Conceptual Design (Phase A) Report for an Atmospheric Dispersion Corrector (ADC) for the Low Resolution Imaging Spectrograph (LRIS)

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Executive Summary

For the foreseeable future, the excellent UV throughput of LRIS will allow Keck observers a distinctive advantage over other 8-10m class telescopes. Without an ADC, however, the performance of LRIS will suffer significantly, even at modest airmasses of 1.3 at only 40 degrees from zenith. This conceptual study of an ADC add-on for LRIS concludes that a "Linear ADC" design using two fused-silica prisms is the only viable one and that it will dramatically improve the use and performance of LRIS.

We have found no major technical risks nor any major sources for schedule slippage, though a more reliable assessment of this is not possible until the Preliminary Design and Critical Design phase.

The key concern is cost. The core design is estimated at $640K. The contingency on the core is an additional $160K, which includes $80K to cover the cost of commercial Sol-Gel optical coatings should Livermore not provide them for low to no cost, as they have in the past. To reduce costs, the core design does NOT include the feature of allowing the ADC unit to be moved in and out of the LRIS view in real-time. Adding this important option would cost approximately $74K including contingency. Other options that add functionality to the core design are presented as well. Key decisions to be made include whether to proceed to the Preliminary Design phase and if so, which of various tradeoffs and options are to be included for further study. This report aims to provide sufficient information for making these decisions.

ADC Phase A Study
31 October 2002

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Appendices

1. Summary

This summary provides a broad overview of the contents of the Phase A LRIS ADC study with focus on major highlights and key points. The locations of details in the remaining report are included for the reader's convenience.

1.1 Background to Phase A study of ADC for LRIS

The need for an atmospheric dispersion corrector was recognized and included as part of the original Keck Telescope design. Several years ago, a phase A study was initiated by J. Nelson to revive the ADC that would be installed as part of the telescope and serve all instruments. This option was discarded due to mechanical difficulties to move the ADC in and out of the field of view in front of the tertiary tower. The Science Steering Committee in October 2001 approved and funded this Phase A study of an ADC for the LRIS alone.

1.2 Need for ADC - Scientific Impact (Appendix A and Chapter 4)

With LRIS acquiring the blue side, the Keck community has an optical-UV imager and spectrograph that is unsurpassed among 8-10m telescopes and will likely remain so for years to come. The atmosphere, however, severely degrades the performance of LRIS at even modest airmasses 1.3 or greater.

This degradation comes in two forms that result from the atmosphere acting as a stronger prism at greater angles from the zenith: distortion of the positions of objects and separation in position of light from the same source at different wavelengths (chromatic dispersion). The former can be partially compensated by slight rotations. The latter can be almost fully compensated by the use of an ADC.

Without an ADC, the astronomer using LRIS at high airmass may lose significant light in spectroscopic mode if the chromatic dispersion is not aligned with the slit and suffer image degradation and photometric precision in imaging mode due to color dependent spread of light through filters. The scientific loss in productivity and efficiency by not having an ADC is difficult to quantify statistically and from past observations, since experienced observers would have so far tried to avoid wasting time working at higher airmasses, thus losing opportunities for longer exposures, access to important scientific targets (e.g., GOODS fields and Galactic center are all at high airmasses all the time from Keck), or use of LRIS in the UV mode altogether. To translate the loss in telescope efficiency is somewhat easier: even at losses of a few 10% of light on average, at $47K per night of Keck (typically the most precious ones during new moon), the losses over a few years would easily total over $1M.

1.3 **Conceptual Design** (Chap 4 & 5)

We started from the Linear ADC explored by Nelson and Mast during their phase A study of an ADC for the telescope. For LRIS, the challenges were to accommodate the ADC as an add-on in front of the existing instrument; include an extra counter-rotation for the ADC to compensate for the rotation of LRIS if the ADC unit was attached to LRIS itself (no such rotation would be needed if the LADC were locked to an alt-az telescope frame); to achieve as high a throughput in the UV as possible without loss of image quality; to ensure adequate counter-weighting if the ADC unit were moved; and to retro-fit software, mask design, the ADC itself, etc. Some of these challenges have yet to be fleshed out and await further detailed study during the preliminary design and critical design phases. But we feel confident the proposed design in this study, namely an LADC installed in front of the LRIS field of view (see figures in Chap 5), will work well, with few if any technical risks or major schedule slippage.

1.4 **Specifications and Constraints** (Chap 2 & Chap 5)

An important part of any conceptual design phase is to establish the specifications and constraints on the instrument and its design and use. For the LRIS ADC, we did not have the benefit of the classical mode of having a scientific advisory committee provide such constraints. Thus we welcome any well-justified modifications at this stage of the project. Indeed, we need inputs from relevant parties to ensure that the LRIS ADC proceeds with the proper constraints and specifications. To set priorities, we have further qualified our list of specs and constraints with different classes: (E) for essential, i.e. must be satisfied in this project; (I) important and should be satisfied within desires of CARA and SSC and budget and schedule; (O) optimal and thus highly desirable for added functionality or performance but of lower priority if costs and schedules are adversely affected. A number of specifications remain to be defined – these we have designated with (T) for TBD. <u>Sections 2.2 and 2.3 give an overview of the specifications and constraints for the LRIS ADC and should be examined closely.</u>

Those items in the (E) category were used to construct what we have termed as the core ADC design.

1.5 **Major Tradeoffs and Alternatives - Core and Options** (Chap 3)

A record of the rationale used to converge on our adopted conceptual design is outlined. As mentioned above, the original phase A study of an ADC presumed one for the telescope that would be useable by any instrument at Cass or Nasymth. The study ultimately decided in favor of instrument-specific ADC's, and that LRIS with its UV coverage needed the first. The next issue of the type of ADC eventually converged on the LADC as the only viable one – the other two result in major problems. The next tradeoff mentioned is the number of ADC's, each optimized for one side of LRIS. The need to include the guider in the ADC field of view precluded more than one ADC. The distance from zenith (ZD) is an important tradeoff that balances prism angle, thickness and thus throughput, thickness and thus volume of the ADC at maximum extension, and image quality. At present, the ingoing essential specification is 60 deg (airmass 2) for the spectral range of 0.32um to 1.1um. The final tradeoff is what defines the **CORE** design of the current study, namely one without real-time removal of the LADC from the LRIS field of view. Balancing the tradeoff in reduced cost, complexity, and time for the construction of the ADC is the loss of flexibility for the user to use the ADC or not (that might result in unnecessary throughput losses when removal would have been the preferred choice); the additional CARA labor for installing and removing the ADC depending on the choice of the observer for each night; and higher risk of lost observing time if the ADC unit fails at night (see Appendix E, item #8). Beyond this option, others mentioned below are largely in the areas of software and transition to use of alternative motors with the existing controllers or new "smart motors" that include built-in controllers.

1.6 **Optical Design** (Chap 4, Appendices A, B, C)

Optical design is perhaps the largest section in total of this Phase A study. Besides Chapter 4 itself, the optical design sections include the original study of ADC by Nelson and Mast (Appendix A), the study of the optical tolerances of the LADC needed by the mechanical engineering (Appendix B), and the study of the effects of non-zero-deviation by Phillips (Appendix C).

Based on Phillips' study (appendix C), we dropped the non-zero-deviation ADC option. Based on cost and risk of the optics and the light losses typically in the UV, the counter-rotating prism design was also dropped. This leaves **the LADC as the only viable option for LRIS.** More work on optical design is still needed at the preliminary design phase, including:

1) Extending the spot diagram work of Nelson in the original ADC phase A study from their 0.4um blue limit to that of 0.32um needed for LRIS;
2) Selecting the prism angle that best balances the effects of any specified ZD limit or volume, thickness of material that affects throughput, optical performance in terms of image quality, and possibly reflections and scattering of light; and
3) Undertaking a more careful study of scattered and reflected ghosts in LRIS with the add-on ADC. A key concern here is the effect of two flat surfaces that lie square with the optical axis to LRIS.

Two issues are worth noting. First is that of throughput: the uncertain transmission (between 0.995 and 0.985) for 10mm of fused silica translates to between 3% and 10% losses for the nearly 70mm needed for the 2 prisms of the LADC. This difference in possible throughput will make the difference in whether the ADC should be used in zero-correction mode. The cost and availability for the higher throughput fused silica needs to be tracked down in the PD phase. The other issue is that of optical coatings, because without the virtually free Sol-Gel coatings from Livermore assumed for the **Core** design, the ADC may require an estimated $80K from contingency to obtain such coatings from a commercial firm.

1.7 **Mechanical Design** (Chap 5)

The optical tolerances of the ADC (Appendix B) were relatively loose, making the mechanical design relatively easy. The core design, along with the **MAIN OPTION** of **including a radially translating stage for the ADC with counterweights**, were explored in sufficient detail to provide: reasonable estimates of weights; cost estimates for materials and fabrication; number of motors and control; information on whether tolerances were met; and identifying key issues such as counterweights. The design also ensures access through the front of LRIS for maintenance and access; removal of the ADC unit; and coverage of the LRIS guider and field with minimal to minor amounts of vignetting. The design will be refined at the PD stage to reflect any new inputs from the optical design on the tradeoff between larger volumes and greater risks of mechanical flexure for the mechanical housing and higher throughput when using prisms with smaller angles.

1.8 **Electronics and Control Design** (Chap 6)

The ADC design is relatively simple and easily accommodated by motors and controls for which UCO/Lick has had extensive experience. The cost estimates should be quite reliable. A possible **OPTION** is to **switch to "smart motors"** that include the control electronics integral to the motor itself. This option will require some learning curve and will likely be of higher cost, but with benefit of transitioning smoothly to the use of such motors in the future.

1.9 **Software** (Chap 7)

Software is a major driver of the costs of the LRIS ADC at this stage. The main purpose of Phase A is to estimate the run-out costs for the ADC software. This in turn depends on identifying areas of software needing support from the software staff, determining the level of expertise needed, and estimating the labor to complete them.

Four areas needing software support were identified:

1) Control software to move the ADC by observers and staff
2) Mask design software that accommodates the ADC
3) Custom software to assess optical performance
4) Custom software that allow observers to better plan their run by predicting PSF, throughput, and spatial distortions due to the atmosphere and given choice of filters and slit widths, with and without the ADC

The control software is fairly straightforward to estimate, both for motors and for user interfaces for the ADC control. Since the current LRIS software does not meet Keck standards, the software team will implement the control software that does meet Keck standards by using a separate control panel (window) from the main LRIS control panel. This does raise the issue of an **OPTION to upgrade the LRIS software** as part of the ADC project. If chosen, then the option raises the question of who (Caltech, CARA, UCO) should undertake this task, from what funding source, and when.

