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TECHNICAL FACILITIES

Atmospheric Dispersion Corrector for the Low Resolution Imaging Spectrograph Delta Conceptual Design Report

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PREFACE

I have assembled this report from information provided by the ADC design team at UCO/Lick. We have collaborated to refine the presentation and we hope you will find it clear and reasonably easy to evaluate.

I have made an analysis of the proposed schedule and budget, and my comments on this are included in the schedule and budget section of the report.

Sean Adkins
Instrument Program Manager
CARA
February 2, 2003

INTRODUCTION

The purpose of this report is to answer specific questions posed by the design review committee in their report on the conceptual design review of the LRIS-ADC held December 2, 2002. The report is divided into 3 sections:

- Optical Design
- Mechanical Design
- Schedule and Budget

Each section contains an introduction that identifies the questions arising from the design review that are addressed by the new material presented in this report. This introduction also summaries the key findings in that section for ready reference.

The design for the ADC as presented in this report represents an evolution of the mechanical design concept, incorporating several improvements as well as shifting the preferred configuration to separate mounting of the ADC rather than permanently attaching it to LRIS. The optical design concepts remain the same as given in the original conceptual design, but further analysis of the expected performance has been provided. The budget and schedule are completely revised from the original conceptual design report and some of the extra cost options from the original conceptual design have been retained.

The revised conceptual design has been reviewed by design and operations personnel at CARA and includes their input into the proposed design.

OPTICAL DESIGN

The questions with respect to optical design in the report of the committee on the conceptual design of the LRIS-ADC were the following:

1. "The Committee wants to see a conceptual design for the entire 0.31 to 1.1 micron wavelength in the delta-CoD."

2. "…it would also like to see an evaluation of the expected transmission in the full wavelength range using the best available measurements of Sol-gel coatings and the best commercial fused silica glasses…"

3. "The Committee wants to see a "back of the envelope" evaluation of the LADC ghost intensities in the LRIS in the delta CoD."

These questions are addressed in the following sections of this report. The findings to follow are now summarized in answer to these questions:

1. The residual dispersion performance of the conceptual design has been evaluated over the wavelength range of 0.31 to 1.1 microns using actual refractive indices for UV-grade fused silica. The results of this analysis show that with a maximum distance between the two prisms of 700mm the residual dispersion over the wavelength range of 0.31 to 1.1 microns is within 0.8" compared to the uncorrected dispersion of 3.39" at a zenith angle of 60 degrees.

2. The transmission of the ADC using transmission data for Corning HPFS Code 7980 fused silica glass, and published data for measured performance of sol-gel+MgF_2 coatings is estimated to be greater than 0.94 at all wavelengths from 0.3 microns to 1.1 microns.

3. The worst case ghost/parent ratio for LRIS-ADC ghost reflections using a simple geometric analysis is estimated to be 6×10^{-5} for a minimum prism separation of 4mm. When the separation is increased to 10mm, the ghost is reduced to 10^{-6} of the parent.

ADC Performance over the Wavelength range of 0.31 to 1.1 Microns

Introduction

The original LRIS-ADC Phase-A Report did not include data for performance at wavelengths less than 0.4 microns, although this material was presented to the review committee at the actual review (http://www.ucolick.org/~phillips/adc/). We have been asked by the committee to provide performance (i.e. residual dispersion) results over the wavelength range of 0.31—1.1 microns, and using actual indices of refraction[1] rather than the interpolation formula used for the review.

One difficulty is that there are various ways to calculate the prism separation to produce optimal results. For example, the Nelson & Mast report simply minimized the rms radii of images. However, this may have the affect of providing very poor corrections at some wavelengths. In the following figures the prism separation is calculated by averaging over the separation needed to superimpose the images at the sample wavelengths onto an image at 0.45 microns. This probably provides a better result for most science applications.

Since the results are given relative to a reference wavelength of 0.45 microns, the residual dispersion at this wavelength is always zero.

The ADC model used is for the original design: 5° prism angle, 700mm maximum separation, and inner surfaces of the prisms perpendicular to the optical axis of the telescope. The sample wavelengths chosen were: 0.32 – 1.10 microns in equal log-intervals (0.32, 0.36, 0.40, 0.45, 0.50, 0.56, 0.63, 0.70, 0.79, 0.88, 0.98, 1.10 microns), and 0.31 microns. The last value is likely to be of extremely low interest, as the Mauna Kea atmospheric extinction is 1.5 magnitudes per airmass at 0.31 microns. At Z=60° the increase in airmass results in a 4 fold increase in extinction. For this reason, observers interested in this wavelength are unlikely to observe far from the zenith, and thus need an ADC. (For comparison, at 0.32 microns the extinction is 0.8 magnitudes/airmass).

Performance Figures

Figure 1 shows the ADC performance over zenith distances of 0—75 degrees, with the current ADC design of a maximum 700mm prism separation (5 degree prisms). The maximum prism separation is reached at Z=54°. The two gray bars show the *uncorrected* dispersion at Z=60° and Z=72° for reference.

[1] The indices at each wavelength were obtained from http://www/luxpop.com for UV-grade fused silica and for air, both at 2º C. The fused silica values are referenced to I. H. Malitson, *J. Opt Soc. Am.* 55, no. 10, pp. 205—1209 (1965). Values from this source agree with those from Corning to within the stated accuracy (3×10^{-5}). They appear to be slightly below those adopted in the Nelson & Mast report by 5×10^{-5}.]

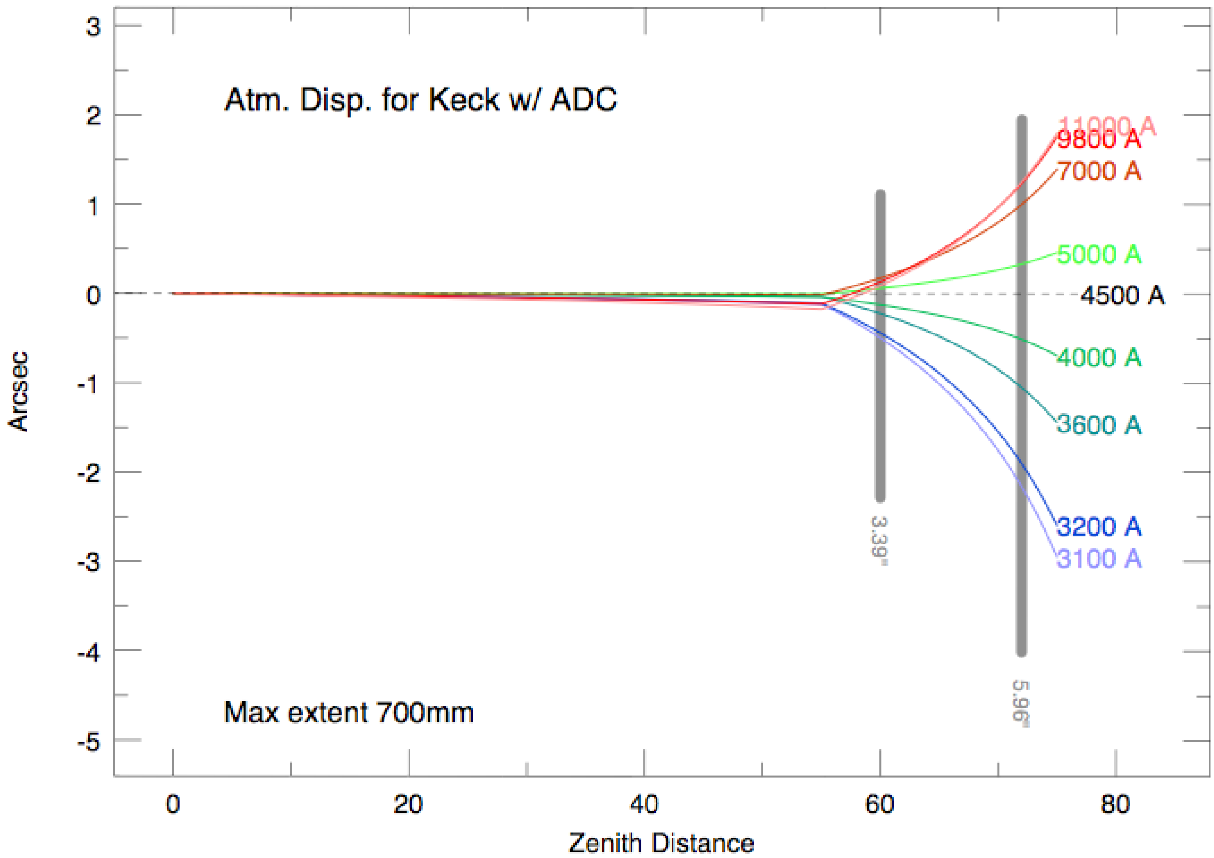


Figure 1: Atmospheric Dispersion for Keck with ADC, 5º Prisms

Figure 2 shows a typical spot diagram for ADC corrected images at all the sample wavelengths. This is at Z=54° and 700mm separation.

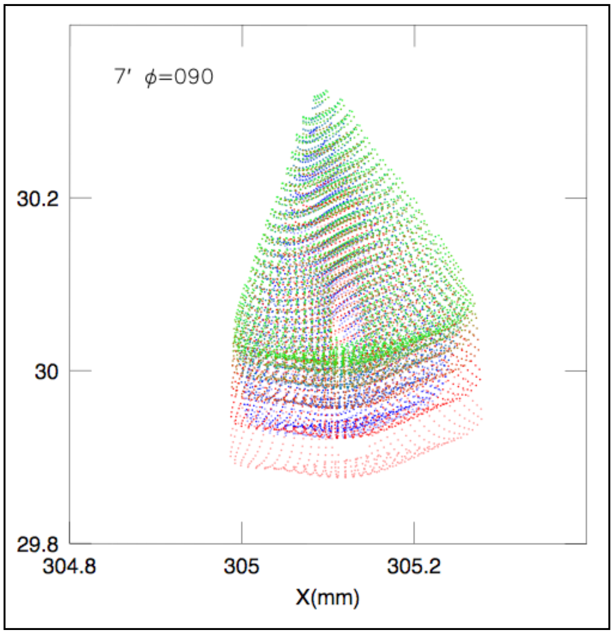


Figure 2: Typical ADC Spot Diagram, 5º Prisms

To illustrate the corrections achievable, figure 3 shows an ADC of the same design but without a limit on maximum prism separation. Full correction is achieved at Z=60° with a prism separation of 845mm. The scale has been magnified compared to the figure above. Note that all curves lie at or below zero because 0.45 microns was chosen as the reference wavelength, as discussed above. Also, note that this figure is identical to figure 1 for zenith distances up to 54°.

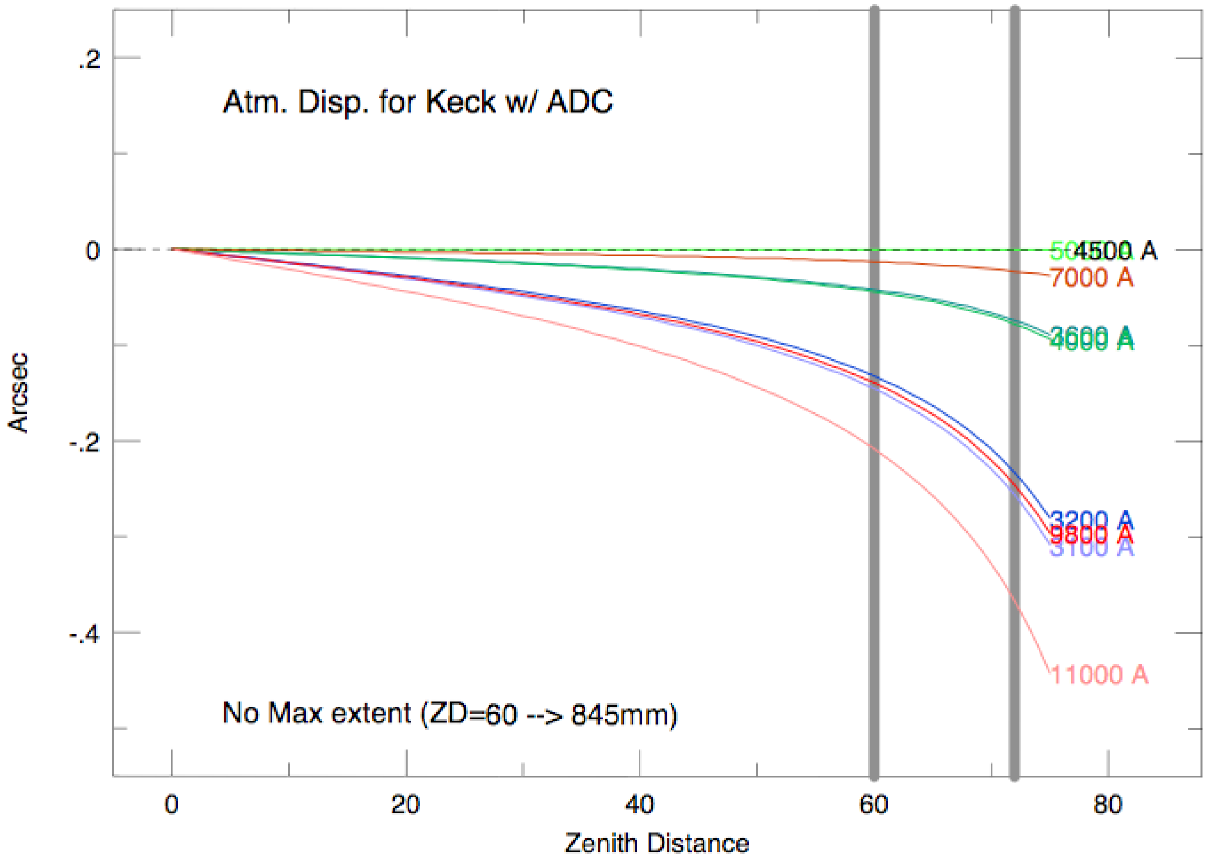


Figure 3: Atmospheric Dispersion for Keck with ADC, No Limit on Prism Separation, 5º Prisms

Residual Dispersion Values

Table 1 gives the residual dispersion values as a function of wavelength for the cases of Z=55° and Z=60° without a limit on the prism separation (700mm for the 55° case, and 845mm for the 60° case). The residual dispersion for Z=60° with a maximum prism separation of 700mm is also shown.

Table 1: Residual Dispersion Values, 5º Prisms

$\lambda(\mu m)$	*Residual (Z=55)*	*Residual (Z=60)*	*Residual (Z=60,700mm)*
0.31	-0.068"	-0.083"	-0.495"
0.32	-0.057	-0.070	-0.419
0.36	0.017	0.020	-0.202
0.40	0.016	0.018	-0.1.5
0.45	0.052	0.062	0.019
0.50	0.052	0.062	0.080
0.56	0.052	0.062	0.132
0.63	0.059	0.071	0.182
0.70	0.041	0.049	0.194
0.79	0.031	0.036	0.211
0.88	-0.007	-0.009	0.193
0.98	-0.063	-0.077	0.152
1.10	-0.120	-0.146	0.108
Rms	0.059"	0.071"	0.235"

PSF Quality

At the review there was a question about the possible differences in the PSFs at wavelengths shorter than 0.4 microns. Since the difference in refractive index is small over the entire wavelength range in comparison to the average index of fused silica relative to air, it was argued that aberrated images should not be very different at the shorter wavelengths. The spot diagrams shown in figures 4 through 6 support this expectation. Each figure consists of a set of spot diagrams at six wavelengths for a point 7' off-axis in the x-direction at the full 700mm prism separation. The three figures are for dispersion (and thus correction) at angles of 0, 90 and 180 degrees with respect to the x-axis.

