved in a cooperative team effort to resolve any problems. This will offer the advantage of a team effort in problem solving, and everyone concerned will automatically be aware of any changes required. System engineering will be responsible for coordination of these efforts and in documenting any interface changes and updated the appropriate error budget.

6.1 Corrections based upon analysis

If the error is something which is fixed and can be estimated accurately by a reasonable amount of analysis, there may be some way to correct for the error elsewhere in the system. An example is using the active control of the secondary position to correct in an open-loop manner bending in the telescope structure which changes with pointing. It is not practical to build a perfectly rigid structure of this size, and the ability to correct for misalignments is built into the system design. This is an example which has been considered, but there may be other similar cases which arise as the program progresses.

6.2 Corrections based upon calibrations

Where the ability to analyze the fixed errors accurately enough is difficult or uncertain, the error may be calibrated by a direct measurement of the effect. Where possible, these types of calibrations should be performed on the system to also verify any analysis results being used. An example might be actual secondary mirror displacement measurements versus telescope pointing.

These would be used in place of the calculated displacements to improve the correction (as long as the measurement error is less than the expected analysis error).

In some cases, actual closed-loop control will be used to compensate for random errors below a certain bandwidth (sort of a real-time calibration). Examples of this include controlling the primary mirror figure and/or alignment using feedback from the wavefront sensor, and controlling the tip/tilt of the secondary mirror using feed back from an imaging sensor to reduce image motion in the final image plane.

6.3 Trades in subsystem requirements

A reasonable effort will be made to meet the goals for the other desired telescope configurations/uses. This will be done by applying the bottoms-up error analysis to these other applications to estimate the system performance. While considering any telescope subsystem trades, these other uses will be considered. Where there is no reasonable method of resolving the subsystem trades to satisfy all possible uses, priority will be given to performance of the IR f/16 Cassegrain configuration operating at 2.2 microns.

7. Monitor performance related subsystem errors

To minimize risks associated with meeting the system level goals, continual monitoring of the design, fabrication, and integration progress will be needed to update the error budget as the program evolves. This will be accomplished by reviews on a regular basis of any interface-related issues. These reviews will monitor any changes of any expected subsystem performance estimates. System engineering will be responsible for tracking of the overall error budget and updating it from a bottoms-up approach as needed. Any problem areas will be identified and tracked specifically until a satisfactory solution is found. Inputs from the responsible engineering areas to this effort will be required along with help to resolve any issues. Major updates/reviews of the error budget should coincide with major design, fabrication, and integration milestones.

8. Definition of Terms

Active Control

Residual errors the telescope wavefront due to inaccuracies in the active control system. (wavefront sensor and control system).

Alignment of Optics

The residual errors associated with how well the telescope can be adequately aligned in a static sense (decenter, defocus, relative tilt).

Coating Thickness (primary and secondary)

Errors in the surface of the mirror caused by non-uniform coating applied to the mirror surface. Low spatial frequency errors will be corrected by the active system.

Coma Induced by Atmospheric Tilt Correction

The time varying optical image quality degradation which occurs when corrections of atmospheric tilt are made to maintain "tracking" but are not the optimum correction. This effect comes from the tracking concept which will take out most of the atmospheric tilt component (90% min. as stated in the science requirement). The secondary mirror is tilted to maintain the image on the guide probe thus removing the atmospheric tilt component. This causes some optical system degradation due to the tilting secondary which changes with time.

Diffraction Size

Percent encircled energy based upon a diffraction calculation of the on axis optical design of the telescope.

Dynamic Image Quality

The time varying optical image quality degradation which occurs when corrections are made to maintain "tracking" but are not the optimum correction. For example, dynamic wind loading on the telescope structure may cause the secondary mirror to decenter with respect to the primary mirror. At medium to higher frequencies, the secondary mirror would be tilted to bring the resulting image motion to zero (back to some nominal set point, i.e. track/guide). This would cause a slight tilt between the secondary and primary which would cause some coma to be introduced in the image. This optical degradation (coma in this case) is what is represented here.

Dynamic Optical Alignment

The time varying optical image quality degradation which occurs when corrections are made to maintain "tracking" but are not the optimum correction. For example, dynamic wind loading on the telescope structure may cause the secondary mirror to decenter with respect to the primary mirror. At medium to higher frequencies, the secondary mirror would be tilted to bring the resulting image motion to zero (back to some nominal set point, i.e. track/guide). This would cause a slight tilt between the secondary and primary which would cause some coma to be introduced in the image. This optical degradation (coma in this case) is what is represented here.

Enclosure (self induced seeing)

Additional degradation over natural site seeing conditions caused by the dome. This includes effects of heat sources within the dome, emissivity of the dome surface, etc.