The mask design software is clearly needed, but raises the issue of which of two packages used by observers (official LRIS version or the one developed by A. Phillips used by many others) or both will be upgraded. The budget assumes only the one developed by Phillips. This then raises the larger but **OPTION**al need of perhaps providing Keck users a **common, uniform mask-making software package** that includes LRIS, DEIMOS, ESI, and perhaps HIRES that can all accommodate custom cut masks.

To assess optical performance during the optical fabrication, integration, testing, and commissioning phases, custom software and technical labor will be needed. Such work is really part of optical design and analysis. There is, however, a significant level of uncertainty on the amount of labor these tasks will take.

To obtain maximum performance from the LRIS with an ADC, the observer would benefit greatly from the OPTION of a **simulation package** that would provide the user information that would guide optimal choices of exposures, whether to lock the ADC or not, whether to include small rotation adjustments during exposure, etc. The information from this simulation package would include the expected throughput, image quality, astrometric precision, image distortions, etc.

Along these lines of optimal performance, we note that CARA needs to accommodate improved LRIS offset guider software that adjusts to the known positional distortions from the atmosphere and ADC and perhaps slight rotational adjustments as well. Any new focus routines that involve the LRIS offset guider will also need to accommodate the LRIS ADC. Any interactions between CARA and Santa Cruz staff in developing these areas are also beyond the scope of the current ADC budget.

1.10 **Budget** (Chap 8)

The cost of the LRIS ADC is likely to be a major issue.

To put the costs into perspective, we have an estimate from Dan Fabricant that the ADC portion of a wide-field corrector for the f/5 focus of the converted MMT on Mt. Hopkins, AZ was around $655K. In their case, the ADC was integrated into the original design, fabrication, and review. In contrast, the LRIS ADC is really an add-on optical component that has to be retro-fitted, along with mechanical modifications to LRIS; recovery, checking, and integration of LRIS mechanical drawings; newly designed Keck-compatible software to be integrated to non-Keck-compatible software; software to accommodate a broader user community (such as the simulation software); four additional rounds of study and reviews; and consideration of upgrades to existing LRIS motors and software, etc. For budget reasons, some of these options are likely to be dropped.

Moreover, we should also keep in mind the costs that are largely hidden but part of all instrument projects. These include the PI's time and salary, UCO Director's time and salary; CARA staff time and salary; reviewer's time and expenses; SSC efforts; other management costs; and post project consultation that often do not include rebilling of time and effort, etc.

And finally, we should remember to balance any consideration of the high costs of the ADC by the loss of data quality (hard to translate in $), telescope efficiency ($47K/night), and scientific productivity and discoveries ($ translation difficult) from LRIS that does not have an ADC.

The table provides a summary of estimated costs for the CORE design of the ADC along with the major options.

SUMMARY TABLE of ADC Budget

CORE COST $640K
CORE CONTINGENCY $160K (includes $80K for coatings)
OPTION A: Radial translating track $67K + $7K contingency
OPTION B: Additional Optical Design Analysis $11K
OPTION C: LRIS software upgrade $62K + $6K contingency
OPTION D: ADC simulation software $29K +$5K contingency
OPTION E: Additional commissioning characterization $8K

1.11 **Schedule** (Chap 9)

Using the current workload, we estimate the dates of various milestones for the project:

• Review of Phase A study	2 Dec 2002
• PDR	9 April 2003
• CDR	16 July 2003
• Preship Review	16 Feb 2004
• First Light	12 April 2004

We see no major technical risk factors that should preclude achieving these milestones. Fused silica of the requisite size and quality are available commercially. Sol-gel is available commercially if Livermore is unable to deliver. Optical design and fabrication, mechanical design and fabrication, electronics and control design, and all aspects of software are otherwise all covered by the existing staff and resources within UCO/Lick

1.12 **Management plan** (Chap 10)

The ADC project will be under CARA's new instrument development program and thus under the oversight of its Instrument Program Manager. The Project Scientist is David Koo, who as faculty and astronomer, will have the usual role of serving as the key contact and coordinator to CARA and SSC and who will have overall responsibility for the project. Assuming approval to proceed with the ADC, the vast bulk of the day-to-day work is expected to be done at UC Santa Cruz by UCO/Lick staff under the project management of Dave Cowley. He will be responsible for the requested monthly reports, major PDR through pre-ship reviews, Gantt project schedules, and budgets and use of contingency funds. The project lead will be the project engineer, Lee Laiterman. Various UCO/Lick staff will be leading the other aspects of the project. Depending on decisions regarding who will be making upgrades to LRIS software and mask-making software, coordination with Caltech, as well as CARA, may be needed.

1.13 **Outstanding issues** (Chap 11)

A number of issues need attention and resolution before or during the preliminary design stage of the LRIS ADC project:

- **Real-Time Removal of the ADC from LRIS Field of View:** A decision is needed on whether the PD plans should include the **OPTION** of the radial translating stage for the ADC.
- **Finalize Throughput Specification:** Agreement is needed on the "best effort" definition of the throughput specification. In fact, all specifications should be finalized.
- **LRIS Modifications:** Agreement on who will be making the LRIS modifications to the hatch and shroud, how will it be funded, and how will it be done and managed. Possibilities include Caltech, Lick, and CARA.
- **CARA Specs:** Cara needs to provide explicit requirements and specifications for any Keck standards on weights, safety, maintenance, operations, user GUI software, etc.
- **Keck Telescope Control Modifications:** Who, how, when, etc. for the guider, telescope control, new focus operations, etc?
- **LRIS Software Upgrade:** Who, how ,when, etc. for upgrading existing LRIS software to meet current Keck standards?
- **Motor Control Upgrade:** A decision is needed as to whether the ADC project will serve as the pathfinder for use of "smart motors" in Keck instruments.
- **Fast Track Option for ADC:** To save time and perhaps money but at higher risks for problems, CARA and SSC may want to consider speeding the project. To achieve this, UCO/Lick may add personnel. If this is not practical and within constraints of required quality, some of the ADC work can be out-sourced to commercial firms.

2. Specifications and Constraints

2.1 Introduction

This section provides the scientific, functional, and operational specifications and constraints to be applied for the design of an Atmospheric Dispersion Corrector (ADC) for the Keck I Low Resolution Imaging Spectrograph (LRIS). A Phase A (conceptual design) study for an ADC for the Keck Telescopes was initiated (PI: Nelson) several years ago but after discarding this option (footnote: largely due to 1) conflicts with infrared modes of operation; and 2) mechanical difficulties of taking the ADC out of the field of view easily and quickly), a revised proposal (PI: Koo) to explore an ADC dedicated to LRIS was approved and funded by the Science Steering Committee (SSC) on 15 October 2001. The nominal due date for the Phase A study has been extended from its original of 1 April 2002 to 31 Oct 2002.

To identify the level of importance and priority, we will use the following classes and codes:

(E) -- these are essential for a baseline, functioning ADC for LRIS and must be satisfied by the project.

(I) -- these are important and should be satisfied, but constrained by the desires of CARA and SSC, budget, and schedule.

(O) -- these are optimal to have and thus highly desirable for added functionality or performance, but are otherwise of lower priority if costs and schedules are adversely affected.

(T) -- these remain TBD, i.e., to be defined at the completion of the Preliminary Design study.

2.2 Scientific Requirements

The ADC shall correct for atmospheric dispersion

1) From 0.32 to 1.1 μm, **(E)**
2) to zenith distance (ZD) of air mass 2.0 (60 deg), **(E)**
3) with minimal degradation (<0.1 arcsec or <10%, whichever is greater) of image quality (FWHM) from the best (10 percentile) seeing images (with no ADC), **(I)**
4) and with best possible throughput (within constraints of commercially available glass and AR coatings, and available space for ADC storage and installation). **(I)**

2.3 Overview of LRIS Design Assumptions and Considerations

1) ADC will be used only for LRIS and shall not impact the observations or performance of other Keck instruments. **(E)**
2) LRIS will operate from atmospheric cutoff at 0.32 μm (3200A) to 1.1 μm (11000A) in both imaging and spectroscopic modes. **(E)**
3) ADC will operate at most to the telescope limit of zenith distance (ZD) of 72 deg (air mass 3.2), with performance as specified by the scientific requirements stated above. **(O)**
4) LRIS user or Keck staff can remove the ADC from the LRIS FOV (guider and detector) in real time. **(I)**
5) Installation, operation, and maintenance of ADC will not place undue hardship on Keck operations and staff. **(E)**
6) Software will conform to existing Keck standards, including telescope communications, user interfaces, and instrument control. **(I)**
7) Failsafe and safety options and modes will conform to Keck Observatory standards. **(E)**
8) Access to LRIS for ADC mechanical tests, software tests, installation, etc., will only be done in Hawaii (i.e., LRIS will not be shipped to Santa Cruz for testing, modifications, or integration). **(E)**
9) Documentation will be to Keck standards, otherwise to UCO standards. **(I)**

2.4 List of Areas Needing Specifications, Requirements, and Constraints (some to be refined at Preliminary Design Phase)

The subtopics and their organization will be as follows:

2.5 Optical Design and Performance
2.6 Modes of Operation
2.7 Mechanical Structure (size, weight, stowability, etc.)
2.8 Software Interfaces (testing, user, calibrations)
2.9 Maintenance, Installation, and Operation Support
2.10 Telescope and Guider System
2.11 Management

2.5 Optical Design and Performance

2.5.1 Basic Design

The basic design is assumed to be the Linear ADC (LADC - also referred to as the Longitudinal ADC). The system is relatively simple and consists of two identical flat-faced prisms that are rotated 180 deg with respect to each other; have parallel surfaces; and can be separated from nearly 0 distance (for virtually nil correction as required at zenith) to that needed for correction of atmospheric dispersion at other zenith distances. A major advantage for alt-az telescopes is that the prisms would not need to be rotated if mounted to the telescope, but in the case of a dedicated ADC attached to a rotating Cassegrain instrument, rotation is needed. The optics is simple and automatically provides zero-deviation beams. Moreover, because fused silica transmits UV (necessary for LRIS-B) and has an index of refraction that nearly matches that of the atmosphere throughout our spectral range of interest (0.32 - 1.1 μm), only a single material is needed. A potential disadvantage is that the images shift in position as the prism separation is changed, but as long as the guider is within the FOV of the ADC and tracks these shifts, this problem is largely solved.