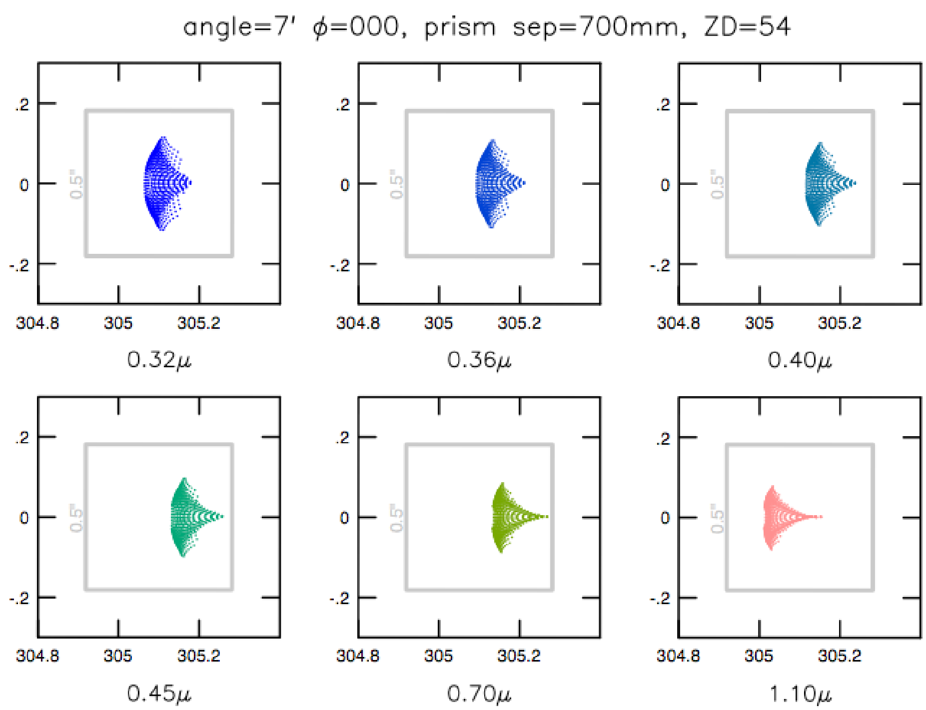


Figure 4: Spot Diagrams for 0º with Respect to the X-axis, 5º Prisms

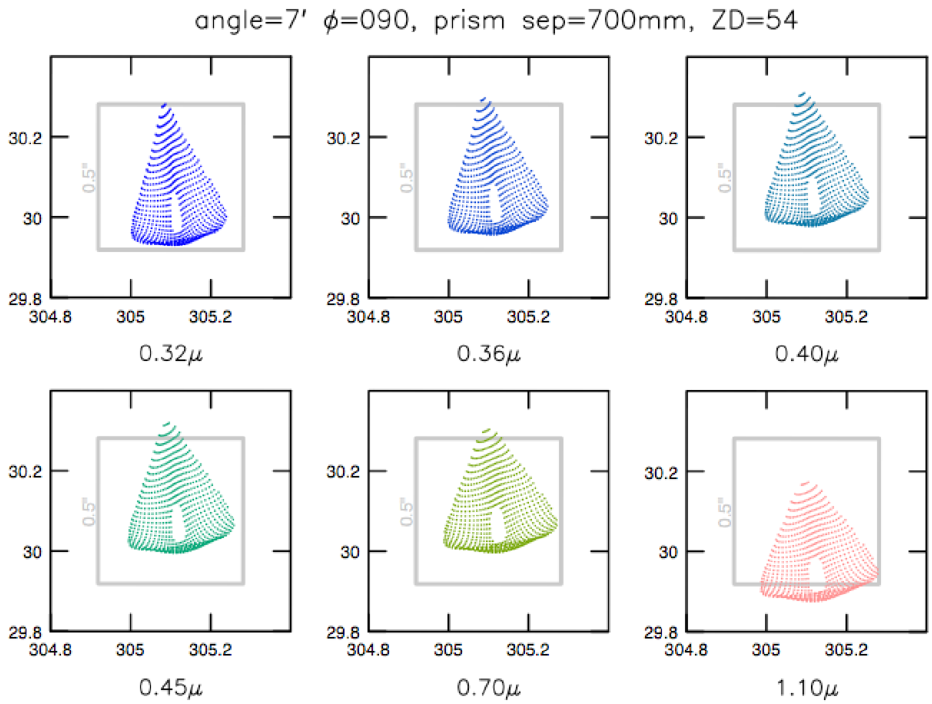


Figure 5: Spot Diagrams for 90º with Respect to the X-axis, 5º Prisms

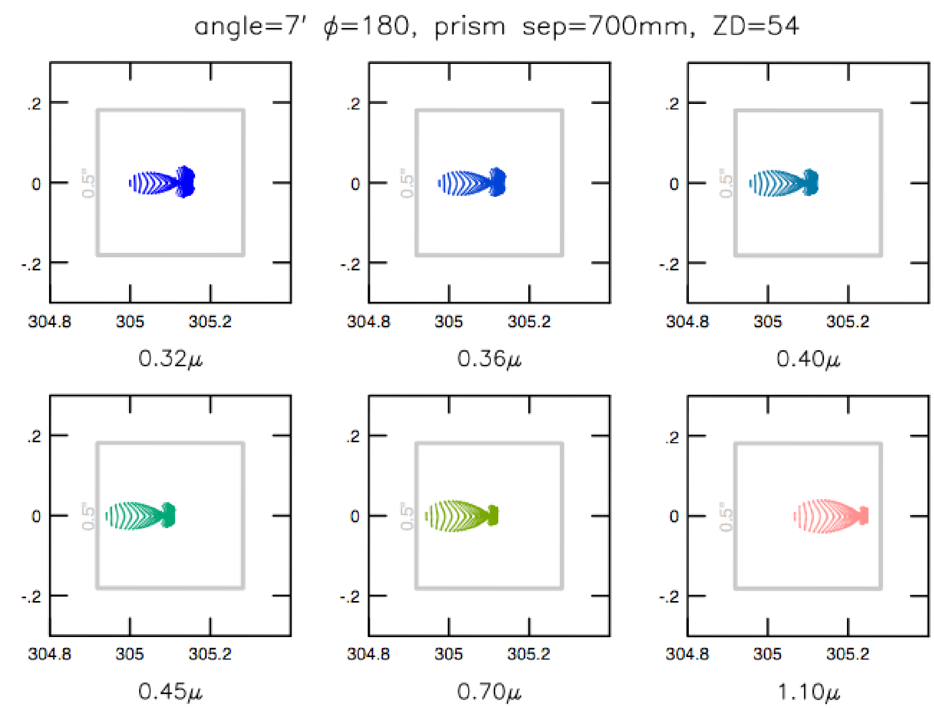


Figure 6: Spot Diagrams for 180º with Respect to the X-axis, 5º Prisms

Full-aperture ADC Performance

The ADC performance described in the previous sections corresponds to the optical configuration of the original conceptual design and to the currently proposed sub-aperture design. A second configuration, the full aperture design has also been proposed and the development of a full aperture configuration for the ADC necessitates an increase in the diameter of the optics. In order to retain the same thickness of fused silica, it was decided that this second design would have twice the travel (around 1400 mm) and half the prism angle for each optic (2.5°). While we anticipate that the performance will be identical to the previous design, we present the performance figures derived for this specific design. These demonstrate our expectations were correct – there is virtually no difference between the 700mm/5° and 1400mm/2.5° designs.

Performance Figures

Figure 7 shows the full-aperture ADC performance over zenith distances of 0—75 degrees, without maximum prism-separation constraints. At Z=60, the full correction requires a separation of 1700mm. As before, the curves are normalized to 4500A.

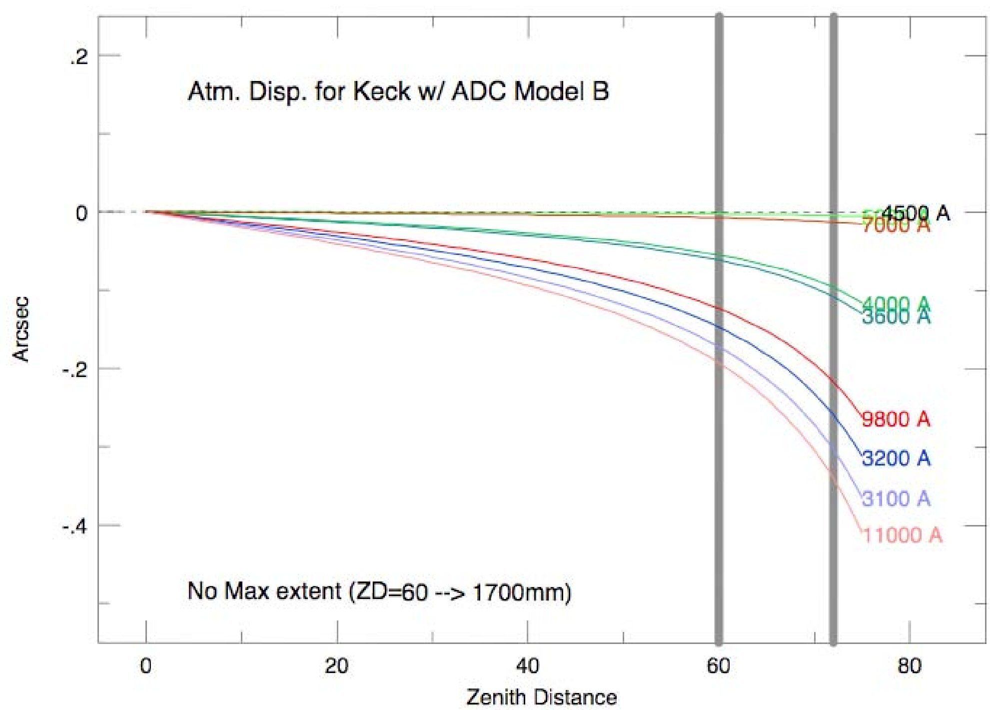


Figure 7: Atmospheric Dispersion for Keck with ADC, 2.5º Prisms

Figure 7 looks similar to, but is not exactly the same as that for the sub-aperture design (figure 1). The difference is almost certainly due to some inaccuracy or round off in calculating the "best" prism separation. Relative to the previous case, the IR correction is slightly better at the expense of the UV correction.

Figure 8 shows a typical spot diagram for ADC-corrected images at all the sample wavelengths. This is at Z=55° and 1400mm separation.

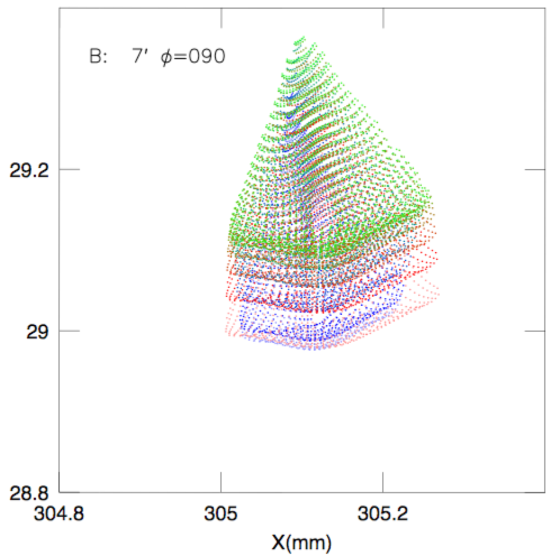


Figure 8: Typical ADC Spot Diagram, 2.5º Prisms

Residual Dispersion Values

Table 2 gives the residual dispersion values as a function of wavelength for the cases of Z=55° and Z=60° without a limit on the prism separation (700mm for the 55° case, and 845mm for the 60° case). The residual dispersion for Z=60° with a maximum prism separation of 1400mm has not been computed for this analysis.

Table 2: Residual Dispersion Values, 2.5º Prisms

λ(μm)	*Residual (Z=55)*	*Residual (Z=60)*	*Residual (Z=60,1400mm)*
0.31	-0.090”	-0.109”	(Not calculated)
0.32	-0.069	-0.084	…
0.36	0.001	0.002	…
0.40	0.007	0.008	…
0.45	0.052	0.063	…
0.50	0.050	0.061	…
0.56	0.059	0.071	…
0.63	0.066	0.080	…
0.70	0.046	0.056	…
0.79	0.035	0.043	…
0.88	-0.003	-0.004	…
0.98	-0.050	-0.060	…
1.10	-0.107	-0.130	…
Rms	0.060”	0.073”	…

As noted in the previous section, the IR correction is slightly better at the expense of the UV correction. This is entirely consistent with a slight difference in calculating the best value for the prism separation, rather than being fundamental to the design.

PSF Quality

The spot diagrams in figures 9 through 11 are for the full-aperture design. They are improved in some cases and worse in others, but the **average** rms-diameter is virtually unchanged at 183µm. The average is calculated from spots at 4, 7 and 10' off-axis, with the prisms oriented at 0, 90 and 180 degrees. The corresponding rms-diameter for the 700mm/5° system was 184µm.