Field Angle Position

Addition degradation (in an rss'd sense) to the on-axis optical design as larger field angles are used. This is typically small for narrow field modes, but may be significant for wide field applications.

Image Quality

Top-level description of telescope system performance. It is given in terms of percentage of encircled energy. The units are arcseconds.

Image Smear

This represents the residual image motion which the track/guide system cannot take out. The net amount of image smear will depend upon the integration time needed for the observation. The science requirement places an upper limit of one hour integration time. For a short integration period ("snapshot") an image may appear to be quite good, but any residual motion over longer integration times will smear the resulting image to appear larger. This is the top-level tacking servo system error budget.

Optical Design

Image size limit based upon the optical design of the telescope including diffraction and field effects.

OSS Structure Delta T (self-induced seeing)

Seeing caused by temperature differences between the Optical Support System (OSS) surface and ambient air. The OSS is all of the telescope system above the primary mirror surface.

Pointing (dynamic optical alignment)

As the wind changes the overall pointing of the telescope structure, the closed-loop tracking system will tilt the secondary (for high-frequency correction) to maintain alignment of the image on the guide probe. This causes a relative tilt of the secondary with respect to the primary (resulting in some coma in the image).

Pointing Residuals (image smear)

As the wind changes the overall pointing of the telescope structure, the closed-loop tracking system will tilt the secondary (for high-frequency correction) to maintain alignment of the image on the guide probe. This represents the residual servo errors or residual motion on the guide probe which will smear out the image over the science detector integration time.

Polishing Residuals (primary and secondary)

Residual errors in polishing the mirror after correction by the active support system.

Primary Mirror Delta T (self induced seeing)

Seeing caused by temperature differences between the primary mirror surface and ambient air. This is also a function of laminar flow across the mirror surface.

Primary Secondary Decenter (image smear)

Relative decenter of the secondary with respect to the optical axis defined by the primary which causes a motion of the image in the focal plane. This represents the residual servo errors or residual motion on the guide probe which will smear out the image over the science detector integration time.

Primary Secondary Tilt (image smear)

Relative tilt of the secondary with respect to the optical axis defined by the primary which causes a motion of the image in the focal plane. This represents the residual servo errors or residual motion on the guide probe which will smear out the image over the science detector integration time.

Primary (surface errors)

Errors in the primary mirror optical surface from various sources.

Primary w.r.t. CR residuals (image smear)

Relative motion of the primary mirror with respect to the Cassegrain Rotator (CR) which causes a motion of the image in the focal plane. This represents the residual servo errors or residual motion on the guide probe which will smear out the image over the science detector integration time.

Residual Articulation System Tilt (image smear- chopping case only)

Residual relative tilt between the primary and secondary due to flexure within the secondary mirror articulation system.

Residual Mirror Tilt (image smear-chopping case only)

Residual relative tilt between the primary and secondary due to mirror mount point flexure.

Residual Top End Tilt (image smear-chopping case only)

Residual relative tilt between the primary and secondary due to top end structural deformations.

Secondary Decenter

Relative decenter of the secondary with respect to the optical axis defined by the primary.

Secondary Defocus

De-spacing of the secondary with respect to the primary from the "nominal" location.

Secondary Mirror Delta T (self induced seeing)

Seeing caused by temperature differences between the secondary mirror surface and ambient air. This is also a function of laminar flow across the mirror surface.

Secondary (surface errors)

Errors in the secondary mirror optical surface from various sources.

Secondary Tilt

Relative tilt of the secondary with respect to the optical axis defined by the primary.

Self Induced Seeing

Additional degradation over the natural site seeing conditions caused by the enclosure and telescope systems.

Servo System Residuals (image smear)

Residual response of the servo system in attempting to hold the image steady in the focal plane. At this time, this is serving as a place holder separate from the other sources of error listed under image smear. Each of the other sources actually feed into the servo system which serves as a filter for the errors caused. This part of the error budget will be reorganized once a system servo model is in place which better represents the combination of errors involved.

Static Image Quality

The basic limit of image quality for the telescope neglecting dynamic effects from image motion and the associated change in optical performance to correct the image motion. There are a couple of items which technically may be considered dynamic, but were included here anyway for a cleaner "grouping" of some errors for some subsystems.

Support Residuals (primary and secondary)

Residual errors in the surface of the mirror due to stress or errors in the support system.

Surface Errors

Errors in the optical surfaces from various sources causing additional degradation to the overall performance.

Telescope (self induced seeing)

Seeing caused by temperature differences between ambient air and the primary mirror, secondary mirror and the optical support structure (telescope structure above the primary).

Thermal Distortion (primary and secondary)

Residual errors in the mirror shape (after correction by active system) caused by thermal changes in time and gradients across the mirror.

Wind buffeting (primary and secondary)

Errors in the mirror shape due to wind pressure (static and dynamic) on the mirror.