2.5.2 Image Quality (see 2.6 for definition of MODES)

2.5.2-A in NULL MODE: **(E)**

No detectable (< 0.1 arcsec) degradation of PSF FWHM as compared to OUT MODE.

2.5.2-B) in FULL MODE: **(I)**

- ZD from 0- 60deg: PSF WIDTH
  The PSF FWHM (1.66 rms radius) compared to OUT-MODE at ZD=0 should be degraded (enlarged) by <15% of that obtained under the best (10 percentile) seeing OR 0.1 arcsec, WHICHEVER IS LARGER. This spec will apply for the full spectral range 0.32-1.1 μm.

  In other words, the image FWHM produced by the ADC at 0.32 μm should be enlarged by no more than 0.1 arcsec to 0.8 arcsec if, under the best seeing, the FWHM of the images at 0.32 um is 0.7 arcsec.

- ZD from 0-60 deg: IMAGE POSITION
  The image positions at 0.32 μm should be shifted relative to that at 1.1 μm by <10% of shifts as induced by atmosphere alone or 0.1 arcsec, WHICHEVER IS LARGER, for the full range of ZD.

  The 0.1 arcsec crossover point is at ZD ~ 30 deg. By airmass = 2.0 or ZD = 60, the differential refraction is 3.3 arcsec so the correction needs to be better than 0.33 arcsec. Although the current ZD range for use of the ADC is 60, when ZD = 72 (airmass 3.3) and the telescope has reached the limit when the wind shutter is vignetting, the difference in position between 0.32 μm image and 1.1 μm image is over 6 arcsec, so the correction of the ADC would be specified to be better than 0.6 arcsec. Such large offsets are likely to result in substantial flux loss through narrow slits that are not aligned with the parallactic angle.

2.5.2-C) in LOCKED MODE: **(E)**

There are inherently no additional specs needed beyond those for the FULL MODE. The actual PSF width and image position performance will depend on the length of exposure and the setting of the ZD.

2.5.3 Throughput **(I)**

The end-to-end throughput of the ADC will be constrained by: the thickness of the prisms that will correct to ZD = 60 deg within the volume allowed by the storage space of LRIS; the best transmitting fused silica available from industry; and the best anti-reflection coatings (Sol-Gel) we can find. A nominal target should be throughput greater than 90% for the full spectral range 0.32 - 1.1 μm.

The best throughput needs to be maintained throughout the life of LRIS, either through use of a long-lasting coating (Sol-Gel can be made durable with treatments such as DDMS or with addition of MgF2) or through recoating (Sol-Gel is relatively easy to remove without polishing).

2.5.4 Scattered Light and Reflections/Ghosts **(T)**

*** what and how do we specify this for imaging and for spectroscopy ? ***
*** what are the current limits on scattering and reflections in LRIS ? ***
*** what are reasonable specs to include at this stage ? ***

For now, we will use the phrase:

Where possible, all internal, exposed, and potentially reflective surfaces will be anodized to minimize reflections and scattered light. Options to minimize the ghosts from the ADC will be explored at the PD and CD stages.

2.5.5 Optical / Engineering Tolerances **(E)**

See June 2002 report (Appendix B) by Terry Mast.

2.6 Modes of ADC Operation

All operational modes of the ADC should be available remotely by the user and staff, and be useable for both imaging and spectroscopy (long slit, mask) (or long slit mask?).

1) Out of optical path (OUT MODE) **(I)**
2) In optical path but with no atmospheric correction (NULL MODE) **(E)**
3) In optical path with full or partial CONTINUAL correction adjusted for zenith distance, filter, temperature, pressure, etc. (FULL MODE) **(I)**
4) In optical path with locked position at given correction (LOCKED MODE) **(E)**

2.7 Mechanical Structure (size, weight, stowability, etc.)

2.7.1 Weight and Balance: The ADC package installed and in full range of modes must be balanced as allowed by existing telescope structure. Weight and balance may also be a consideration for ADC removal and installation. **(E)**
*** Keck engineers: We need a spec sheet here for the variation in torques induced by switching modes and during operation of the ADC.

2.7.2 Size **(E)**

1) The ADC+LRIS should be an integrated unit that can be stowed in the current parking structure space for LRIS.

2) The total operational ADC system should be installable using current equipment and fit within the existing "Cass instrument module." If this is not possible, designers will need to work closely with Keck staff on any necessary modifications.

2.7.3 Speed of ADC Motions **(I)**

The switch from NULL MODE to OUT MODE or back shall take no longer than three minutes, roughly the minimum time for setup. The time needed to move the outer ADC prism from NULL MODE (for ZD = 0) to full extension (for ZD = 60) should take no longer than five minutes, roughly the time to slew the telescope by 60 degrees.

2.7.4 LRIS Modifications

1) The existing hatch door may be modified or replaced to accommodate the ADC. **(E)**

2) Design of the ADC must ensure that the front end of LRIS can accommodate access by Keck staff at a level needed for LRIS repairs and maintenance. Any alternative must be coordinated with Keck staff. **(E)**

3) The LRIS Front Shroud must be truncated at two corners to avoid interference with the ADC support frame. **(E)**

2.8 Software Interfaces (testing, user, calibrations)

2.8.1 Telescope Interface **(E)**

The ADC will communicate with the telescope using the current DCS.

2.8.2 Instrument Interface **(E)**

The ADC instrument control software will comply with Keck standards.

2.8.3 User Interface **(O)**

The ADC user interface will be integrated into the existing one, if not too costly, and otherwise provided in a self-contained window panel.

2.8.4 Calibration Software **(I)**

The ADC software will include scripts or programs needed to calibrate the ADC system, including rotation rate and zero point; prism separation distance and zero-point; optical alignment of ADC and LRIS optical axes.

2.8.5 Performance Analysis **(I)**

The ADC software will include scripts or programs needed to assess the performance of the ADC during commissioning and any routine tests.

1) Spectrograph optical performance (throughput and vignetting, PSF quality as a function of position, spatial shifts as a function of position, scattering, reflections, etc., all as a function of wavelength)

2) Guider performance and focus performance

3) Mechanical performance (tracking errors and stability, flexure, rotation accuracy, etc.)

2.8.6 Slit Mask / Observing Preparation Software **(I)**

The slit mask preparation software will be modified to include the effects of the ADC in showing the user shifts in position of objects in an image or spectrum due to the atmosphere, with and without the ADC.

2.8.7 Model and Simulation of PSF Changes with ADC **(O)**

If not too expensive, software tools will be provided to users so that they may model the expected PSF and spatial shifts due to the atmosphere and ADC distortions for specified exposures and zenith distance.

2.8.8 Documentation **(I)**

All software will be documented to within Keck standards.

2.9 Maintenance/Operation/Safety Support **(T)**

2.9.1 Tasks and Schedule

*** The ADC will need maintenance at no more than XX hours of Keck staff per month. Routine maintenance includes oiling, replacement of switches, check of any safety features, grounding, etc.
*** What are the requirements here?

2.9.2 Installation

The ADC shall take no more than XX minutes to remove or install onto LRIS.

2.9.3 Optical System

*** The ADC shall require cleaning or maintenance of the optical system no more frequently than XX months per year.

2.9.4 Safety Features/Requirements

*** Is there a standard list from Keck? How are these to be determined?

2.9.5 Documentation

The documentation for installation, maintenance (optical, mechanical, electrical), safety procedures, etc., shall be within Keck standards

2.10 Telescope and Guider System Requirements

To exploit the full gains of an ADC, the Keck I Telescope control and guiding system should:

1) compensate for field distortions (atmosphere and ADC) to guide as if at center of LRIS FOV when using the offset guider; **(I)**
2) have the telescope rotation compensate for field rotation during observations resulting from differential refraction (i.e., these are additional corrections to field rotation beyond that needed for alt-az telescope mounts). **(O)**

If the offset guider is not in the FOV of the ADC, both of the above will significantly depend on the specific observations chosen by the observer: filter for imaging, and spectral range for spectroscopy. **(I)**

If the ADC introduces color dependent distortions due to slight mismatches between the index of refraction of fused silica and air, the previous corrections may need to be made even if the offset guider is in the ADC FOV. **(O)**

2.11 Management

2.11.1 Structure **(E)**

The LRIS-ADC project will abide by the new instrument program management structure recently outlined by J. Beletic, including command structure, reporting requirements, schedule for feedback and response, etc.

2.11.2 Reviews/ Committees **(I)**

Standard PDR, CDR, and Pre-ship reviews will be undertaken for the ADC project.

2.11.3 Coordination of CARA Tasks (Guider, LRIS mods, Focus software) **(T)**

*** Will some of the workload be done by Keck, and if so, how will that be managed?

3. Major Alternatives and Trade-Offs

3.1 Location of ADC

a) Telescope (Non-instrument Specific)

Pros:

- Single ADC for entire suite of existing and future instruments
- Cost potentially lower than separate ADC for each instrument
- Ease of operation – part of telescope
- Single motor operation if Linear ADC (LADC) is adopted

Cons (i.e., advantages for instrument specific option)

- Large optics (1-m diameter class) for single telescope ADC to cover full 20 arcmin FOV of any potential focal plane (Cassegrain, Nasymth); potentially very expensive up-front cost; difficulty in acquiring special NIR-transmitting fused silica, or difficulty in getting broadband coatings.
- Large wavelength range for single telescope ADC to accommodate current and future instruments, i.e., from 0.32 μm to near-IR (1.3 μm or greater).
- Optimization of image quality is difficult, especially since the large distance from the focal plane results in potentially much larger non-chromatic image distortions.
- Additional and large source of thermal radiation with negative impact on NIR instruments, especially those with existing pupil stops designed for current baffling tower, secondary structures, etc. Thus the ADC must be easily removable in near real time to allow flexible switch of instruments at night (e.g., from DEIMOS on one Nasymth platform to the other with NIRSPEC in AO mode).

b) Instrument Specific

Despite rather extensive efforts by UCO/Lick engineer Matt Radovan during the initial Phase A study of the ADC to find a solution to the last problem in the Cons list above, none was found that would enable easy removal of an ADC that was part of the telescope (located between the tertiary mirror and the secondary mirror) to a storage position totally out of sight from the FOV of NIR instruments. Thus a recommendation was made to the Keck Science Steering Committee to have ADC's dedicated to individual instruments. Due to the enormous effect of atmospheric dispersion in the UV on image quality, LRIS with its new UV sensitive side (LRIS-B) was considered top priority for further Phase A study of an ADC.