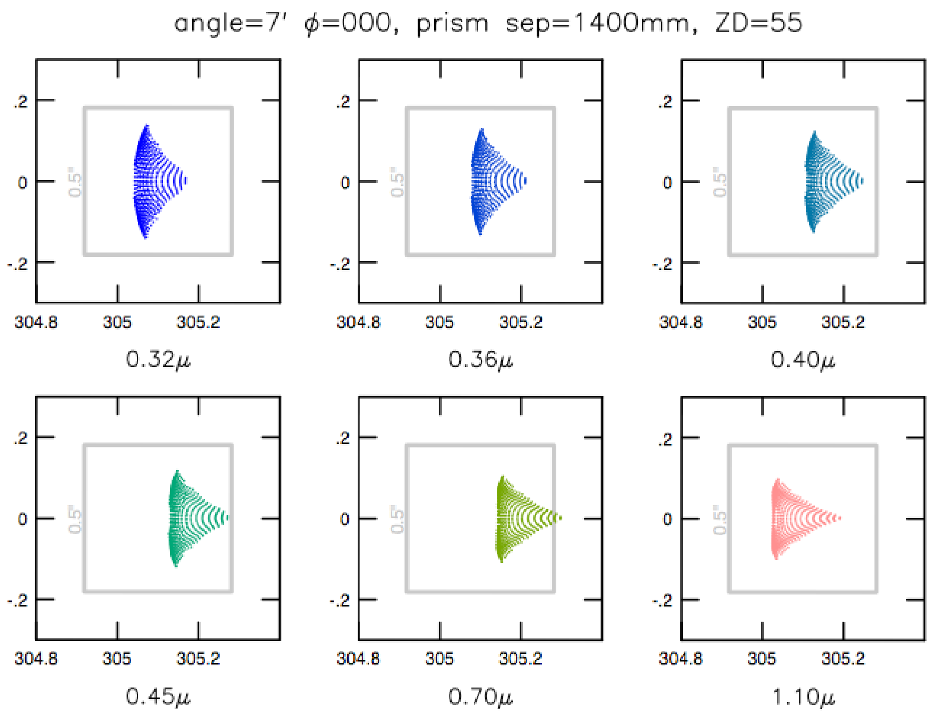


Figure 9: Spot Diagrams for 0º with Respect to the X-axis, 2.5º Prisms

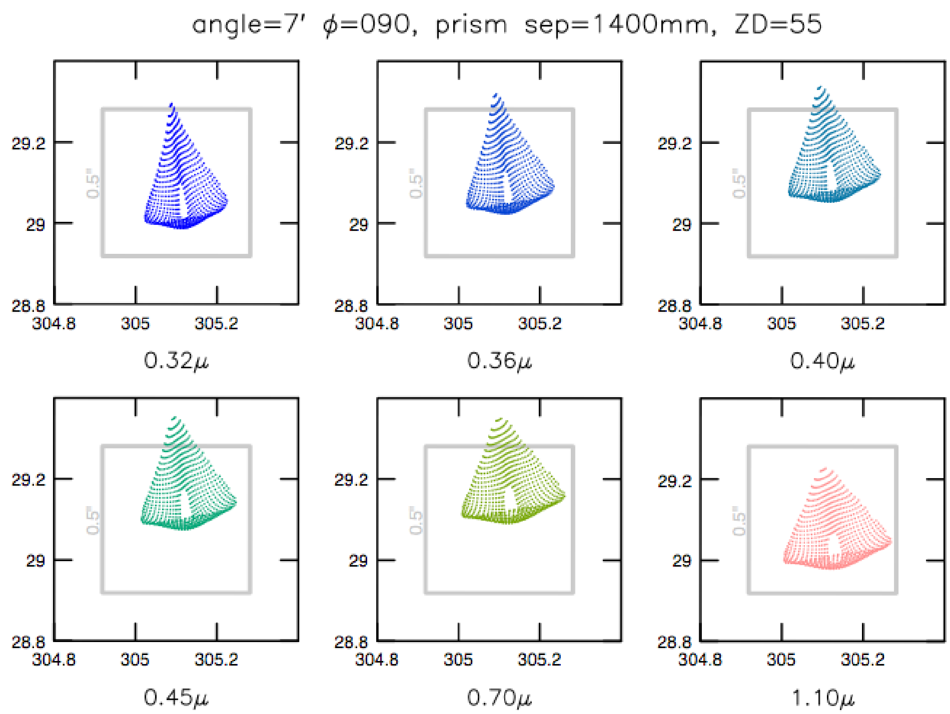


Figure 10: Spot Diagrams for 90º with Respect to the X-axis, 2.5º Prisms

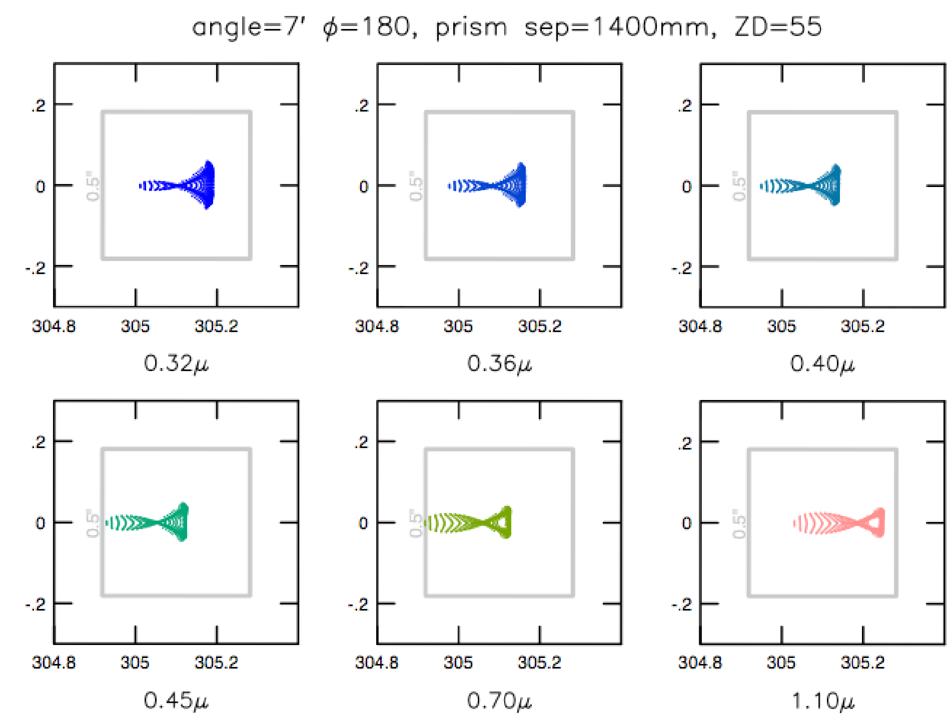


Figure 11: Spot Diagrams for 180º with Respect to the X-axis, 2.5º Prisms

Throughput Estimates

We have been asked by the review committee to provide throughput estimates using the best values for sol-gel coatings and glass transmission available. We have succeeded in obtaining good transmission values for fused silica; the sol-gel+MgF_2 curves have proven somewhat more problematic.

Fused Silica Transmission

Figure 12 shows a transmission curve for 1cm of fused silica, which was provided by Corning (HPFS Code 7980).

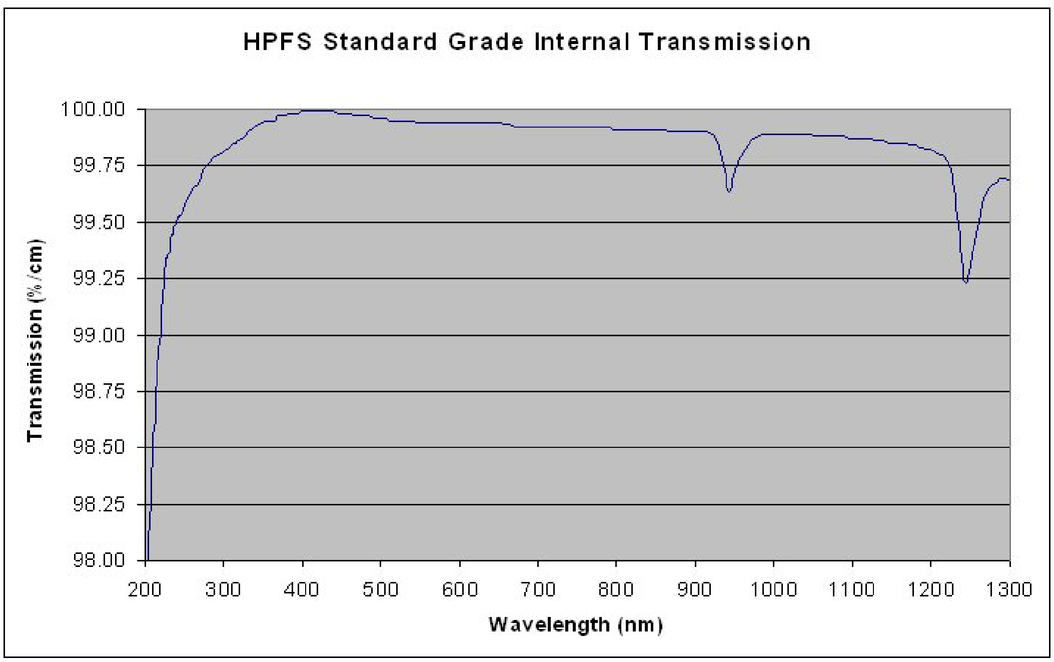


Figure 12: Transmission Curve for Fused Silica

From this, we can estimate the transmission of 70mm of fused silica as shown in table 3.

Table 3: Transmission of 70mm of Fused Silica

$\lambda(\mu m)$	*10mm*	*70mm*
0.30	.998	.986
0.32	.9985	.9895
0.35	.9995	.9965
0.40	.9999	.9993
0.45	.9998	.9986
0.50	.9996	.997
0.60	.9995	.996
0.70	.9993	.995
0.80	.9992	.994
0.90	.9990	.993
0.93	.9963	.974
1.00	.9989	.992
1.10	.9987	.991

We see that the **total** glass losses are about or less than 1% throughout the range, except for a small dip to 2.6% around 0.93 microns.

Sol-gel Coatings

Information on sol-gel+MgF2 coatings has been more difficult to obtain. James Stilburn kindly provided information on the measured throughput of the GMOS ADCs, and removing the glass absorption gives us sol-gel+MgF2 transmission over 0.4—1.1 microns as shown in table 4. Note that the absorption in the AR coating should be negligible, so the losses can be assumed to be due to reflectance. The "4-surfaces" values are calculated from GMOS-S.

Table 4: Transmission of Sol-gel+MgF2

$\lambda(\mu m)$	*GMOS-S*	*GMOS-N*	*4-surfaces*
0.40	0.9902	-	0.961
0.45	0.9938	0.9848	0.975
0.55	0.9938	0.9929	0.975
0.65	0.9967	0.9942	0.987
0.75	0.9993	0.9969	0.997
0.85	1.0000	0.9981	1.000
0.90	0.9990	-	0.996
1.00	0.9994	0.9985	0.998
1.10	0.9955	0.9955	0.982

The UV has been more difficult to assess. Statements in reports for SOAR and the CTIO Blanco Telescope ADC claim sol-gel+MgF2 coatings are better than 99% over the full range we are interested in. Throughput measurements for the Blanco ADC at 0.35 and 0.334 microns support the AR coating performance at these levels when adjusted for falling glass transparency, but this depends sensitively on the properties of the glass.

The throughput of broadband AR coatings for the Prime Focus Imaging Spectrograph design for the South African Large Telescope is shown in figure 13[2] as given by Nordsieck. This figure shows sol-gel+MgF2 coatings transmitting at 99% or better over the entire range from 0.32 up to almost 1 micron, falling slowly to about 98.8% around 1.1 microns, but these values appear to be calculated rather than actual measurements. However, "tuning" the coating involves varying the layer thicknesses, which should scale closely with the desired wavelengths, and the required scaling (0.31/0.40) does not seem extreme. Note that the peak transmission in figure 13 does not reach those measured for the GMOS coatings. In summary, we feel confident the UV transmission will be at or better than 99%.

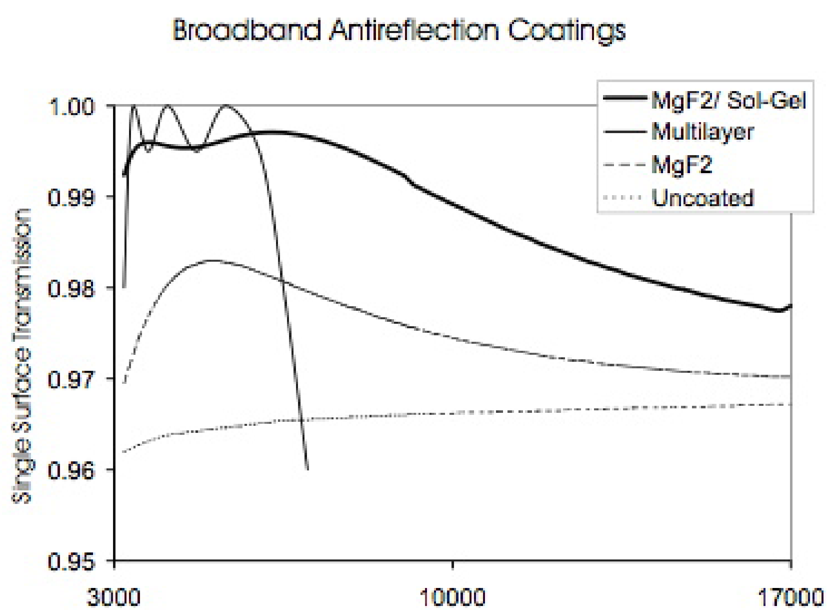


Figure 13: SALT/PFIS Broadband Anti-reflection Coatings

[2] Nordsieck, http://www.sal.wisc.edu/PFIS/docs/archive/public/talks/asr_05111_vg.pdf

The total throughput of the glass (70mm of HPFS 7980) and AR coatings using the values above and assuming 0.99 for a single coating or 0.96 for 4 surfaces for the wavelengths below 0.4 microns, gives the estimated total throughput shown in table 5.

Table 5: Estimated Total ADC Throughput

$\lambda (\mu m)$	*Estimated Total Throughput*
0.30	0.947
0.32	0.951
0.35	0.957
0.40	0.960
0.45	0.974
0.55	0.972
0.65	0.983
0.75	0.992
0.80	0.994
0.90	0.989
0.93	0.971
1.00	0.990
1.10	0.973

Internal Reflections in the ADC

We have been asked by the review committee to consider internal reflections in the ADC. This section discusses simple calculations of likely "ghost" reflections in the linear ADC. The worst case comes from the inner two surfaces, where it is estimated to be less than 10^{-4}, and falls rapidly as the prism separation increases.

There are 4 surfaces (referred to as S1, S2, S3 and S4, in the order that light passes though the two prisms), leading to 6 surface pairs that could produce ghosts. In the following, α is the prism angle of the individual prisms, and we assume 70mm total thickness for the combined prisms. We then consider the reflections due to each surface pair.

S1/S2: Internal to the first prism. Using the design orientation of the prism, light entering this prism vertically (approximately true) is emitted at an angle $\alpha(n-1)$. Light reflected off surfaces S1 and S2 is emitted at an angle of $\alpha(3n-1)$, that is, different by $2n\alpha$ from the direct pass. For prism angles of 5°, this angle is over 14°. Since angles over about 4° completely miss the grating/mirror, this surface pair is deemed innocuous for ghosts.

S1/S3: Since surfaces S2 and S3 are parallel, this pair behaves the same as S1/S2 except that there is additional defocus due to the increased path length of prism separation.

S3/S4: equivalent to S1/S2.

S2/S4: equivalent to S1/S3.

S2/S3: These are the parallel inner surfaces of the prisms, and are the most problematic. The difference in path length ($2\Delta z$) results in a defocus depending on prism separation. For an order-of-magnitude effect, we consider the defocus spot size compared to a 0.5" disk in estimating an intensity difference. The ghost/parent contrast (per given area) is then

$$\left(\frac{2\Delta z/15}{0.363}\right)^2 r_1 \cdot r_2$$

or

$$\left(\frac{d}{0.363}\right)^2 r_1 \cdot r_2$$

where $d = 2\,\Delta z\,/15$ is the defocused spot diameter, r_1 and r_2 are the reflectance at each surface, and Δz is measured in mm. We adopt reflectance of 0.01 for each surface. For a minimum separation of 4mm, we see a maximum value ghost/parent ratio of 6×10^{-5}; at 10mm, the ghost is reduced to 10^{-6} of the parent.