3.2 Type of ADC for LRIS

The three possible ADC designs include:

1) Traditional counter-rotating prism design: Has the advantage of being compact and self-contained, but a major disadvantage of not providing zero-deviation

output beams (see discussion in Section 4.3 and on the consequences of such finite-deviation prism systems in Appendix C).

2) Counter-rotating prisms with additional optical components to provide for zero-deviation beams: This design retains the advantages of the traditional counter-rotating prisms and overcomes the major disadvantage, but at the cost of additional optics that may dramatically hurt throughput as well as have greater expense, risk, and complexity for the optical components.

3) Linear ADC – prism pair: This design is optically very simple; provides excellent throughput for the UV by using only fused silica whose index of refraction matches well that of the atmosphere over a very wide range of wavelengths; automatically provides zero-deviation beams, but with the main disadvantage of needing a larger volume to operate.

Given the wide spectral range covered by LRIS and the availability of space in front of LRIS during operation and storage, the LADC was the natural choice for the conceptual design stage. This was especially true given that prior Phase A optical design study was of the LADC by T. Mast and J. Nelson for the telescope ADC.

3.3 Number of LADCs for LRIS

In principle, one can optimize throughput and performance by having different ADCs for different wavelength coverage. This option in the form of a dual ADC (one with coatings optimized for the full range of 0.32 μm to 1.1 μm and another where the coatings were more finely tuned for just the UV and blue where an ADC would be most needed) was seriously considered at the start, but the resulting constraint on the size of each ADC to cover BOTH the LRIS detector FOV and the offset guider FOV made it difficult to retain.

3.4 Zenith Distance (ZD) Limit for ADC

The ingoing position was to have the ADC operate over the full 0.32 μm to 1.1 μm range from the zenith to the maximum ZD allowed by Keck, namely 72 deg, after which the wind shutters begin to vignette the FOV. But considering the enormous loss of UV (over 0.5 mag per unit air mass) at high air masses above 2 (60 deg), the platform limit at air mass 1.55 of Keck I, the rapidly poorer seeing at high air masses, plus the already tight constraint on ADC volume and throughput (see optical design section), we have used a limit of 60 deg as the limit of ADC operation for correction from the UV (0.32 μm) to 1.1 μm. A more restricted range of wavelengths would allow the ADC to work to higher ZD.

3.5 Real-time Removal of ADC from LRIS FOV

We assume that some observers would prefer to forego the ADC (OUT-MODE) in some observations in order to avoid any throughput losses. We thus included the radial translating track in the mechanical design that would move the ADC in and out of the field of view. This mode of operation also easily provides a natural storage mode for the ADC that would include a cover. To achieve balance during the translation of the ADC, dynamic counter-weighting is needed.

Most observers, however, are likely to use the ADC for the vast fraction of their observations, so we considered the OUT-MODE to be an option rather than essential part of the CORE ADC. The main gain of not having the OUT-MODE option would be a reduction in the costs of the ADC by $67K (and $7K contingency) that would be needed to pay for the radial translating track system and greater simplicity.

The drawbacks include:

a) lack of flexibility to choose the ADC or not in real-time, thus resulting in some throughput losses when observing near zenith with the ADC; overall degradation of images if the ADC is not used at high airmasses; and choice of targets that can be adjusted for weather and location of clouds;

b) increase load on CARA staff to attach and detach the ADC to LRIS, perhaps on a daily basis, depending on the desires of an observer on a given night; (see appendix E, item #8)

c) increase risk of losing observing time if problems with the ADC arise that would normally be handled by moving the ADC out of the way;

d) greater difficulty in calibrating and checking the ADC when the OUT-MODE is not available.

4. Optical Design

4.1 Introduction of Atmospheric Effects

The atmosphere acts as a sheet of glass overhead (zenith), and as a prism whose refraction increases with ZD to lower elevations. The prism-like atmosphere results in two main observable effects. The first is due to refraction causing a shift in the position of an object relative to its position free of an atmosphere. For objects that are at slightly different ZD, the "differential refraction" results in relative positional shifts. When considered over time, a given FOV will show distortions that can be quite complex. As seen in Figure 4-1, the distortions mimic a combination of slight rotations and pincushion effects, with the amount and type of distortion dependent on the ZD, the time interval, the size of the FOV, and whether one is observing north or south. Typical shifts range from negligible (a few 0.01 arcsec) to potentially significant (a few 0.1 arcsec).

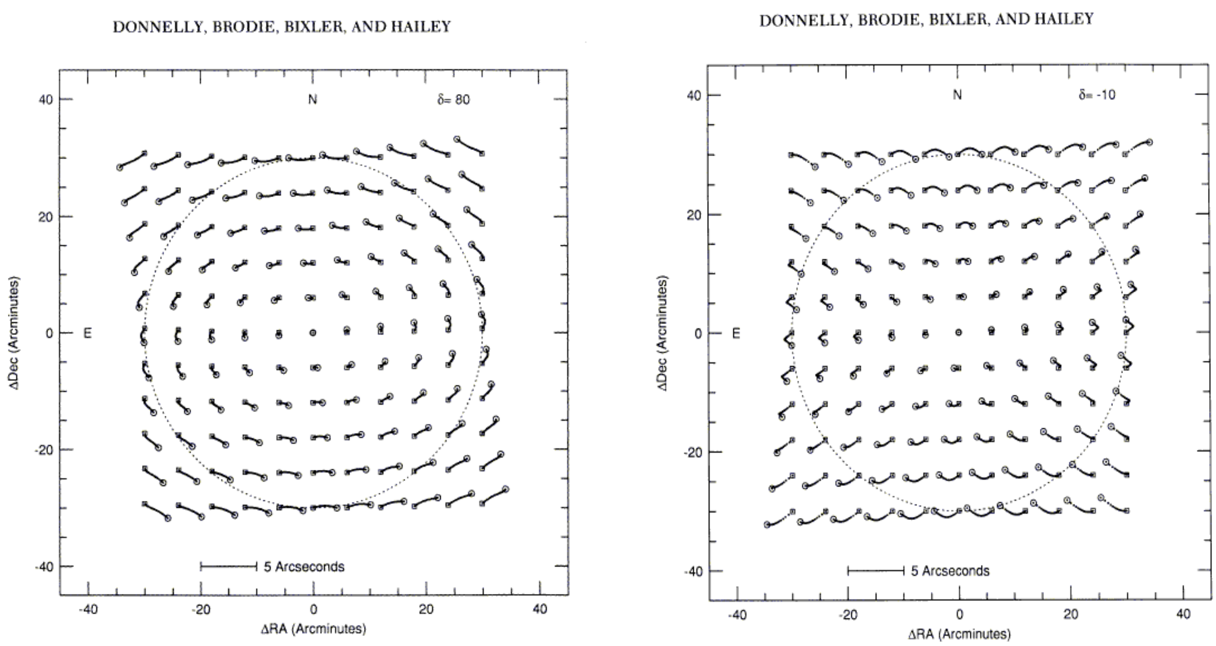


Figure 4-1 from Donnelly et al (1989 PASP 101, 1046) shows the relative image motions over a 6-hour period at Mt. Hamilton due to differential refraction effects. The tracks shown appear to be largely a rotation-like pattern to the north (left) and a pincushion-like pattern to the south (right). See the article for the details.

The second observable effect is the result of color dependent refraction that shifts the position of light of one wavelength relative to that of another wavelength. Fig. 4-2 shows the size of the effect in arcsecs versus ZD. Note that by an air mass of 2.0 (ZD = 60 deg), UV light would be displaced by over 3 arcsec from the same point at 1 μm. Even over the range spanned by a single broadband filter, especially the U band, significant degradation of the images can result. The chromatic effect is relatively constant over typical FOV of even 10's of arc minutes.

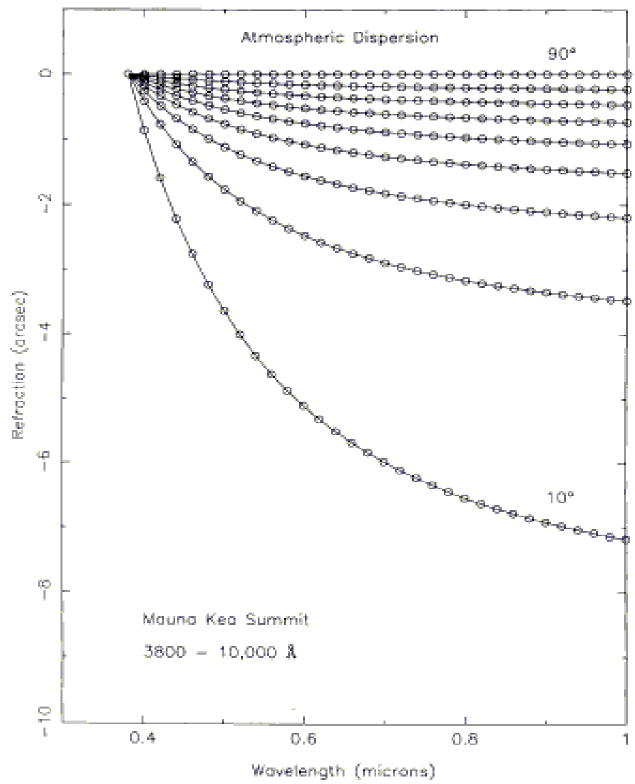


Figure 4-2 from Cohen and Cromer (1988 PASP 100, 1582) shows for the summit of Mauna Kea the chromatic atmospheric dispersion in arcsec as a function of elevation (90-ZD) for wavelengths from 0.38 to 1.0 μm. The third curve from the bottom corresponds to ZD = 60 (air mass 2.0).

4.2 Overview of Impact of Atmospheric Refraction on Science

The four areas in which observations are affected include:

1) Image Quality: For direct images, both refraction effects result in degradation of the sharpness of the PSF, with the chromatic dispersion degradation dependent on the spectral width of the filter passband. Such image degradation results in lower average surface brightness, and thus generally brighter thresholds in detection of faint objects and poorer signal-to-noise ratio (S/N) in the photometry. More insidious is that the differential effect varies over the FOV, so that any such thresholds and S/N effects are spatially varying. Similarly insidious is the variation of the PSF due to the combined effects of the spectral response of the imaging filter, spectral shape of the object, atmospheric extinction as a function of wavelength, and chromatic dispersion that together make precision photometry nearly impossible without the ADC.

2) Flux loss: Except for the result of increased atmospheric extinction at greater air mass, the total flux of the degraded images are preserved in direct images. However, in spectroscopic mode the more extended images, whether from differential refraction

or chromatic dispersion, may result in significant light loss through finite slit widths (see detailed discussion by Cohen and Cromer, 1988, PASP 100, 1582; Cuby, Bottini, and Picat, 1998, SPIE, 3355, 36C) or fiber diameters (see Donnelly, et. al., 1989, PASP 101, 1046). Again note that the spatial variation in the differential refraction over the field results in spatially varying amounts of light loss. Such variations are also dependent on the original size and shape of the objects, the relative orientation of the slit to the refraction effects, and the spectral shape of the objects and the wavelength.

3) Spatial Image Quality in Spectral Mode: Even if the slitlets are aligned with the parallactic angle to minimize light losses, there are problems induced by atmospheric dispersion. At a minimum, the location of the spectrum within a slitlet will vary with wavelength, necessitating longer slitlets to contain the spectrum. In addition, varying dispersion during an exposure will produce a degraded spatial profile, where the amount of degradation depends on the wavelength difference with respect to the effective guiding wavelength. Such degradation results in both a loss of contrast (critical for faint sources) and difficulty interpreting spatial information.

4) Positional Errors: The spatially varying distortions from differential refraction easily result in positional variations that affect astrometry from direct images (up to several 0.1 arcsec over the LRIS FOV at high ZD). Thus positions of images taken at one ZD may not be reliable for fabricating masks to be observed at another ZD without corrections for refraction effects, even if the same instrument is used. Subtler are the differences in the center of gravity of images due to chromatic effects on objects with different colors, again at the few 0.1-arcsec level (see Fig. 3 of Avila, Rupprecht, and Beckers, 1997, SPIE 2871, 1222). For high accuracy velocity work (i.e., where fraction of the slit width in the spectral direction is important), the relative positions of targets within each slit must be well understood or stable, especially under good seeing conditions when light of compact objects may be less uniform across the slit, and thus any centroid shifts (astrometric errors or differential refraction effects) result in significant shifts in velocity.

4.3 ADC Designs

Based on the previous discussion, the scientific need for an atmospheric corrector in many observational programs is clear. In the case of instruments that span a wide range of wavelengths, especially from the UV and blue to the far red, the loss of flux through narrow (1 arcsec or less) slits of a spectrograph at high ZD due to the chromatic atmospheric dispersion effects can be devastating. Losses of 10% or more would occur at even modest air masses and wavelength ranges. Such losses would be the equivalent of many nights of Keck time per year.

It should be noted that although the differential refraction effects may be important (and even dominate in some cases), the chromatic dispersion is the only one that can be corrected in practice. Note, however, that the rotational component of the differential refraction effects can, in principle, be accounted for in the rotation and position model of a telescope control system. Also, for systems with real-time adjustments of the positions of slits or fibers, the differential refraction effects can be fully corrected with no additional optical components. The following discusses ADC's (possessive, not plural, right?) in the context of making only chromatic dispersion corrections.

As discussed by Avila, et al (1997, SPIE 2871, 1222) for the LRIS-like (UV sensitive, multi-object spectrograph) case of the Focal Reducer Spectrograph (FORS) on the VLT (and summarized here), three basic ADC designs (Figure 4-3) were considered: single prism ADC, zero-deviation ADC, and the linear ADC (LADC).

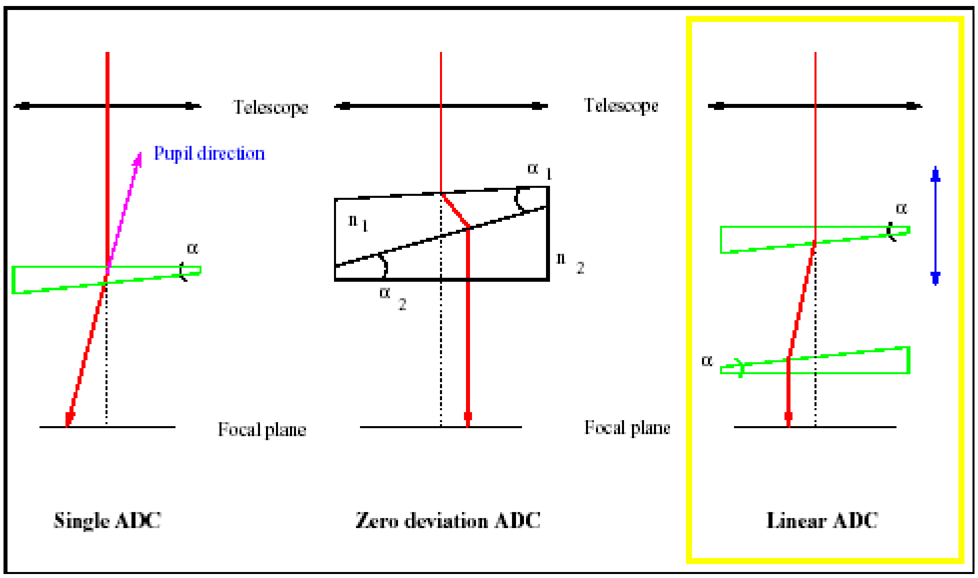


Figure 4-3: Basic Principles of three Different ADC Designs – from Avila, et. al.

The single pair of rotating wedges that make up a single prism ADC has the virtue of being very simple, compact, cheap, and effective in giving good image quality; however, it suffers from unacceptable image and pupil tilts at large ZD. Such tilts on the size scale of LRIS result in the beam actually missing the grating altogether. Even if the distances can be reduced to avoid this problem, the relative rotation of the prisms with respect to the detector would have such tilts and result in severe degradation of image quality (see Appendix C). This design is thus unacceptable.

The zero-deviation prism ADC is made by adding optical components that tilt the image and pupil back into the original incoming direction (and position); but at the expense of needing multi-glass optics, which then usually suffer from large throughput losses (especially in the blue and UV where the corrections by the ADC are most needed), higher weight, and greater costs. The SOAR project explored ADC options that reached the 0.32 μm needed for LRIS, and concluded that the only solution for the conventional zero-deviation prism design required silica and CaF2.

CaF2 is fragile, very expensive, and not likely to be made in large size (>250mm), and so they chose the LADC design.

This third design is comprised of simple prisms of opposite orientation that are separated by a distance depending on the amount of correction, and was originally proposed as the solution adopted by VLT for the FORS instrument. This design is relatively simple, produces good image quality, has no pupil or image tilts, acceptable throughput, weight, and cost; but does suffer from needing a much larger volume than the traditional ADC to operate, and also from image shifts that depend on the correction. Having the guider be within the FOV of the LADC solves the latter problem. Two other key advantages are gained with the LADC. For LADCs that are directly attached to telescopes with alt-az mounts, no rotation is needed to keep the prism orientation the same with respect to the horizon. (In the case of LRIS, however, the LADC is attached to the rotating instrument and thus must be counter-rotated for proper corrections.) For broadband correction from the UV to the near-IR, fused silica is nearly ideal as the prism material, for its index of refraction (n) nearly matches that of the atmosphere over the full wavelength range of interest (see equations and figures in Appendix A report by Nelson and Mast).

4.4 Overview of Phase A Optical Design Studies

The extent and level of detail of the optical design for the Phase A study were limited by the history of the study and available resources. As listed below, substantially more work at the preliminary and critical design stages will be needed to understand the performance and trade-offs for the LADC design. But the key purpose of converging on a credible conceptual optical design has been achieved, thanks largely to the earlier Phase A work of Jerry Nelson (PI), Terry Mast, and Brian Sutin on using the LADC for the Keck Telescope. In this case, all instruments downstream at either the Cassegrain or Nasymth would receive chromatically corrected images.

Despite the enormous benefit of this single, relatively simple and effective ADC for all optical (UV to 1.3 μm) instruments, this approach was abandoned after two unacceptable problems could not be solved without major redesign of the baffle tower region between the secondary and tertiary mirror region; or requiring unacceptable operations cost, namely the use of crane installation and removal of the ADC. The first problem was the conflict with infrared modes of operation if the ADC were to be left in place after installation, since the ADC would be a major thermal source. Second, our engineers could find no mechanical solution 1) to take the ADC off the telescope without using the crane or redesigning the telescope structure itself; 2) to remove and store the ADC easily and quickly within the existing baffle tower or tertiary mirror structure while keeping it totally out of the field of view of IR instruments.

On 15 October 2001, the SSC approved continuing the Phase A study (PI: Koo) of an ADC, but only as one dedicated to LRIS. Two optical design studies were completed, both included in the Appendices of this report:

1) Atmospheric Dispersion Correctors for the Keck Telescopes by Jerry Nelson and Terry Mast, last updated September 2002

   This Phase A Study of an ADC for the Keck Telescopes includes:
   · an introduction to atmospheric effects and the LADC design;
   · calculations of the prism pair separation as a function of wavelength range from 0.4 μm to 1.3 μm and ZD;
   · calculations of the residual dispersion after ADC correction with fused silica prisms due to the slight mismatches to the index of refraction for air;
   · Zemax ray-trace analysis of the performance of the LADC to determine the optimal relative orientations of the prisms with respect to the optical axis and to each other, and the image quality over the 20 arcmin diameter FOV of the Keck focal plane;
   · evaluation of the vignetting, ghosts, and transmission of the ADC system;
   · image quality error budget and sensitivities; and
   · prism properties. Highlights are summarized below.

2) Atmospheric Dispersion Compensation for LRIS: Phase A Design and Tolerances, by Terry Mast (version June 2002)

   This purpose of this study was to provide engineering tolerances for the LRIS LADC and is largely based on scaling the results from the Keck Telescope ADC Phase A study above. The engineering tolerances were critical for our engineer to develop the conceptual design for the mechanical structure of the LRIS ADC. After an overview of the Keck ADC design and its relation to that for LRIS, the report provides the specifics for the LRIS LADC and then estimates the tolerances from the prism position and angle error budget. This report recommends that a ray-trace study specific to the LRIS ADC be made at the next phase (preliminary design). Highlights from this study are summarized below.

4.5 Phase A Study of Optimal Prism Configuration

Based on minimizing the image rms sizes, Mast found that the optimal prism geometry is to have parallel inner faces of the prisms; no tilt of the prisms with respect to the optical axis; and about 680 mm separation for 5 deg prism pairs to correct to ZD = 60 over the spectral range of 0.4 to 1.3 μm.