The location of this ghost will be somewhat offset from the primary image. The rays will be parallel to the parent beam, so the offset is simply the translation of the rays,

$$\Delta x = 2\ \Delta z\ \tan\theta$$

where θ ranges from about 0.5 to 1.3 degrees. Thus, at 10mm prism separation, the offset is 0.64" at maximum -- this will still be in the wings of the typical seeing-profile PSF.

S1/S4: This is equivalent to S2/S3, but with the overall addition of 2 × (70/n)mm of defocus. Thus, surface pair S2/S3 will dominate over this pair (except at large prism separation where ghost effects are negligible from either pair).

In conclusion, only the inner surface pair is of any concern. The maximum contrast of ghost/parent is given by $r_1 \cdot r_2$ (at which point the ghost falls on top of the parent) and rapidly declines as the prisms separate.

MECHANICAL DESIGN

The question with respect to mechanical design in the report of the committee on the conceptual design of the LRIS-ADC was the following:

> "The Committee wants the project, as part of the delta-CoD, to investigate the pros- and cons- of the two mounting options."

The following sections describe the outcome of further investigation into the mounting of the ADC in order to answer this question. The results of this investigation and the conclusions of the ADC design team in consultation with CARA are summarized as follows:

1. The ADC should be mounted as a stand-alone module and not attached to LRIS.

2. There are two configurations of a stand-alone ADC, one with a full aperture optic and one with a sub-aperture optic. The full aperture optic does not need to rotate with LRIS and as a result is mechanically and operationally simpler. However, the full aperture version can only be removed from the LRIS FOV by a telescope configuration change. The full aperture version is also estimated to cost $101K more to construct.

3. The CARA Instrument Program Manager in consultation with CARA staff and the ADC design team has made a detailed trade-off analysis comparing the two ADC configurations (see appendix C). After review it is agreed by the CARA personnel involved in the project that the full aperture version is preferred for maintenance and reliability reasons. The full aperture version is recommended by CARA provided that the ~5% maximum reduction in throughput due to the ADC is acceptable for the majority of LRIS users so that the ADC can remain installed for most of the time that LRIS is in use.

4. The ADC design team also wishes to comment that they are confident that either version can be built and made reliable.

5. The full aperture version of the ADC has the additional advantage of representing a design that can be replicated for Keck II and perhaps generalized for use with other instruments at the Cassegrain focus.

Introduction

The conceptual design report for the LRIS-ADC proposed permanent mounting of the ADC to LRIS. This was driven primarily by a problem with parking space on the deck at the Keck I Cassegrain position. Because there was no extra space available on the deck, and it was thought that a removable ADC would require additional deck space, the conceptual design concentrated on making the ADC a permanent part of LRIS.

After the conceptual design review the mounting considerations for the ADC were investigated further. Bill Mason (Instrument Engineer, WMKO/CARA) had earlier proposed the use of the tertiary mirror transfer module as a possible way to support an independent ADC, but this suggestion was not brought forward in any clear communication at a time when it could influence the work of the conceptual design. However, upon further investigation it became clear that permanently mounting the ADC to LRIS had serious drawbacks.

First, the proposed mounting of the ADC to the front of LRIS required that counterweights be attached to LRIS to compensate for the change in the center of gravity resulting from the addition of the ADC. There are very limited options for locating these counterweights, making the balancing very difficult.

Second, the ADC and its associated counterweights will add to the load on the LRIS main bearing and the rotator drive motor. This is expected to have an adverse effect on the performance of the LRIS rotator, and might require upgrading of the drive motor leading to further impact on the availability of LRIS.

Third, it is possible that mounting the ADC on the front of LRIS could increase flexure of the LRIS structure; this could have adverse effects on the optical performance of the instrument.

Fourth, while the proposed design for permanent mounting of the ADC to LRIS attempted to minimize the impact on maintenance access it became clear that the proposed mounting arrangement would still have a negative impact on service turnaround time.

For these reasons independent mounting of the ADC with installation and removal from the Keck I tower using the tertiary mirror transfer module has been re-evaluated and is now thought to be the better choice.

Proposed ADC Configurations

This review presents two possible configurations of the LRIS-ADC. They are both configured as a separate module installed in the tertiary tower of Keck I as shown in figure 14.

Both configurations make use of the tertiary mirror transfer module for insertion into the telescope and for storage of the ADC when it is not in use. A jacking stand will be provided at the back of the transfer module to support and store the ADC when the transfer module is in use for other purposes, such as serving as a counterweight for the tertiary mirror.

The two configurations are labeled “full aperture” and “sub-aperture.” Both configurations use the same optical principles presented in the original conceptual design report. The full aperture configuration includes prisms that are large enough to illuminate the full radius swept out by the LRIS science field. As a result, these prisms do not have to rotate and the only active control is the translation required to vary the dispersion correction. The sub aperture configuration includes prisms that are sized to illuminate only the science and guider field of view at a particular rotation angle of LRIS. This optical assembly must then rotate about the telescope axis to follow LRIS rotation and counter-rotate about its own optical axis to keep the prisms in the proper orientation to the atmosphere. Opposite this assembly is an open space that can be rotated into the LRIS field of view to operate LRIS without the ADC optics in the light path.

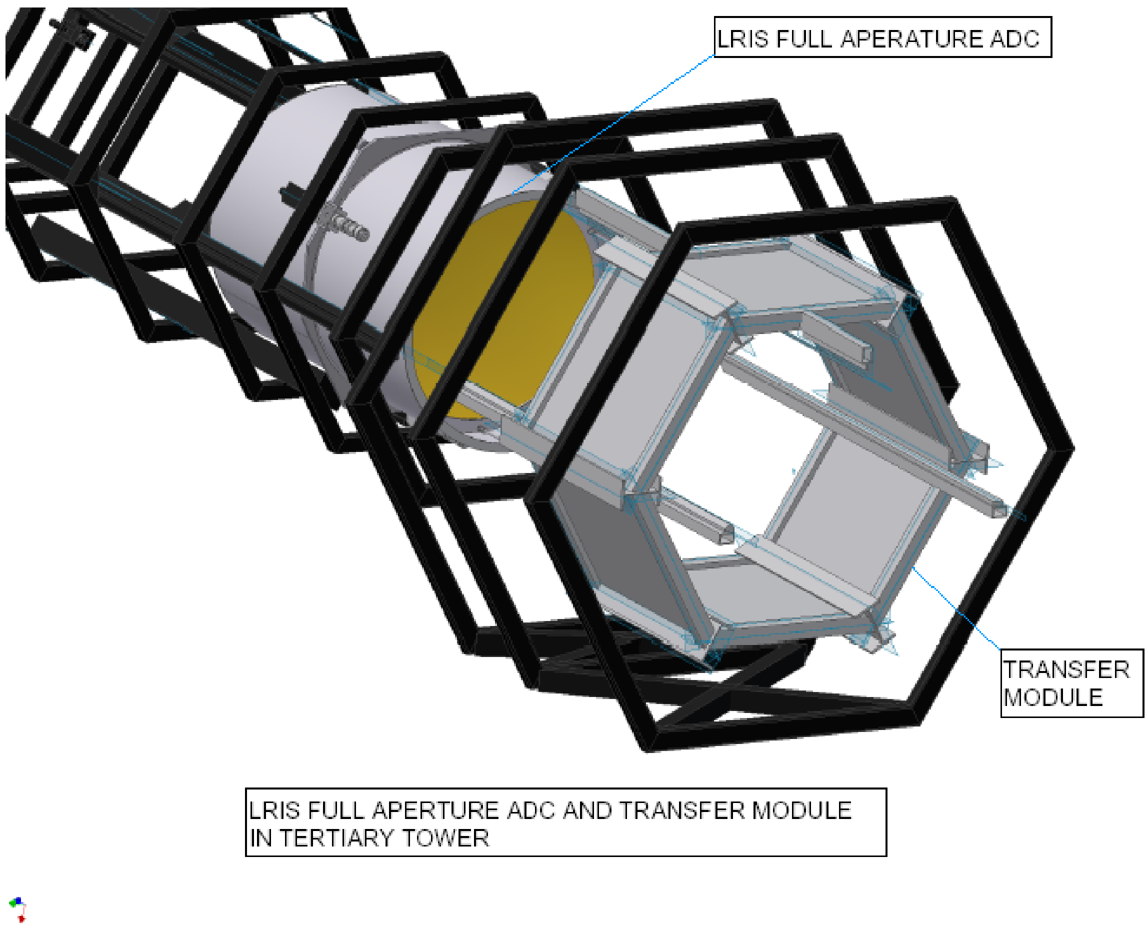


Figure 14: ADC Configuration in Tertiary Tower

Module – Telescope Interface

Three defining points must be added to the tertiary mirror tower, and some analysis is required to determine the optimum locations for these in terms of the structure of the tertiary mirror tower. The radial location of the defining points will also have to be planned so that they are compatible with the forward Cassegrain module and the tertiary mirror modules. Based on the information available at present it appears that it is possible to add suitable defining points, which suggests that mounting the ADC as an independent module in the tertiary mirror tower is feasible. The determination of the mounting points for the ADC would be part of the work performed by CARA during the preliminary design phase.

Both options assume actively cooled electronics enclosures that are mounted remotely from the ADC. These electronics can be located up to 150 feet from the ADC. An option that is priced separately is to look at using smart motors to reduce the size of the required electronics enclosures. The location of the electronics enclosures and the provision of power and so on would be part of the work performed by CARA during the definition of the ADC interface as part of the preliminary design phase.

Full Aperture ADC

This option makes use of optics that are approximately twice as large in diameter as the optics in the original conceptual design. This is shown in figure 15. The angle of the prisms has been reduced from 5 degrees to 2.5 degrees and the travel has been doubled to keep the same thickness of glass in the light path and therefore the same transmission loss as the smaller diameter optics. Vignetting at the edge of the ADC field is much more severe than generally seen at the edge of the telescope field and quickly makes the edges of the field unusable as you move radially outward into the vignetted area. The proposed costs include prisms that are large enough to cover the full science field without vignetting, but they strongly vignette ~7% of the guider field. As an extra cost option it is possible to provide prisms that would also cover the entire guider field.

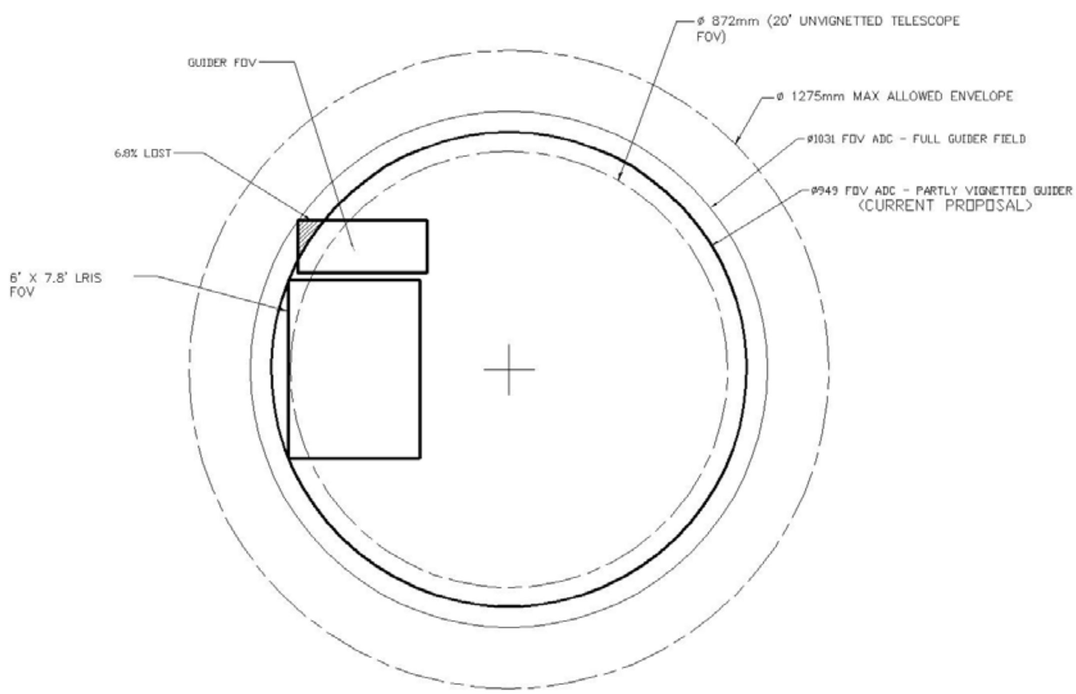


Figure 15: LRIS Full Aperture ADC Optical Relationship

An exploded view of the full aperture design is shown in figure 16. Both optics move toward and away from the center of the module and as a result the center of gravity of the module stays the same without active counter weights. This also decreases the unsupported length of the lead screws and the rate of travel required to vary dispersion correction. The module mounts on defining points that are near its center of gravity.

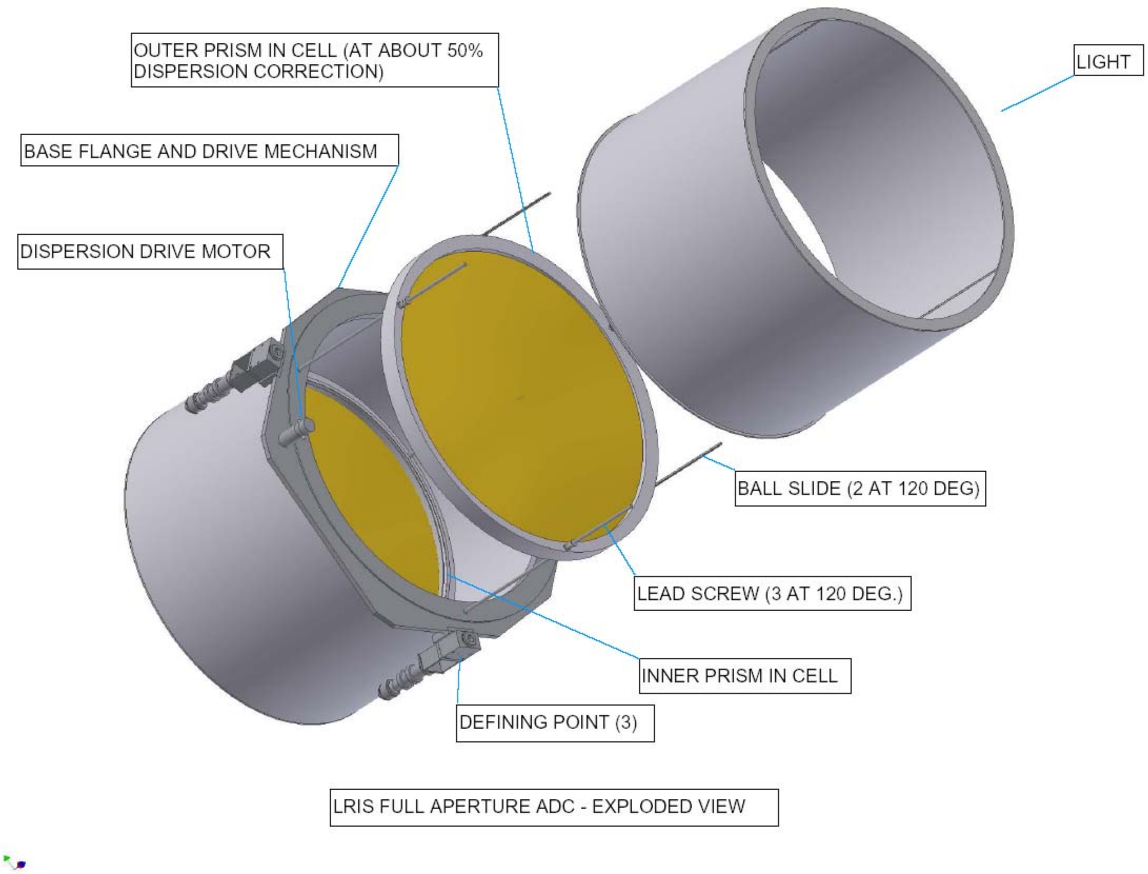


Figure 16: LRIS Full Aperture ADC – Exploded View

The light path is offset 30mm going through the ADC. Therefore, the outer optic is increased 15mm in diameter and its center is offset 15mm upward to fully fill the inner optic.