4.6 Phase A Study of Prism Properties

- Type: simple fused silica prisms with 5 degrees angle
- Volume and Mass: thin edge of 10 mm, central thickness of 34 mm, and physical diameter of 580 mm with maximum separation of 680 mm and weight of 25 Kg.
- Material Quality and Availability: need to search for the highest throughput fused silica and with very uniform index of refraction at the few parts per million level; Corning's product # 7980 is a possibility.
- Coating Limitations: needs more research on availability and cost, but Sol-Gel appears to provide excellent anti-reflection properties along with broadband coverage. CaF2 is also worth examining.
- Polishing Limitations: Mast suggests using a commercial firm for polishing.

4.7 Phase A Study of Optical Tolerances for Mechanical Design

Spatial shifts at the +/- 20mm and uncertainties of the angles at 0.1-degree level will not adversely impact the quality of ADC corrected images. These are "easy" to meet.

4.8 Phase A Study of Throughput and Vignetting

Both of these will need further study at the next phase. Present rough estimates place throughput at between 85% and perhaps just above 90% over the full spectral range. Current mechanical design results in relatively minor amounts of vignetting for the LRIS guider, but little if any in the primary science FOV (see mechanical design section).

4.9 Phase A Study of Image Quality

No optical design study has been made specifically for LRIS ADC, but the one for the larger Keck Telesope LADC can be used to first order. An examination of the image rms sizes from the Keck Telescope study shows values under 200 μm or FWHM (1.66 x rms radius) of under 0.3 arcsec out to the 10 arcmin limit of the Keck FOV and over 0.4 to 1.3 μm range. Since the ratio of the LRIS LADC distance from the focal plane is 0.072 that of the Keck LADC study, scaling by this reduction factor of 0.072 results in negligible image degradation values at the 0.02 arcsec level, much smaller than typical seeing. Thus we are optimistic that the specifications for image degradation by the LADC will be met. This simple scaling result needs to be independently checked during the preliminary design phase with an optical design study that is specific to the LRIS ADC and extended in the spectral range to the UV to 0.32 μm.

4.10 Need for Improved Guider and Telescope Pointing/Rotation Model

To reduce the effects of differential refraction on the best overall image quality throughput for the FOV, the offset guider (note that the slit-viewing guider will automatically be viewing the center of the LRIS FOV) should be designed to track as if it were at the center of the instrument's FOV. Moreover, because the pattern of relative shifts due to differential effects appears roughly as a slight rotation (see figure 4-1 above), the telescope tracking system should include a correction for this rotation-like component to ensure the best image quality.

4.11 Optical Design Tasks for Preliminary Design (PD) & Critical Design (CD) Phase

- Develop atmospheric model to allow detailed study of relative contributions of ADC and atmosphere (Zemax includes routines to handle atmospheric effects).

- Redo optical design study specifically for LRIS LADC option, including: extension from 0.4 μm to 0.32 and reduction of upper limit of 1.3 μm to 1.1 μm; spot diagrams; image quality for different filters; amount of distortions due to ADC.

- Trade-off among prism spacing, prism angle, throughput, ghosts, size, weight, and costs.

- Track down availability and costs of the highest transmitting fused silica, with Sol-Gel (with reasonable durability) or MgFl coating ; obtain better estimate of expected highest possible throughput.

- Detailed study of potential ghosts (reflections) due to LADC design.

- Determine amount of variation in the image quality at different temperatures from summit to testing sites, if such variations exist.

- Software (see Software section) and hardware for testing of ADC in Santa Cruz.

- Software (see Software section) for testing of ADC attached to LRIS in Hawaii.

- Software (see Software section) for commissioning and on-sky performance analysis.

- Software (see Software section) for upgrade of LRIS mask-making system to account for ADC and improved performance.

- Specification of upgrades needed to Guider software and options, telescope/Cassegrain pointing and rotation model, and new modes or procedures for focusing.

4.12 Budget

Our optician, Dave Hilyard, estimates that the cost of materials and labor for the optics will be roughly \$64K for the high grade fused silica material, \$5K for materials and supplies, and \$32K for the labor of cutting and polishing the prisms. Another 2.5 weeks (\$9K) is needed for contingency. Livermore has traditionally provided the optical coatings (Sol-Gel) at no cost, but if that situation changes, we estimate the cost of Sol-Gel coatings from a commercial source to be \$80K. This uncertainty has been included as part of the contingency for the CORE ADC.

Our optical designer, Drew Phillips (in consultation with Terry Mast for some of the design work), estimates that the transition to Zemax, the implementation of an atmospheric model for performance evaluations and operational studies of both chromatic and differential refraction effects, optimization work on prism angles and throughput, etc., will total about 9 weeks of work (\$25K) and 4 weeks contingency (\$11K)

The grand total for the optics, including contingency, is thus estimated to be about \$147K.

This cost does not include the development of optical analysis software, the use of the software for analysis of data taken during the testing phases at Santa Cruz and Hawaii, or the work during the commissioning phase of the ADC project.

4.13 Summary

For purposes of the conceptual design phase, we have been successful in finding at least one solution to solve the atmospheric chromatic dispersion problem. We find that the simple “trombone” two-prism LADC design, using fused silica and Sol-Gel coatings, will plausibly meet the image quality, spectral range, and throughput requirements of a UV-efficient ADC for LRIS.

The simple prism design introduces unacceptable tilts of the optical beam and has thus been dropped from further consideration. Given that the use of CaF2 is likely to be very expensive, risky, and possibly impossible due to availability of large boule sizes (0.6 m) needed to cover the LRIS FOV, the more conventional zero-deviation prism design has been dropped as well. The LADC is thus the only viable option at this time.

The team, however, has a number of important optical design tasks to complete in the next phases, including ray-trace checks of the performance, optimization of the design for throughput, optical quality, and support structure size and weight.

5.0 Mechanical Design

5.1 Summary

The CORE ADC design is based on a dedicated device, permanently attached to LRIS. Within the ADC reside a fixed prism and a translating prism. Their spacing can be actively changed from a minimum of zero (4 mm in practice) to a maximum of 700 mm, depending on the amount of dispersion correction desired.

The ADC attaches to LRIS via a welded truss structure. This structure mounts to the inner race of the main LRIS bearing, using the same mounting point locations that had previously been used for a front truss assembly that is no longer in use.

The currently existing relevant LRIS hardware was measured and captured in a 3D CAD model. On the basis of that information, a conceptual mechanical design for a linear ADC has been completed.

As an important option to the CORE design, the cylindrical ADC rides on a linear stage, enabling it to be radially positioned in or out of the LRIS field of view. When out of the FOV, it is intended to have no effect on the optical performance of LRIS.

5.2 Functional Requirements

The design is driven by the following constraints and requirements:

1) Optical Coverage – the ADC must cover as much of the current LRIS and guider FOV as possible. A compromise was made to maximize LRIS FOV coverage at the expense of some guider coverage (see Figures 5-1 and 5-2).

2) Maximum envelope – the design must conform to the size limitations defined in the document CARA-SK055 (880), Rev A "Keck I and II Cassegrain Instrument Interface Envelope." Additionally, Keck staff set a soft limit of 1- meter protrusion from the forward-most surface of LRIS to ensure that the ADC would impose no undue storage and navigation problems on the Keck deck.

3) Impact on Maintenance – the presence of the ADC must not unduly affect current LRIS maintenance operations. In particular, access to LRIS internal components must not be compromised. Toward this aim, the conceptual design includes a feature that allows it to be manually hinged away from LRIS.

4) Counter rotation – to perform correctly, the ADC optics must maintain a constant vertical orientation with respect to gravity. Since the ADC rotates with LRIS, the ADC optical tube assembly must counter rotate. The design includes a bearing and appropriate rotation mechanism to accomplish this.

5) Counterbalancing – if the option of the translating ADC is adopted, the additional weight of the ADC will necessitate a change of on-axis counterbalancing to LRIS,

as well as to the telescope. This will be a one-time, permanent adjustment. However, since the center of gravity of the ADC optical tube assembly is, in its two positions, radially offset relative to the centerline of the main LRIS structure, there is a need to provide an active radial counterbalance system. This will ensure that ADC-induced torque loading will not burden the LRIS rotational mechanism.

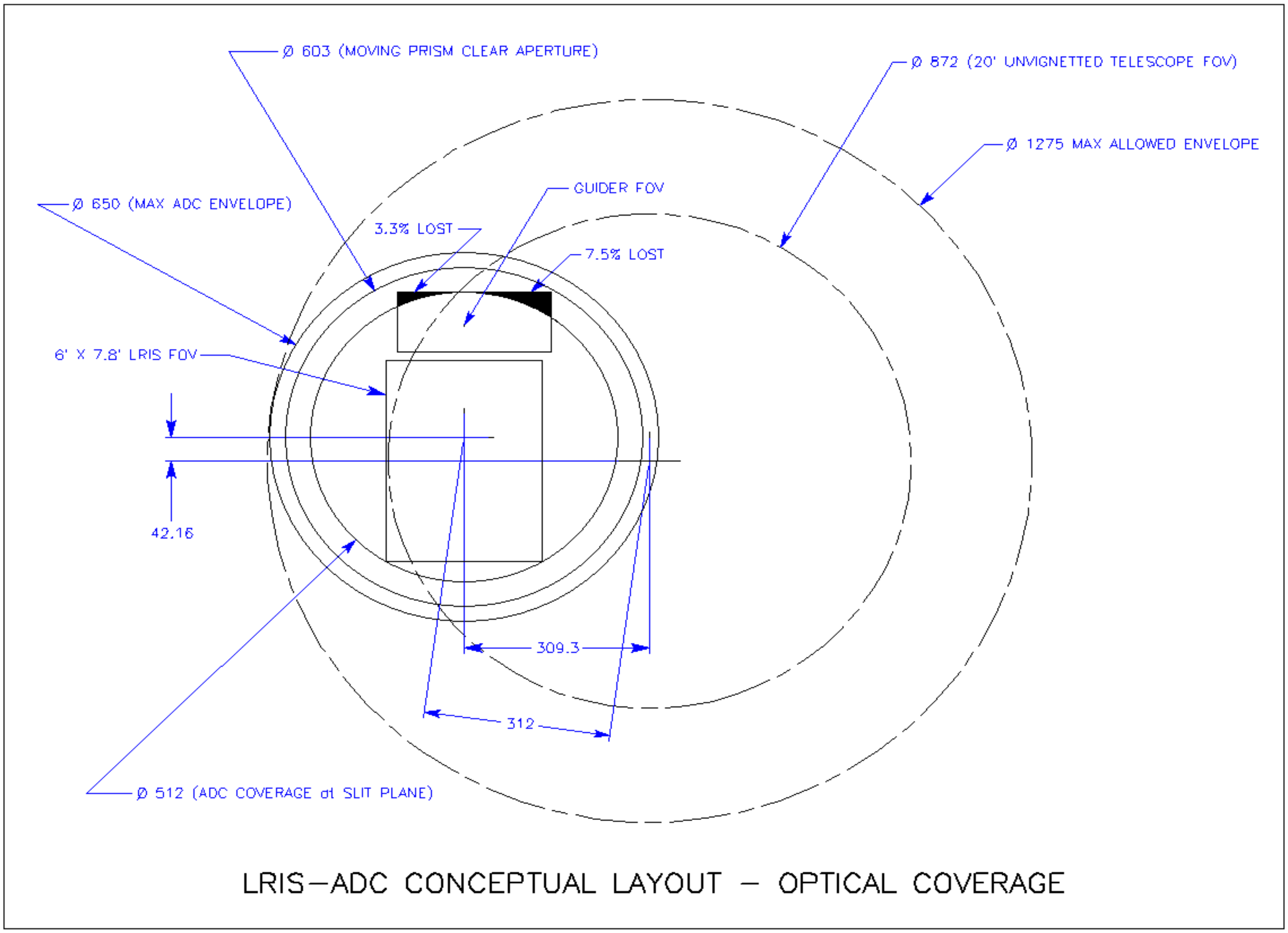


Figure 5-1: Relationship between LRIS and ADC

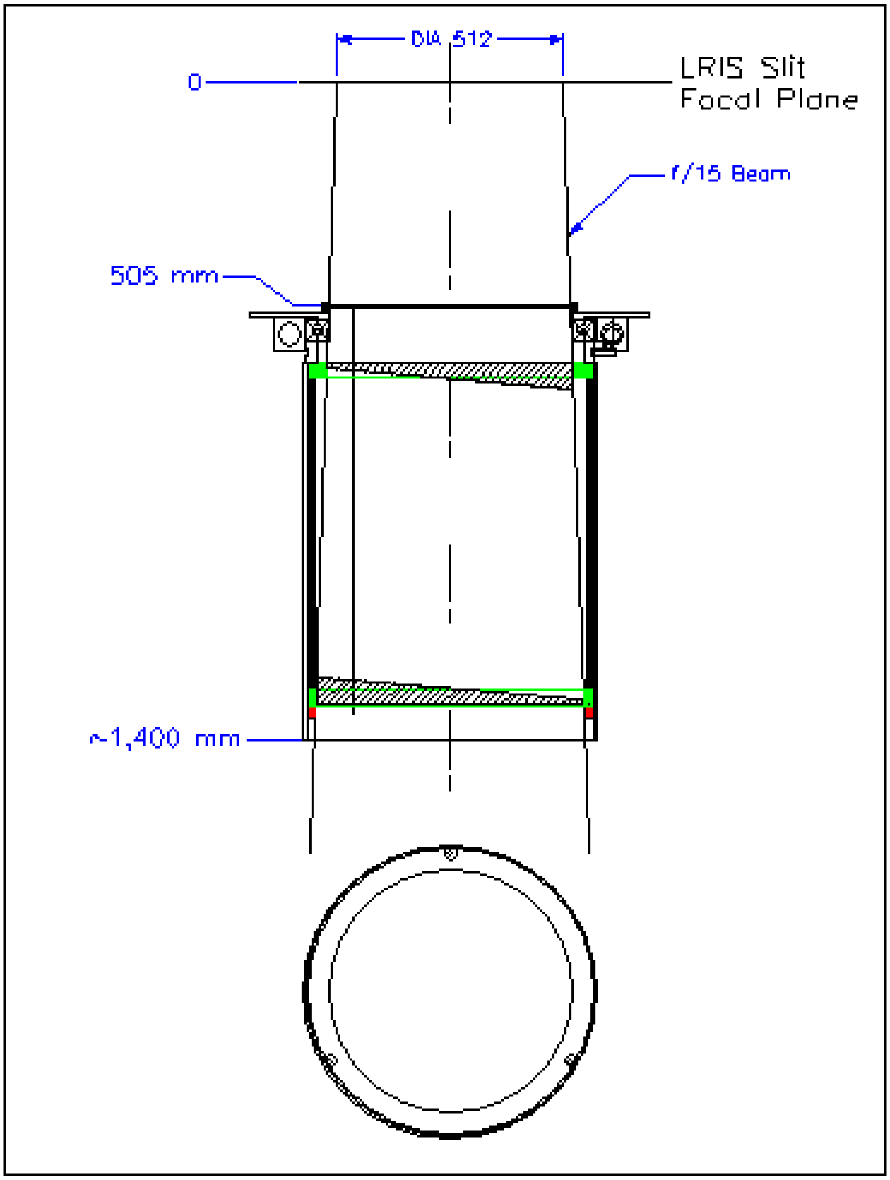


Figure 5-2: Optical Path through the Linear ADC

CAD Images of Conceptual Design

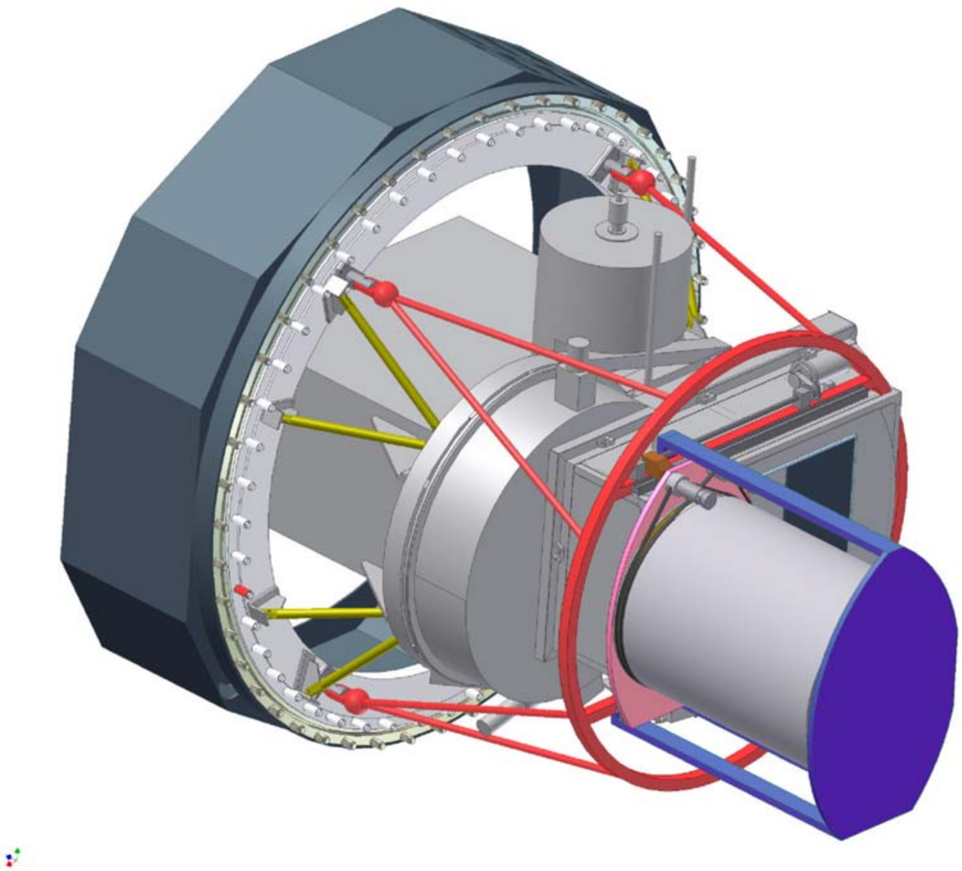


Figure 1

View of LRIS with ADC attached. ADC is in parked position under protective overhang.

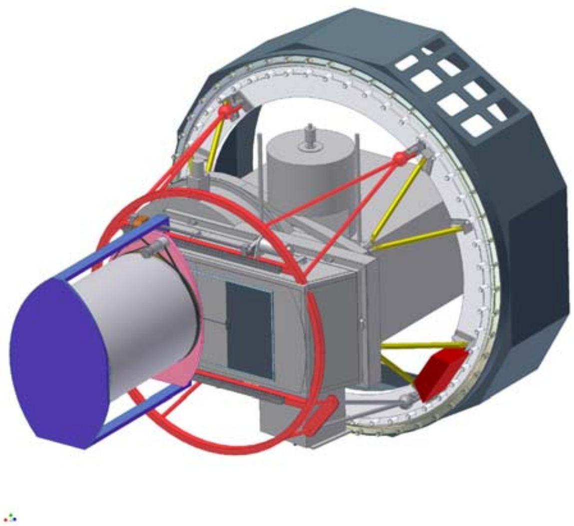


Figure 2

Same configuration as Figure 1, but from a different vantage point. Note the interference at the corner of LRIS's front shroud and the ADC circular frame member.

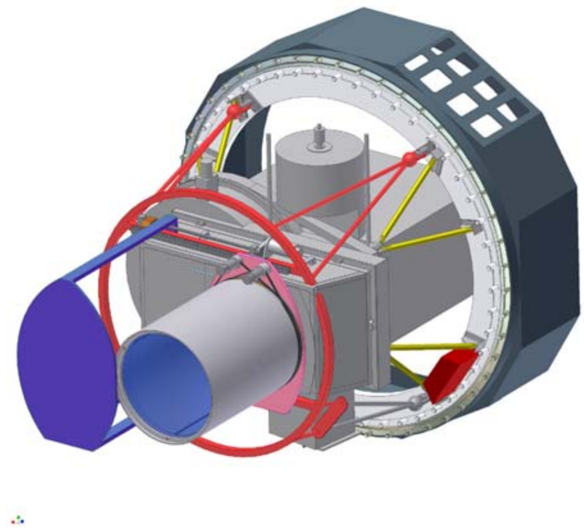


Figure 3

ADC is shown in its deployed position in front of the LRIS window.