A Galil motor drives the dispersion correction through a toothed belt driving 3 lead screws. Idler pulleys are provided as required. The design includes fiducials and limits on the optic travel and encoders on the lead screws as well as the encoder on the drive motor. The drive system is located near the defining points.

Two linear ball slides provide a radial constraint for the prism cells. The slides will be specified to provide the same performance in tension and compression and will therefore provide the proper constraint at all zenith distances.

Sub-Aperture ADC

This option uses optics that are the same size as those in the original conceptual design, resulting in some vignetting of the LRIS guider field and slight vignetting of the LRIS science field. The relationship of the sub-aperture optics to the LRIS fields is shown figure 17.

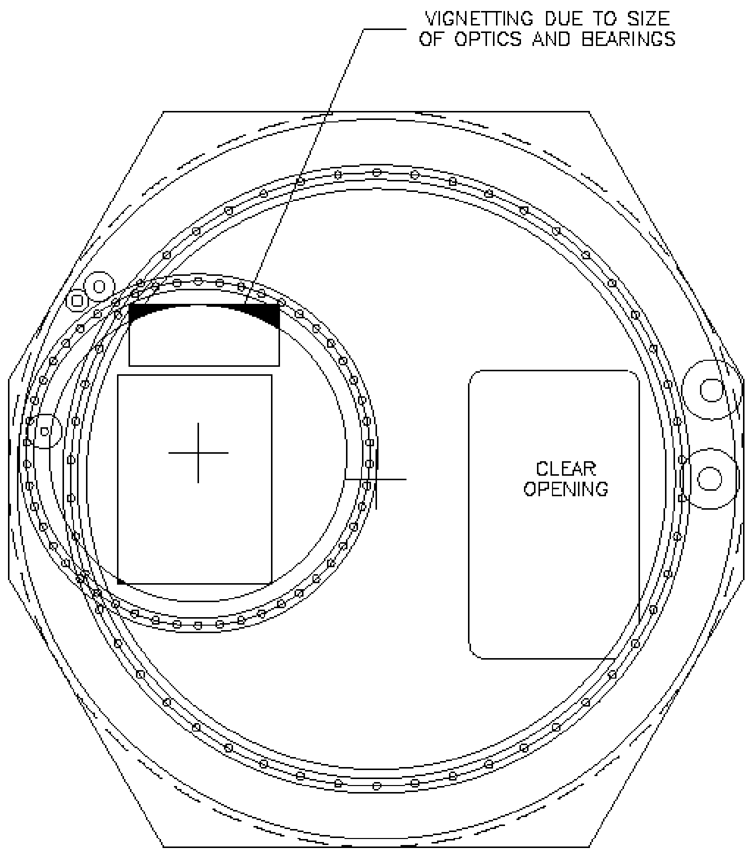


Figure 17: Sub-aperture ADC Optical Relationship

Figure 18 shows the configuration of the sub-aperture ADC module. The two optics are located in the optical tube assembly and both optics move toward and away from the center of the tube and as a result the center of gravity of the module stays the same without active counter weights. This also decreases the unsupported length of the lead screws and the rate of travel required to vary dispersion correction. The design details of the optical tube would be very similar to that of the full aperture version except for the method of driving the lead screws.

The optical tube assembly must rotate in synchronization with LRIS so as to maintain its position in front of LRIS' FOV. Additionally, a gear mechanism is employed to de-rotate the optical tube assembly so as to maintain its vertical orientation with respect to the horizon. The ADC can be taken out of the FOV of LRIS in real time by rotating it 180 degrees out of phase with respect to LRIS.

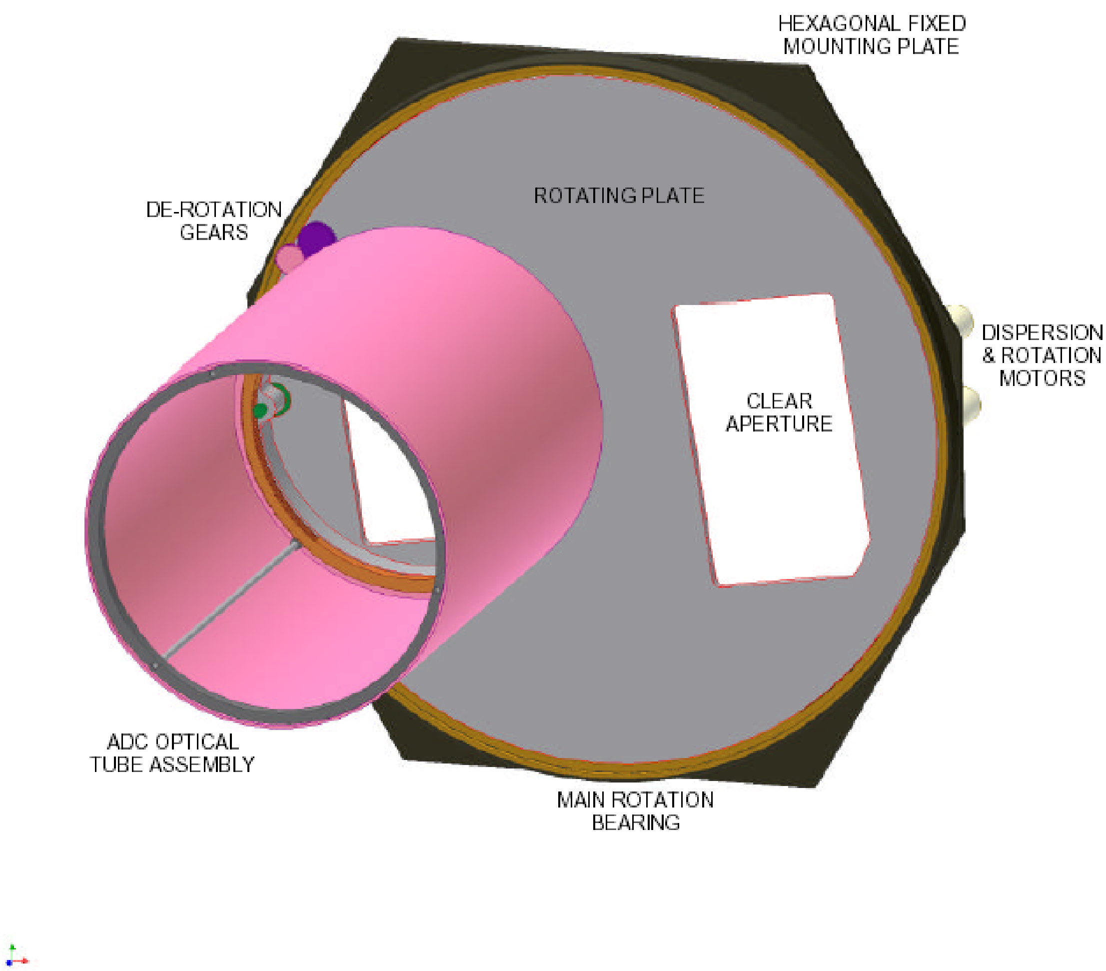


Figure 18: Sub-aperture ADC Assembly

The optical tube must both revolve around the LRIS centerline, as well as de-rotate, and normally a cable wrap would be used to feed power and signals to the ADC motors and encoders. However, during development of this concept, it was found that this approach would be problematic due to its impact on optical vignetting as well as on LRIS cabling infrastructure.

A conceptual design has been completed that features fixed motors, eliminating the need for a cable wrap. This comes at the cost of greater mechanism complexity, but we believe it is a reasonable tradeoff. The issue of directly driving the main rotation via a mechanical takeoff from LRIS was evaluated, but rejected based on the fact that it offered no reduction in cost or mechanism complexity compared to a motorized approach. Additionally, there is anecdotal information from CARA that the LRIS drive motor has little supplementary torque available to drive an additional load.

This design does not require moving counterweights to maintain a constant composite center of gravity. The design will be inherently passively balanced throughout its range of operating positions.

Pros:

- Optical material and fabrication cost minimized
- Real time removal of the ADC

Cons:

- Some vignetting of incoming beam occurs, although mostly limited to LRIS guider field.
- Mechanically more complex than full-aperture approach, so possibly less reliable

SCHEDULE AND BUDGET

In its report on the conceptual design of the LRIS-ADC the committee asked for a review of the budget and schedule:

> "The Committee found it hard to evaluate the reality of the Budget and schedule that was presented. It requested that the new WMKO Instrument Program Manager (Sean Adkins) be directed to review this part of the CoD with the result to be reported in the delta-CoD presentation."

The schedule is presented first in the following sections since it represents the basis for arriving at the labor cost figures in the budget. The schedule and budget have been developed with input from Sean Adkins, (CARA Instrument Program Manager) and the methodology used in creating both the schedule and the budget have been reviewed and analyzed by the CARA Instrument Program Manager. Based on this participation and analysis it is the Instrument Program Manager's conclusion that the budget represents a realistic and reasonable estimate of the time and costs involved. There is always the consideration that problems or unexpected obstacles may affect the final cost, but it is expected that consistent oversight will reduce the number of surprises in this regard, and also allow a more pro-active management of schedule problems and contingencies.

Introduction

A preliminary schedule and budget has been developed for both the full aperture and sub-aperture configurations of the ADC. The schedules for the full aperture and sub-aperture ADC may be found in appendices A and B. Each budget includes a contingency and also includes an estimate for the work that CARA must perform for mechanical and interface design, program management and installation and commissioning.

Milestones

The dates for the major milestones for both the full and sub-aperture versions of the ADC are as follows:

Milestone	Full Aperture ADC	Sub-Aperture ADC
Begin Preliminary Design Phase	3/11/03	3/11/03
PD Review	6/09/03	7/09/03
Begin Critical Design Phase	7/10/03	8/07/03
CD Review	9/03/03	1/12/04
Pre-Ship Review	8/03/04	8/13/04
Installation and Testing	9/01/04	9/10/04
First Light	9/28/04	10/08/04
On Sky Tests Completed	10/01/04	10/13/04

It should be noted that the milestone dates in this table, and the dates in the schedules found in appendices A and B are based on a start date approximately 4 weeks after the planned date for the delta conceptual design review. It may be that the project will not be able to start as early this planning reflects, and if a long start-up delay is encountered there may be issues with personnel availability for some parts of the project.

Analysis of the Schedule

The schedule for the delta conceptual design as originally presented did not include an adequate allowance for testing, both before shipment and at installation and commissioning. The schedule as presented results from the addition of a longer period for pre-shipment testing, as well as increased attention to installation and commissioning activities.

The schedule also did not include the tasks that CARA personnel would perform during the design and installation phases. Milestones related to the CARA activities have been added to the schedule. Task descriptions for the CARA activities are included in appendix D.

The accuracy of the estimate provided by the schedule for pre-shipment testing, and for installation, testing and commissioning is constrained by the absence of a detailed test plan which is recommended as a task for the preliminary design phase, with refinement to occur in the critical design phase. This area of the schedule represents a greater area of uncertainty for this reason, but given the modest scope of the proposed design this does not represent a risk of high magnitude.

The schedule is based on the same methodology used in the preparation of the budget, and represents a bottom up analysis of the effort required to design, build, test and install the ADC. It is the opinion of the CARA Instrument Program Manager that the proposed schedule can be taken to represent a good plan for the design and construction of the ADC, and is a good prediction of the time required to perform these tasks.

Budget for the Full Aperture ADC

The budget for the full aperture version of the ADC is shown on the next page. The contingency estimate is based on 20% of the total for each area except for optics. The optics contingency is based on a 20% contingency for labor and a 5% contingency for optical materials.

The budget includes the cost of CARA personnel for all of the tasks that CARA personnel would perform during the design and installation phases of the project. The budget also includes materials supplied by CARA for installation of the ADC and modification of the LRIS instrument hatch. No contingency has been added for the CARA activities.

The costs for the full aperture version of the ADC can be summarized as follows:

PD Phase	CD Phase	Fabrication, Assembly, Test	Installation & Commissioning	Contingency	Total
$140,920	$107,461	$544,249	$82,502	$169,014	$1,044,146

Full Aperture ADC

Area	Item	Notes	Labor Time	Rate	PDR	CDR	Fab&Assy	Cost	Sub-Total
Optics									
	Optical Design Analysis (Drew)	Includes 4 weeks testing during fab.	9.0 man-wks	$70/hr	$11,200	$2,800	$11,200	$25,200	
	Optical Material	Based on actual quotation					$190,312	$190,312	
	Fabrication Labor						$120,105	$120,105	
									$335,617
Electronics									
	Materials						$12,370	$12,370	
	Labor		12.5 man-wks	$55/hr	$8,800	$8,800	$9,900	$27,500	
									$39,870
Software									
	Labor (Will Deich)		15.0 man-wks	$70/hr	$7,000	$28,000	$7,000	$42,000	
	Slitmask Design Software	Minimal updates to existing code	1.0 man-wks	$70/hr			$2,800	$2,800	
									$44,800
Mechanical Fab.									
	Fabrication Material						$5,860	$5,860	
	Water Jet Cutting						$1,000	$1,000	
	Labor (Shop)		14.0 man-wks	$55/hr	$2,200	$2,200	$26,400	$30,800	
	Purchased Parts						$3,760	$3,760	
									$41,420
Mechanical Eng.									
	Labor		16.0 man-wks	$65/hr	$20,800	$10,400	$10,400	$41,600	
									$41,600
Reviews									
	Labor		27.0 man-wks	$65/hr	$20,800	$20,800	$20,800	$62,400	
	Travel								
									$62,400
Miscellaneous									
	Travel					$2,500	$5,000	$7,500	
	Project Management	10% of Labor			$7,080	$7,300	$24,841	$39,221	
	Sol-gel	Due to use of larger tank at LL					$1,000	$1,000	
	Performance/Calibration Software Docs.		4.0 man-wks	$70/hr			$11,200	$11,200	
									$58,921
Commissioning									
	Labor	Includes 4 wks Drew's time	11.0 man-wks	$65/hr			$28,600	$28,600	
	Instrument Transport						$11,200	$11,200	
	Travel						$23,375	$23,375	
									$63,175
				Labor	$70,800	$73,000	$248,405	$392,205	
				Materials	$0	$0	$214,302	$214,302	
				Expenses	$0	$2,500	$39,575	$42,075	
				Project Management	$7,080	$7,300	$24,841	$39,221	
				Total	$77,880	$82,800	$527,123	$687,803	**$687,803**
CARA									
	Requirements Document	SMA	1.0 man-wks		$2,376				
	Defining Points Design		6.2 man-wks		$18,094				
	LRIS Hatch Modifications Design		4.0 man-wks		$7,842				
	Interface Design		4.4 man-wks		$10,504				
	Baseline Rotation/Displacement Software		2.2 man-wks				$5,252		
	Baseline Software Design/Implementation		2.2 man-wks				$15,756		
	Interface Control Document		6.6 man-wks		$15,756				
	Safety/Operations/Weight/Balance Reviews		6.6 man-wks			$15,756			
	Install Defining Points		3.1 man-wks				$10,741		
	Install Electrical/Cooling Provisions		5.3 man-wks				$15,026		
	Implement LRIS Hatch Modification		1.3 man-wks				$7,506		
	Acceptance Test Plan Development		1.9 man-wks		$1,681	$420			
	Installation/Testing/Commissioning		8.1 man-wks				$19,327		
	Documentation Reviews		3.1 man-wks				$7,353		
	Project and Milestone Meetings		7.1 man-wks		$4,412	$5,515	$12,132		
	Program Management	~10% of SMA's time	5.0 man-wks		$2,376	$2,971	$6,535		
									$187,330
				Total	$140,920	$107,461	$626,751		**$875,133**
Contingency									
	Optics							$38,577	
	Electronics							$7,974	
	Software (Deich)							$8,960	
	Mechanical Fabrication							$8,284	
	Mechanical Engineering							$8,320	
	Reviews							$12,480	
	Miscellaneous							$11,784	
	Commissioning							$12,635	
	Sol-gel Coating	This contingency is in case LL can't/won't coat						$60,000	
									$169,014
							Grand Total		**$1,044,146**

Budget for the Sub-Aperture ADC

The budget for the sub-aperture version of the ADC is shown on the next page. The contingency estimate is based on 20% of the total for each area except for optics. The optics contingency is based on a 20% contingency for labor and a 5% contingency for optical materials.

The budget includes the cost of CARA personnel for all of the tasks that CARA personnel would perform during the design and installation phases of the project. The budget also includes materials supplied by CARA for installation of the ADC and modification of the LRIS instrument hatch. No contingency has been added for the CARA activities.

The costs for the sub-aperture version of the ADC can be summarized as follows:

PD Phase	CD Phase	Fabrication, Assembly, Test	Installation & Commissioning	Contingency	Total
$154,120	$136,281	$400,891	$82,502	$167,656	$941,451

Sub-Aperture ADC

Area	Item	Notes	Labor Time	Rate	PDR	CDR	Fab&Assy	Cost	Sub-Total
Optics									
	Optical Design Analysis (Drew)	Includes 4 weeks testing during fab.	9.0 man-wks	$70/hr	$11,200	$2,800	$11,200	$25,200	
	Optical Material	Based on actual quotation					$64,250	$64,250	
	Fabrication Labor		11.5 man-wks	$70/hr			$32,200	$32,200	
									$121,650
Electronics									
	Materials						$12,370	$12,370	
	Labor		16.5 man-wks	$55/hr	$8,800	$8,800	$18,700	$36,300	
									$48,670
Software									
	Labor (Will Deich)		18.0 man-wks	$70/hr	$11,200	$30,800	$8,400	$50,400	
	Slitmask Design Software	Minimal updates to existing code	1.0 man-wks	$70/hr			$2,800	$2,800	
									$53,200
Mechanical Fab.									
	Fabrication Materials						$8,000	$8,000	
	Outside Services (water jet, broaching)						$13,000	$13,000	
	Labor (Shop)		22.0 man-wks	$55/hr	$2,200	$2,200	$44,000	$48,400	
	Purchased Parts						$28,000	$28,000	
									$97,400
Mechanical Eng.									
	Labor		32.0 man-wks	$65/hr	$28,600	$33,800	$20,800	$83,200	
									$83,200
Reviews									
	Labor		27.0 man-wks	$65/hr	$20,800	$20,800	$20,800	$62,400	
	Travel								
									$62,400
Miscellaneous									
	Travel					$2,500	$5,000	$7,500	
	Project Management	10% of Labor			$8,280	$9,920	$19,870	$38,070	
	Performance/Calibration Software Docs.	Drew	4.0 man-wks	$70/hr			$11,200	$11,200	
									$56,770
Commissioning									
	Labor	Includes 4 wks Drew's time	11.0 man-wks	$65/hr			$28,600	$28,600	
	Instrument Transport						$11,200	$11,200	
	Travel						$23,375	$23,375	
									$63,175
				Labor	$82,800	$99,200	$198,700	$380,700	
				Materials	$0	$0	$125,620	$125,620	
				Expenses	$0	$2,500	$39,575	$42,075	
				Project Management	$8,280	$9,920	$19,870	$38,070	
				Total	$91,080	$111,620	$383,765	$586,465	$586,465
CARA									
	Requirements Document	SMA	1.0 man-wks		$2,376				
	Defining Points Design		6.2 man-wks		$18,094				
	LRIS Hatch Modifications Design		4.0 man-wks		$7,842				
	Interface Design		4.4 man-wks		$10,504				
	Baseline Rotation/Displacement Software		2.2 man-wks				$5,252		
	Baseline Software Design/Implementation		2.2 man-wks				$15,756		
	Interface Control Document		6.6 man-wks		$15,756				
	Safety/Operations/Weight/Balance Reviews		6.6 man-wks			$15,756			
	Install Defining Points		3.1 man-wks				$10,741		
	Install Electrical/Cooling Provisions		5.3 man-wks				$15,026		
	Implement LRIS Hatch Modification		1.3 man-wks				$7,506		
	Acceptance Test Plan Development		1.9 man-wks		$1,681	$420			
	Installation/Testing/Commissioning		8.1 man-wks				$19,327		
	Documentation Reviews		3.1 man-wks				$7,353		
	Project and Milestone Meetings		7.1 man-wks		$4,412	$5,515	$12,132		
	Program Management	~10% of SMA's time	5.0 man-wks		$2,376	$2,971	$6,535		
									$187,330
				Total	$154,120	$136,281	$483,393		**$773,795**
Contingency									
	Optics							$14,693	
	Electronics							$9,734	
	Software (Deich)							$10,640	
	Mechanical Fabrication							$19,480	
	Mechanical Engineering							$16,640	
	Reviews							$12,480	
	Miscellaneous							$11,354	
	Sol-Gel Coatings	This contingency is in case LL can't/won't coat						$60,000	
	Commissioning							$12,635	
									$167,656
							Grand Total		**$941,451**

Options

The original conceptual design for the ADC included a number of optional items that were costed separately. The original option A, a provision for real time removal of the ADC from the LRIS optical path is included by definition in the sub-aperture version and is not required for the full aperture version, so the original option A has been deleted.

A new option A has been added, this allows for a small increase in the diameter of the full aperture optics to eliminate the slight vignetting of the guider field that is present in the current design for this version. As previously discussed this vignetting is considered small enough that it is likely to be acceptable given that the guider FOV shown in the figure "LRIS Full Aperture ADC Optical Relationship" represents the range over which the smaller actual guider field of the LRIS can travel, not the FOV of the guider itself.

Option A: Larger optics for the full aperture version $78,000

This option covers the incremental cost increase due to increasing the aperture size of the optics to eliminate all vignetting of the LRIS guider field.

Option B: Additional Optical Design $11,000

This option was described in the original conceptual design report in section 4.11. This option provides for additional optical design analysis for specific details of the LRIS optical system including image quality for different filters and the effect of the ADC on distortion and PSF.

Option C: LRIS software upgrade $68,000

This option incorporates options 2 and 3 as described in section 7.2.5 of the original conceptual design report. This option would update the LRIS user interface to a dashboard-style interface, and would possibly require modifying the LRIS keyword service.

Option D: ADC simulation Software $34,000

This option was described in the original conceptual design report in section 7.5. This option would provide a software package to allow the user to predict the complex and subtle PSF and distortion changes that the ADC would cause in the image. If this option is pursued then CARA involvement in its development may be required, this would add approximately 0.1 FTE of engineering level time or $10,500 to the cost of this option.

Option E: Additional Commissioning $ 8,000

This option was described in the original conceptual design report in section 7.4. This is for Drew Phillips to take and analyze data at the time of commissioning to quantify the optical performance of the ADC. If this option is pursued then CARA involvement in its development may be required, this would add approximately 0.1 FTE of engineering level time or $10,500 to the cost of this option.

Option F: Smart Motor investigations $30,000

This option corresponds to option 1 as described in section 7.2.5 of the original conceptual design report. This option would provide for investigations into alternative servo motor systems to the Galil system that has been used on all spectrographs built by UCO/Lick for the last 10 years.

Analysis of the Budget

This section presents an analysis of the budgets for the proposed LRIS-ADC versions. The CARA Instrument Program Manager through consultation with the ADC design team has prepared this analysis.

The methodology employed to create the proposed budget is a bottom-up aggregation of the cost of individual tasks, materials and fabrications. Each of the specific disciplines has some variation in the details of the methodology and this analysis will describe the approach taken by each discipline.

Mechanical Estimates

The mechanical estimates for design labor are based on the experience of the mechanical designers, comparing the anticipated design work with similar projects they have done in the past. The estimates are based on a conceptual design that has been refined to the level of sub-assembly detail, including the development of a preliminary bill of materials.

The preliminary bill of materials and the conceptual drawings have been reviewed with UCO/Lick instrument shop staff and the estimates for fabrication time and materials have been prepared using their estimates.

The methodology used for these estimates is sound, and the experience of the personnel involved is sufficiently extensive to warrant a reasonable confidence in their estimates.

Optical Estimates

The optical design portion of this project is comparatively simple. In fact, a significant portion of the design has been done as part of the work performed to date including the conceptual design. The work done to date has provided a good understanding of the work remaining, and allows a reasonable estimate of the time required.

The materials portion of the optical estimate is based on actual vendor quotations for the required material. David Hilyard (UCO/Lick) has made the fabrication estimate, and because of his very extensive experience it seems reasonable to rely on that estimate.

Electronic/Electrical Estimates

The electronic and electrical estimates are based on the experience of the team with similar motion control systems. The estimate assumes the use of a Galil multi-axis controller in a diskless PC and uses motors, encoders and interconnections similar to those used on a number of instruments built by the same team.

The base of experience in this regard is significant, and it seems reasonable to rely on these estimates.

Software Estimates

An experienced programmer has prepared the software estimates. However, software is the most difficult kind of design and implementation task to estimate. While the estimates seem reasonable, it is also likely that the uncertainty is much higher in this area of the project than any other.

Integration and Test

The estimates for integration and test activities are based in part on experience. However, a detailed test plan would not be developed until the preliminary design phase, and in the absence of this the estimates for testing activities are not well detailed. The allowance for this phase has been increased, and in fact may be somewhat over the labor actually required.

Installation and Testing at the Telescope

The estimates for installation and testing have been developed in consultation with CARA personnel. There is a sufficient body of experience in this area at CARA to suggest that given the limited detail available at this conceptual design stage, the estimates for installation and testing can be relied upon.

Commissioning and Hand-over

The commissioning and hand-over process has also been reviewed with CARA personnel, however, given the limited detail in the testing activities this portion of the estimate contains a greater degree of uncertainty.

RECOMMENDATIONS FOR THE PRELIMINARY DESIGN PHASE

As part of the management of the program to develop this instrument it is recommended that a requirements document be developed by CARA in collaboration with the ADC design team. This document would fully define the expected performance of the ADC as well as provide specific requirements for each design discipline. It is also recommended that a detailed acceptance test plan be developed in the preliminary design phase and refined in the critical design phase. This test plan would include tests to be performed prior to shipment and also tests to be performed at installation and commissioning.

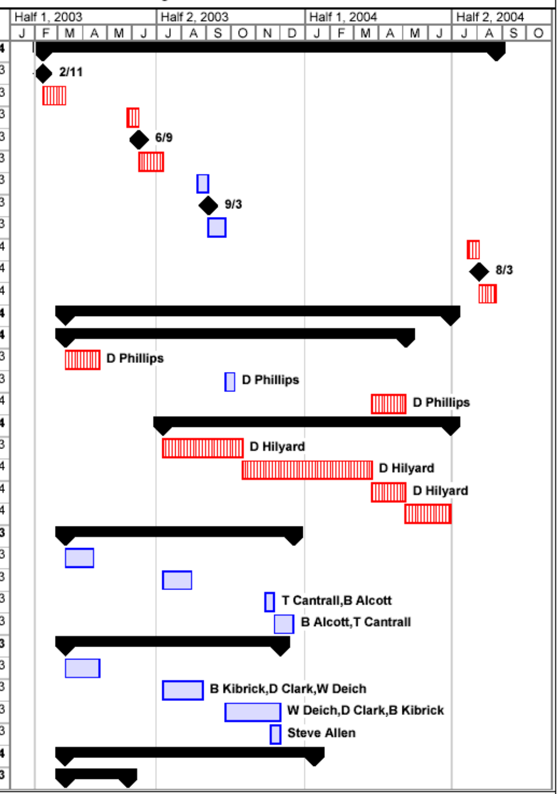
APPENDIX A – FULL APERTURE ADC SCHEDULE

Fri 1/31/03

LRIS ADC Full Aperture-Core Project

All Tasks

ID	Task Name	Duration	Start	Finish
35	**Reviews**	**385 days**	**Tue 2/11/03**	**Tue 8/24/04**
36	Phase A Review	0 days	Tue 2/11/03	Tue 2/11/03
37	Post Phase A Period	4 wks	Tue 2/11/03	Mon 3/10/03
38	Prep for PDR	2 wks	Tue 5/27/03	Mon 6/9/03
39	PDR	0 days	Mon 6/9/03	Mon 6/9/03
40	Post PDR Period	4 wks	Tue 6/10/03	Wed 7/9/03
41	Prep for CDR	2 wks	Thu 8/21/03	Wed 9/3/03
42	CDR	0 days	Wed 9/3/03	Wed 9/3/03
43	Post CDR Period	3 wks	Thu 9/4/03	Wed 9/24/03
44	Prep for PSR	2 wks	Wed 7/21/04	Tue 8/3/04
45	PSR	0 days	Tue 8/3/04	Tue 8/3/04
46	Post PSR Period	3 wks	Wed 8/4/04	Tue 8/24/04
1	**Optics**	**325 days**	**Tue 3/11/03**	**Tue 6/29/04**
2	**Optical Design Analysis**	**285 days**	**Tue 3/11/03**	**Tue 5/4/04**
3	Optical Design-PDR	6 wks	Tue 3/11/03	Mon 4/21/03
4	Optical Design-CDR	1.5 wks	Thu 9/25/03	Mon 10/6/03
5	Optical Testing Analysis	6 wks	Wed 3/24/04	Tue 5/4/04
6	**Optical Fabrication**	**240 days**	**Thu 7/10/03**	**Tue 6/29/04**
7	Optical Materials Order/delivery	14 wks	Thu 7/10/03	Wed 10/15/03
8	Optical Fabrication	20 wks	Thu 10/16/03	Tue 3/23/04
9	Optical Acceptance Testing	6 wks	Wed 3/24/04	Tue 5/4/04
10	Optical Coatings	8 wks	Wed 5/5/04	Tue 6/29/04
11	**Electronics**	**197.5 days**	**Tue 3/11/03**	**Thu 12/18/03**
12	Electronics-PDR investigations	5 wks	Tue 3/11/03	Mon 4/14/03
13	Electronics-CDR investigations	5 wks	Thu 7/10/03	Wed 8/13/03
14	Electronic mountings	1.5 wks	Thu 11/13/03	Mon 11/24/03
15	General wiring	3 wks	Mon 11/24/03	Thu 12/18/03
16	**Software**	**185 days**	**Tue 3/11/03**	**Mon 12/1/03**
17	Software-PDR level investigations	6 wks	Tue 3/11/03	Mon 4/21/03
18	Software-CDR investigations	7 wks	Thu 7/10/03	Wed 8/27/03
19	Software-Coding/code check	9 wks	Thu 9/25/03	Mon 12/1/03
20	Software-Slitmask Design Mods	5 days	Thu 11/20/03	Mon 12/1/03
21	**Mechanical Engineering**	**205 days**	**Tue 3/11/03**	**Mon 1/12/04**
22	**ME-PDR level design**	**55 days**	**Tue 3/11/03**	**Mon 5/26/03**



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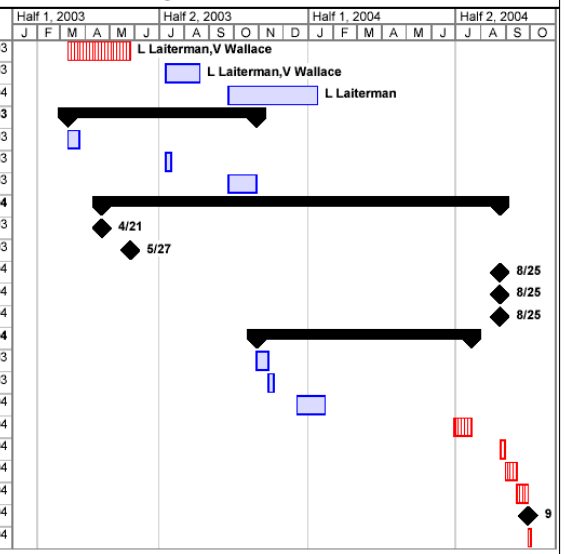
Fri 1/31/03

LRIS ADC Full Aperture-Core Project

All Tasks

ID	Task Name	Duration	Start	Finish
23	Design updates of ADC	11 wks	Tue 3/11/03	Mon 5/26/03
24	ME-CDR level design	6 wks	Thu 7/10/03	Wed 8/20/03
25	ME-Fabrication supervision	13 wks	Thu 9/25/03	Mon 1/12/04
26	**Mechanical Fabrication**	**165 days**	**Tue 3/11/03**	**Wed 10/29/03**
27	MF-PDR investigations	10 days	Tue 3/11/03	Mon 3/24/03
28	MF-CDR investigations	1 wk	Thu 7/10/03	Wed 7/16/03
29	MF-Fabrication	5 wks	Thu 9/25/03	Wed 10/29/03
52	**CARA tasks**	**335 days**	**Mon 4/21/03**	**Wed 8/25/04**
53	Location of defining points	0 days	Mon 4/21/03	Mon 4/21/03
56	ICD complete	0 days	Tue 5/27/03	Tue 5/27/03
54	Defining Points Installed	0 days	Wed 8/25/04	Wed 8/25/04
55	LRIS Hatch Modifications Installed	0 days	Wed 8/25/04	Wed 8/25/04
57	Interface infrastructure installed	0 days	Wed 8/25/04	Wed 8/25/04
30	**Assembly and Test**	**175 days**	**Thu 10/30/03**	**Tue 7/20/04**
31	MF-Assembly	2 wks	Thu 10/30/03	Wed 11/12/03
32	MF-Initial Mechanical Testing	1 wk	Thu 11/13/03	Wed 11/19/03
33	Initial Electronics testing	3 wks	Thu 12/18/03	Thu 1/22/04
34	Pre Ship Tests	3 wks	Wed 6/30/04	Tue 7/20/04
47	Shipping	5 days	Wed 8/25/04	Tue 8/31/04
48	Installation and Mech/Elec Tests	2 wks	Wed 9/1/04	Tue 9/14/04
49	Software and Optical Tests	2 wks	Wed 9/15/04	Tue 9/28/04
50	First Light	0 days	Tue 9/28/04	Tue 9/28/04
51	On Sky Tests	3 days	Wed 9/29/04	Fri 10/1/04



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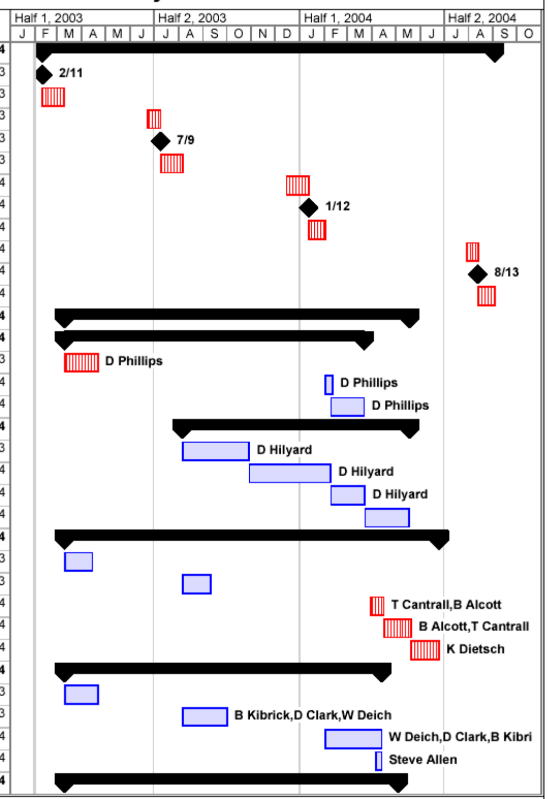
APPENDIX B – SUB-APERTURE ADC SCHEDULE

Fri 1/31/03

LRIS ADC- Sub Aperture-Core Project

All Tasks

ID	Task Name	Duration	Start	Finish
35	**Reviews**	**392.5 days**	**Tue 2/11/03**	**Fri 9/3/04**
36	Phase A Review	0 days	Tue 2/11/03	Tue 2/11/03
37	Post Phase A Period	4 wks	Tue 2/11/03	Mon 3/10/03
38	Prep for PDR	2 wks	Tue 6/24/03	Wed 7/9/03
39	PDR	0 days	Wed 7/9/03	Wed 7/9/03
40	Post PDR Period	4 wks	Thu 7/10/03	Wed 8/6/03
41	Prep for CDR	2 wks	Tue 12/16/03	Mon 1/12/04
42	CDR	0 days	Mon 1/12/04	Mon 1/12/04
43	Post CDR Period	3 wks	Tue 1/13/04	Mon 2/2/04
44	Prep for PSR	2 wks	Fri 7/30/04	Fri 8/13/04
45	PSR	0 days	Fri 8/13/04	Fri 8/13/04
46	Post PSR Period	3 wks	Fri 8/13/04	Fri 9/3/04
1	**Optics**	**295 days**	**Tue 3/11/03**	**Tue 5/18/04**
2	**Optical Design Analysis**	**254 days**	**Tue 3/11/03**	**Mon 3/22/04**
3	Optical Design-PDR	6 wks	Tue 3/11/03	Mon 4/21/03
4	Optical Design-CDR	1.5 wks	Tue 2/3/04	Thu 2/12/04
5	Optical Testing Analysis	6 wks	Tue 2/10/04	Mon 3/22/04
6	**Optical Fabrication**	**190 days**	**Thu 8/7/03**	**Tue 5/18/04**
7	Optical Materials Order/delivery	12 wks	Thu 8/7/03	Wed 10/29/03
8	Optical Fabrication	12 wks	Thu 10/30/03	Mon 2/9/04
9	Optical Acceptance Testing	6 wks	Tue 2/10/04	Tue 3/23/04
10	Optical Coatings	8 wks	Wed 3/24/04	Tue 5/18/04
11	**Electronics**	**322.5 days**	**Tue 3/11/03**	**Fri 6/25/04**
12	Electronics-PDR investigations	5 wks	Tue 3/11/03	Mon 4/14/03
13	Electronics-CDR investigations	5 wks	Thu 8/7/03	Wed 9/10/03
14	Electronic mountings	2.5 wks	Wed 3/31/04	Fri 4/16/04
15	General wiring	5 wks	Fri 4/16/04	Fri 5/21/04
16	Initial Electronics testing	5 wks	Fri 5/21/04	Fri 6/25/04
17	**Software**	**270 days**	**Tue 3/11/03**	**Tue 4/13/04**
18	Software-PDR level investigations	6 wks	Tue 3/11/03	Mon 4/21/03
19	Software-CDR investigations	8 wks	Thu 8/7/03	Wed 10/1/03
20	Software-Coding/code check	10 wks	Tue 2/3/04	Tue 4/13/04
21	Software-Slitmask Design Mods	5 days	Wed 4/7/04	Tue 4/13/04
22	**Mechanical Engineering**	**285 days**	**Tue 3/11/03**	**Tue 5/4/04**



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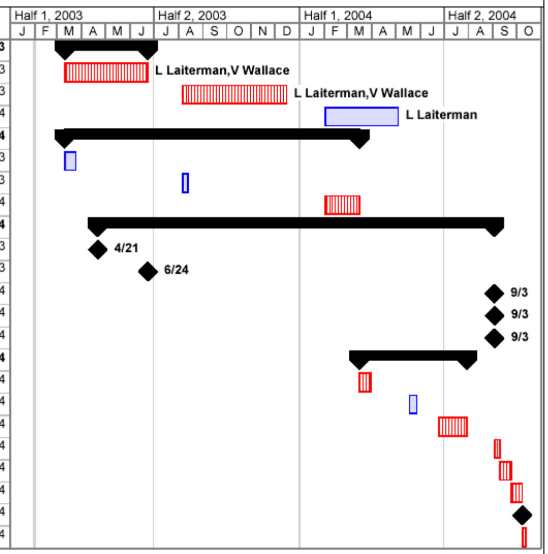
Fri 1/31/03

LRIS ADC- Sub Aperture-Core Project

All Tasks

ID	Task Name	Duration	Start	Finish
23	**ME-PDR level design**	**75 days**	**Tue 3/11/03**	**Mon 6/23/03**
24	Design updates of ADC	15 wks	Tue 3/11/03	Mon 6/23/03
25	ME-CDR level design	18 wks	Thu 8/7/03	Mon 12/15/03
26	ME-Fabrication supervision	13 wks	Tue 2/3/04	Tue 5/4/04
27	**Mechanical Fabrication**	**250 days**	**Tue 3/11/03**	**Tue 3/16/04**
28	MF-PDR investigations	10 days	Tue 3/11/03	Mon 3/24/03
29	MF-CDR investigations	1 wk	Thu 8/7/03	Wed 8/13/03
30	MF-fabrication	6 wks	Tue 2/3/04	Tue 3/16/04
52	**CARA tasks**	**342.5 days**	**Mon 4/21/03**	**Fri 9/3/04**
53	Location of defining points	0 days	Mon 4/21/03	Mon 4/21/03
56	ICD complete	0 days	Tue 6/24/03	Tue 6/24/03
55	LRIS Hatch Modifications Installed	0 days	Fri 9/3/04	Fri 9/3/04
54	Defining Points Installed	0 days	Fri 9/3/04	Fri 9/3/04
57	Interface infrastructure installed	0 days	Fri 9/3/04	Fri 9/3/04
31	**Assembly and Test**	**97.5 days**	**Wed 3/17/04**	**Fri 7/30/04**
32	MF-Assembly	2 wks	Wed 3/17/04	Tue 3/30/04
33	MF-Initial Mechanical Testing	1.5 wks	Wed 5/19/04	Fri 5/28/04
34	Pre Ship Tests	5 wks	Fri 6/25/04	Fri 7/30/04
47	Shipping	5 days	Fri 9/3/04	Fri 9/10/04
48	Installation and Mech/Elec Tests	2 wks	Fri 9/10/04	Fri 9/24/04
49	Software and Optical Tests	2 wks	Fri 9/24/04	Fri 10/8/04
50	First Light	0 days	Fri 10/8/04	Fri 10/8/04
51	On Sky Tests	3 days	Fri 10/8/04	Wed 10/13/04



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APPENDIX C – LRIS-ADC CONFIGURATION TRADE-OFF ANALYSIS

This appendix describes a trade-off analysis performed to help select one of the two alternative configurations for the LRIS-ADC.

Rationale for the Analysis

The design of the ADC for the LRIS instrument has converged on a separate module installed in the tertiary tower of Keck I. This separate module has two possible configurations. Both configurations make use of the tertiary mirror transfer module for insertion into the telescope and for storage of the ADC when it is not in use. A jacking stand will be provided at the back of the transfer module to support and store the ADC when the transfer module is in use for other purposes, such as serving as a counterweight for the tertiary mirror.

The two configurations are labeled “full aperture” and “sub-aperture.” Both configurations use the same optical principles presented in the original conceptual design report. The full aperture configuration includes prisms that are large enough to illuminate the full radius swept out by the LRIS science field. As a result, these prisms do not have to rotate and the only active control is the translation required to vary the dispersion compensation. The sub aperture configuration includes prisms that are sized to illuminate only the science and guider field of view at a particular rotation angle of LRIS. This optical assembly must then rotate about the telescope axis to follow LRIS rotation and counter-rotate about its own optical axis to keep the prisms in the proper orientation to the atmosphere. Opposite this assembly is an open space that can be rotated into the LRIS field of view to operate LRIS without the ADC optics in the light path.

Each of the proposed configurations has desirable features. They also differ significantly in implementation cost. However, implementation cost cannot be taken in isolation as the only factor in choosing a configuration, issues like reliability and overall utility should also be considered. This raises the need for a trade-off analysis. In this case we are choosing to perform this analysis in a simple manner by listing the salient features and making an evaluation of those features for each configuration. We can then determine by inspection the significant differences and weigh those differences to arrive at a preference for one of the configurations.

The features of the two configurations have been divided into two broad categories, operational features and implementation features.

Operational refers to all of the features of the configuration that relate to actual use of the ADC by the observatory. It should be assumed for the purposes of this analysis that from an operational perspective the instrument starts its working life fully operational and meeting all of the agreed upon specifications.

Implementation refers to the features of the configuration that affect the development program in areas such as cost and schedule risk.

The operational feature table C-1 on the following pages lists all of the important operational features where the two configurations differ. The implementation features cover the top-level aspects of the design, construction and test phases as well the cost of implementation. The highlighted texts in the table are those differences that seem significant as determined by inspection.

Table C-1: Operational Feature Comparison

Operational Feature	Full Aperture Version	Sub-aperture Version
Observing		
ADC performance		
• Residual dispersion	Same	Same
• Range of zenith angle	Same (for a given prism separation range)	Same (for a given prism separation range)
• Throughput	Same	Same
	Cannot be removed from LRIS FOV, so approximately 5% maximum throughput loss is present at all zenith angles even when dispersion compensation is not desired	Can be removed from LRIS FOV during observing
Vignetting	Approximately 7% loss of guider total FOV range	Approximately 11% loss of guider total FOV range
	No vignetting of LRIS FOV	Small (less than 1%) vignetting of LRIS FOV
Spot Quality	Equal to, or slightly better than the sub-aperture version	Equal to full aperture version
Set-up	Requires selecting: 1) Compensation setting 2) Continual correction or fixed correction	Requires selecting: 1) Compensation setting 2) Continual correction or fixed correction 3) ADC in or out
Control during exposure	Adjustment of dispersion for zenith angle if continual correction selected	1) Adjustment of dispersion for zenith angle if continual correction selected 2) Rotation to match LRIS rotation mode

Table C-1: Operational Feature Comparison Cont'd.

Operational Feature	Full Aperture Version	Sub-aperture Version
Observing cont'd.		
Consequences of failures		
• Compensation axis fails	Do without compensation, fixed compensation now in beam, can work around if software tools are available to calculate total dispersion resulting from fixed compensation setting	Cannot rotate ADC, may loose observing time due to loss of LRIS rotation capability because ADC window cannot track LRIS
• Rotation axis fails	Not applicable	May loose observing time due to loss of LRIS rotation capability because ADC window cannot track LRIS
Telescope Configuration	If dispersion compensation is not required, and throughput loss is a problem then ADC must be removed from in front of LRIS by a configuration change	ADC can rotate out of LRIS FOV, so no configuration change is required to avoid throughput loss
Operational Cost	Higher if throughput loss forces frequent removal	Higher if increased complexity results in more frequent repairs

Table C-1: Operational Feature Comparison Cont'd.

Operational Feature	Full Aperture Version	Sub-aperture Version
Size and Weight	1400 mm overall travel, est.	700mm overall travel, est.
	1500 mm overall length,	800mm overall length,
	Approximately the same weight as the sub-aperture version	Approximately the same weight as the full-aperture version
Reliability Factors	1 motor for compensation axis	2 motors:
	four encoders:	compensation, rotation
	three with associated limit switches for compensation lead screws	two encoders:
	one for compensation motor	one for compensation motor
		one for rotation motor
	1 servo axis - compensation	2 servo axes – compensation and rotation
	Same optical tube design as sub-aperture version, but larger	Same optical tube design as full aperture version but smaller
	1 timing belt for compensation lead screw drive	5 ring gears:
		3 for motion control coupling for compensation
		1 for motion control coupling for rotation
		1 for de-rotation of optical tube

Table C-1: Operational Feature Comparison Cont'd.

Operational Feature	Full Aperture Version	Sub-aperture Version
Interface		
• Cabling		
○ ADC to control enclosure	1 motion control axis and associated control signals, four encoders	2 motion control axes and associated control signals, two encoders
○ Control enclosure to telescope systems	Same	Same
	No cable wrap	No cable wrap
• Control Enclosure	Same size	Same size
	Possibly easier to eliminate control enclosure by using "smart motors"	2 axes in coordinated motion with DCS, difficult to eliminate control enclosure by using "smart motors"
• Power	Slightly less than sub-aperture version	Slightly more than full-aperture version
• Cooling	Possible requirement to glycol cool compensation motor	Possible requirement to glycol cool compensation and rotation motor
	Same (needed for control enclosure)	Same (needed for control enclosure)
Maintenance	Relatively simple mechanism and control, probably easier to disassemble for repairs	More complex mechanism and one more control axis, may be harder to disassemble for repairs
	Better access to parts for service due to larger size	

Table C-1: Operational Feature Comparison Cont'd.

Implementation Feature	Full Aperture Version	Sub-aperture Version
Mechanical	Overall design is less complex than sub-aperture version, much easier design task System is larger and may require greater attention to structural design and rigidity Larger size makes it easier to make full aperture version rigid Clear aperture size of 1000mm makes optical tube assembly quite large	More complex design, many more moving parts Difficult design task System is more compact than full aperture version
Optical	Same	Same
Electrical	Simpler electrical/electronic system with one motor and one motion control axis	More complex electrical/electronic system, two motors and two motion control axes
Software	Simplest baseline software, no rotation or in/out options	More complex software needs to understand LRIS rotation modes and track DCS with 2 axes; in and out options; more fault conditions to handle
Interface	Less demanding on cabling between electronics enclosure and ADC module Only one motor possibly needing glycol cooling	More cabling between electronics enclosure and ADC module Two motors possibly needing glycol cooling

Table C-1: Operational Feature Comparison Cont'd.

Implementation Feature	Full Aperture Version	Sub-aperture Version
Testing	Only one motion control axis, easier to test and verify for correct operation and fault handling	Two motion control axes, more complex system, harder to verify for correct operation, more fault combinations to identify and test
Cost	Approximately $101K more than sub-aperture version; this is due to much higher glass cost for larger prisms offsetting savings in design and mechanical/electronics costs	$101K less expensive than full aperture version

Results of the Analysis

The information in the feature tables is summarized in the trade-off analysis shown in table C-2. In general the features selected for inclusion in this table are those whose evaluation is significantly less desirable in one configuration or the other.

The table has three columns: the selected feature, the full aperture version's evaluation and sub-aperture version's evaluation. The evaluation columns contain entries reflecting less desirable evaluations. For example, the feature "Observing, Throughput" contains an entry for both versions since there is a throughput loss in both versions, and the ideal ADC would of course have zero throughput loss. On the other hand, the feature "Observing, Set-up" has an entry only for the sub-aperture version because the set-up of this version is more complex than the full aperture version and this clearly increases the chances for operational errors.

Table C-2: Trade Off Analysis

Feature	**Full Aperture Version**	**Sub-aperture Version**
Observing, Throughput	Always 5% loss	5% loss when in beam for compensating
Observing, Vignetting	7% guider FOV range	11% guider FOV range & 1% LRIS FOV
Observing, Set-up		More complex
Observing, Control		More complex, must match LRIS rotation
Observing, Consequences of failures		Loss of rotation results in loss of observing time
Telescope Configuration	May need to be removed when throughput loss is not acceptable	
Operational Cost	Higher if throughput loss forces frequent removal	Higher if increased complexity results in more frequent repairs
Reliability Factors	Larger optical tube	– 2 motors instead of 1 – 2 servo control axes instead of 1 – 5 ring gears
Interface, Control Enclosure		Difficult to eliminate by using smart motors
Maintenance		More complex, may be harder to disassemble for repairs
Implementation, Mechanical	Larger, more structural design concerns, big optical tube	More complex to design, more moving parts

Table C-2: Trade Off Analysis Cont'd.		
Feature	**Full Aperture Version**	**Sub-aperture Version**
Implementation, Electrical		More complex due to additional motion control axis
Implementation, Software		More complex, needs to understand LRIS rotation modes, 2 motion control axes must track DCS, more fault conditions to handle
Implementation, Testing		More complex, harder to verify, more fault combinations to consider
Implementation, Cost	101K more than sub-aperture version	

Based on the approach taken in this analysis, the full aperture version has fewer negative evaluations for its features and should be preferred on that basis. This simple analysis does not weight either the features or the evaluations beyond the simple attribution of more or less desirable, but it is consistent with the intuition of CARA staff that the simpler, albeit more expensive configuration is the better one.

We can also make a brief comment about the possibility that ADC failure might cause a loss of an entire night of LRIS observing. We have examined the possibility of removing the ADC from in front of LRIS during the night, and it does appear possible that if the night attendant and the observing assistant were trained in the procedures that this could be done within an approximate 2 hour period, making it possible that a full night would not usually be lost in the event of an ADC failure.

APPENDIX D – CARA ACTIVITIES FOR THE LRIS-ADC

Introduction

The proposed atmospheric dispersion compensator (ADC) for the LRIS instrument will involve some work by CARA staff in addition to the work of the ADC project team. This appendix provides information on the anticipated tasks, and these task descriptions were used for the purposes of making estimates on the labor and materials costs required to perform these tasks.

CARA Activities

The activities to be performed by CARA staff for the LRIS-ADC project are as follows:

1. Provide Instrument Program Management
2. Write a Requirements Document
3. Perform Design and Analysis as Required to Establish Defining Points for the LRIS-ADC
4. Design modifications to the LRIS Hatch
5. Determine Electronic/Electrical Interface Requirements
6. Determine Cooling Interface Requirements
7. Write an Interface Control Document
8. Review Safety and Operations
9. Review Weight and Balance
10. Install Defining Points
11. Build and Install Electronic/Electrical/Cooling Interfaces
12. Implement LRIS Hatch Modifications
13. Implement Baseline Software Requirements to Interface the LRIS-ADC
14. Develop an Acceptance Test Plan
15. Participate in Pre-ship Testing
16. Participate in Installation/Testing/Commissioning
17. Participate in Project Meetings, Milestone Reviews and Other Meetings as Required

Additional detail on these activities is provided in the following paragraphs:

1. Provide Instrument Program Management

The CARA Instrument Program Manager (Sean Adkins) will provide management, fiscal and technical oversight to the project throughout its duration.

2. Write A Requirements Document

This task consists of writing a requirements document to fully define the expected performance of the LRIS-ADC as well as provide specific requirements for each design discipline. The Instrument Program Manager will write this document based on input from CARA personnel (to be determined) and in consultation with the LRIS-ADC design team.

3. Perform Design and Analysis as Required to Establish Defining Points for the LRIS-ADC

This task consists of determining the appropriate locations for defining points in the tertiary mirror tower on Keck I for the mounting of the LRIS-ADC. Mechanical design analysis may be required to determine the best locations for these mounting points along the major axis of the tower because the tower structure may exhibit modal flexure and resonance.

The task also includes preparing engineering drawings to document the installation of these defining points so that CARA personnel can make the required modifications to the Keck I tertiary mirror tower.

4. Design modifications to the LRIS Hatch

The current LRIS hatch opens outward and would interfere with the new ADC. The current proposal is to replace this hatch with a sliding door. This task consists of designing the new hatch and mechanism and preparing engineering drawings for the fabrication and installation of the new hatch.

5. Determine Electronic/Electrical Interface Requirements

This task consists of determining the electronic and electrical interface requirements for the LRIS-ADC through consultation with the LRIS-ADC design team. This includes connections between the LRIS-ADC control electronics and the observatory systems as well as connections between the LRIS-ADC control electronics and the LRIS-ADC module. This task would then document these requirements in the form of drawings and written documents as appropriate to provide a basis for the corresponding sections of the Interface Control Document.

6. Determine Cooling Interface Requirements

The LRIS-ADC design assumes an actively cooled electronics enclosure that is located up to 150 feet from the LRIS-ADC. This task consists of determining the location of the enclosure and establishing the cooling requirements through consultation with the LRIS-ADC design team and appropriate CARA staff. This task would then document these requirements in the form of drawings and written documents as appropriate to provide a basis for the corresponding sections of the Interface Control Document.

7. Write an Interface Control Document

This task consists of writing a document to define in detail the interface between the LRIS-ADC and the telescope/LRIS instrument. This task includes mechanical engineering for definition of the ADC envelope and access requirements and the creation of CAD models as appropriate.

8. Review Safety and Operations

This task consists of reviewing the ADC interface and operations and the modifications to the observatory systems for safety, reliability, maintainability and cost effectiveness.

9. Review Weight and Balance

This task consists of determining weight and balance constraints and ensuring that the realized ADC design will conform to these constraints as indicated in the ICD.

10. Install Defining Points

This task consists of installing the defining points in the Keck I tertiary mirror tower and making any other required modifications to the detailed structure of the tower to mount the LRIS-ADC.

11. Build and Install Electronic/Electrical/Cooling Interfaces

This task consists of building and installing the required electronic and power cabling and interconnection panels/points as well as any required cooling connections for the LRIS-ADC and its associated electronics enclosure.

12. Implement LRIS Hatch Modifications

This task consists of fabricating, assembling, testing and installing the modified LRIS Hatch.

13. Implement Baseline Software Requirements to Interface the LRIS-ADC

The baseline software architecture for the LRIS-ADC assumes a separate GUI and associated keyword service. The ADC has its own rotator that must track the rotation of LRIS using position data from the DCS data stream. Dispersion correction is a function of zenith angle, and the ADC introduces a displacement in the image position as a function of the amount of dispersion correction. This displacement needs to be taken into account by various guiding and pointing components in the telescope systems. In particular these are the following: Offset Guider, Pointing/Rotation Model for Keck I, Focus Routines (MIRA, etc). It will also be necessary to add a new control row to the OA startup screen called “dcsgui”. This task consists of the design, coding and testing to accommodate image displacement, rotator communications and the OA startup screen changes. This task also includes limited support activities for experienced visiting programmers and providing occasional assistance with code builds, releases and pre-installation testing.

14. Develop an Acceptance Test Plan

This task consists of writing a detailed acceptance test plan in the preliminary design phase and refining it in the critical design phase. This test plan would include tests to be performed prior to shipment and also tests to be performed at installation and commissioning. The test plan would be developed in consultation with the LRIS-ADC design team and CARA personnel.

15. Participate in Pre-ship Testing

Approximately 5 weeks are allocated in the current project schedule for pre-shipment testing. At a point to be determined, near then end of this period, one or more instrument specialists from CARA would travel to UCO/Lick to participate in this testing process and become familiar with the operation of the instrument.

16. Participate in Installation/Testing/Commissioning

Approximately 4 weeks are allocated for the installation and testing of the LRIS-ADC at the Keck I telescope. This task includes all participation by CARA personnel in the installation, mechanical, electrical, software and optical testing of the LRIS-ADC. This task also includes approximately 3 nights of “on sky” testing of the LRIS-ADC as a commissioning process. This task includes the review of the spares package and service requirements to ensure completeness. This task also includes participation in “hand-over” including a review of the final documentation package provided by the LRIS-ADC design team.

17. Participate in Project Meetings, Milestone Reviews and Other Meetings as Required

This task captures time required to participate in project meetings (monthly), milestone review meetings such as PDR and CDR, and any other meetings that may be required during the project.