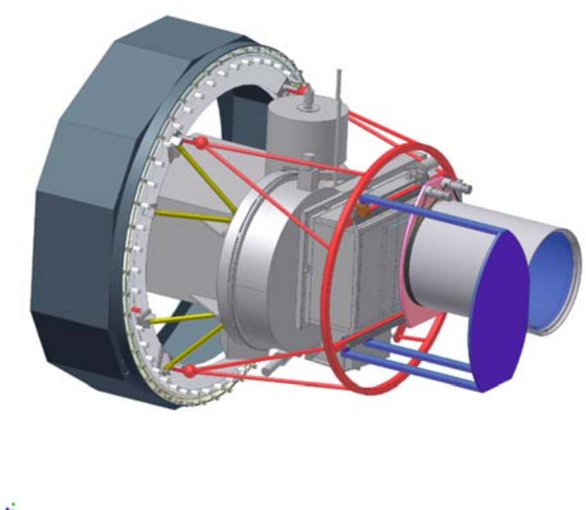


Figure 4

Another view of deployed ADC

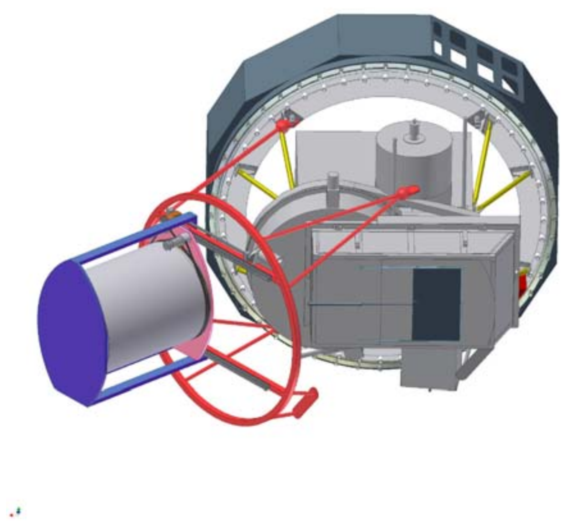
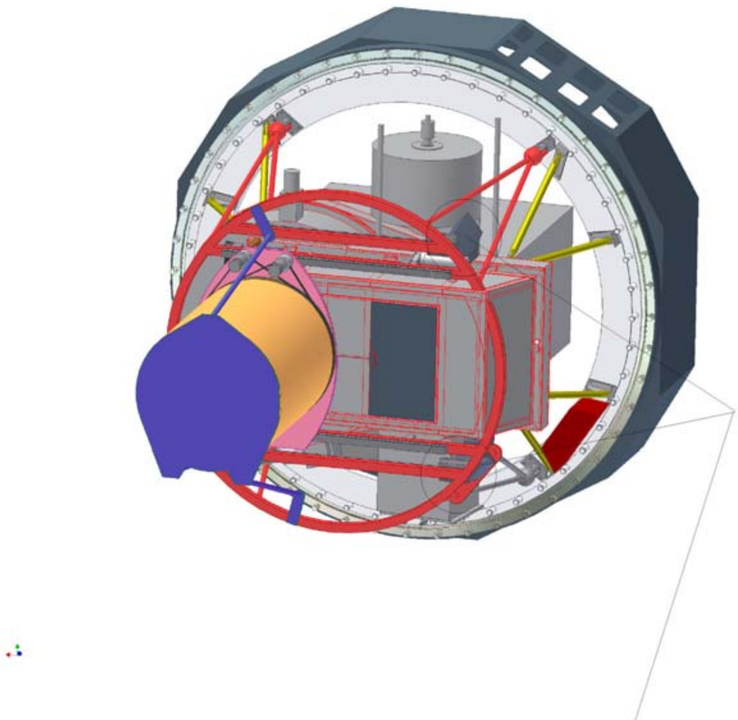
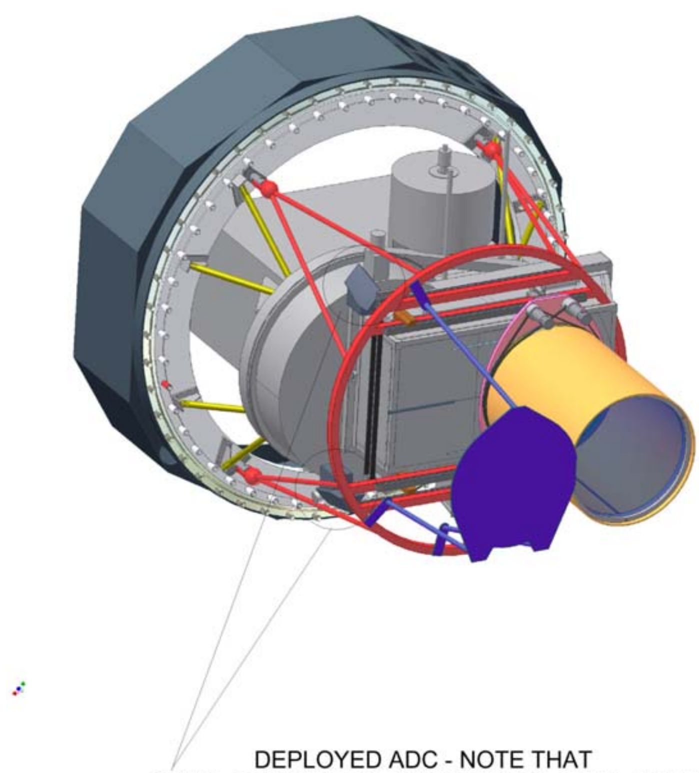


Figure 5

Illustrates how ADC hinges out of the way to enable access to LRIS front shroud for maintenance.



ADC ASSEMBLY SHOWING COUNTERWEIGHTS



DEPLOYED ADC - NOTE THAT
COUNTERWEIGHTS HAVE MOVED TO THE LEFT

ADC Preliminary Bill of Materials w/Weight Estimates

rev 092702

Item #	Part Name	Sub-Assembly	QTY	Description	Volume (cm3)	Material	Density (g/cm3)	Weight (lb)	Traverses Across?	Rotates with ADC?
1	Attachment Feet	Structural Attachment	4	Weldment	348	Steel	7.86	24.1	N	N
2	Pivot Pin	Structural Attachment	4	Commercial	11	Steel	7.86	0.8	N	N
3	Attachment Truss	Structural Attachment	1	Weldment using round and square tubing	6951	Steel	7.86	145.5	N	N
4	Parking Garage Assembly	Miscellaneous	1	Weldment with Machined Plate & Tubing	2872	Aluminum	2.71	17.2	N	N
5	Traverse Leadscrew Bushing	Radial Traverse Mechanism	4	Machined block and commercial bearing	73	Steel	7.86	5.1	N	N
6	Traverse Leadscrew	Radial Traverse Mechanism	2	Commercial, with machined modifications	286	Steel	7.86	9.9	N	N
7	Traverse Leadscrew Pulley	Radial Traverse Mechanism	2	Commercial	40	Aluminum	2.71	0.5	N	N
8	Traverse Leadscrew Nut	Radial Traverse Mechanism	2	Machined block and commercial leadnut	175	Bronze	8.87	6.8	Y	N
9	Traverse Motor	Radial Traverse Mechanism	1	Galil DC Servo Motor #500-1000		Motor	3.85	9.7	N	N
10	Traverse Motor Pulley	Radial Traverse Mechanism	1	Commercial	30	Aluminum	2.71	0.2	N	N
11	Traverse Timing Belt	Radial Traverse Mechanism	1	Kevlar Reinforced Elastomer	22	Nylon	1.13	0.1	N	N
12	Traverse Sync Timing Belt	Radial Traverse Mechanism	1	Kevlar Reinforced Elastomer	110	Nylon	1.13	0.3	N	N
13	Traverse Linear Shaft	Radial Traverse Mechanism	2	Thomson AccuGlide Rail, 1000mm Long	932	Steel	7.86	32.3	N	N
14	Traverse Linear Bearing	Radial Traverse Mechanism	3	Thomson AccuGlide Linear Ball Guide	360	Steel	7.86	18.7	Y	N
15	Traverse Counter-weight	Radial Counterweight	4	Machined or Cast Lead, w/Protective coating		Lead	11.37	157.6	Y	N
16	Traverse CW Linear Bearing Shaft	Radial Counterweight	2	Thomson AccuGlide Rail, 1000mm Long	932	Steel	7.86	32.3	N	N
17	Traverse CW Linear Bearing Carriage	Radial Counterweight	2	Thomson AccuGlide Linear Ball Guide	360	Steel	7.86	12.5	Y	N
18	Traverse CW Lead Screw Assembly	Radial Counterweight	2	Commercial, with machined modifications	286	Steel	7.86	9.9	N	N
19	Traverse CW Lead Screw Motor	Radial Counterweight	2	Galil DC Servo Motor #50-1000		Motor	3.85	5.2	N	N
20	ADC Optical Tube	Optical Tube Assembly	1	660mm OD X 1/4" wall X 800mm long	10459	Aluminum	2.71	62.5	Y	Y
21	Tube Base Mounting Ring	Optical Tube Assembly	1	Machined	2262	Aluminum	2.71	13.5	Y	Y
22	Dispersion Adjustment Ring Gear	Optical Tube Assembly	1	Fabricated, internal and external teeth	252	Brass	8.47	4.7	Y	Y
23	ADC Rotational Bearing	Optical Tube Assembly	1	Kaydon RealiSlim #JG220XPO		Steel	7.86	16.8	Y	Y
24	Rotational Bearing Retainer	Optical Tube Assembly	1	Machined	373	Aluminum	2.71	2.2	Y	Y
25	Dispersion Adjust Leadscrew	Optical Tube Assembly	3	Commercial, with machined modifications	76	Steel	7.86	4.0	Y	Y
26	Dispersion Adjust Leadscrew Pinion	Optical Tube Assembly	3	Commercial, with machined modifications	6	Brass	8.47	0.3	Y	Y
27	Dispersion Adjust Leadscrew Bearing	Optical Tube Assembly	6	Commercial	2	Steel	7.86	0.2	Y	Y
28	Prism Cell, Fixed	Optical Tube Assembly	1	Machined Ring	1423	Aluminum	2.71	8.5	Y	Y
29	Prism, Fixed	Optical Tube Assembly	1	563mm OD, 5 deg wedge, 10mm at thinnest, coated	8620	Fused Silica	2.71	51.5	Y	Y
30	Prism Cell, Translating	Optical Tube Assembly	1	Machined Ring	1391	Aluminum	2.71	8.3	Y	Y
31	Prism, Translating	Optical Tube Assembly	1	603mm OD, 5 deg wedge, 10mm at thinnest, coated	10388	Fused Silica	2.71	62.1	Y	Y
32	Leadscrew Bearing Support, Outer	Optical Tube Assembly	1	Machined Ring	601	Aluminum	2.71	3.6	Y	Y
33	Base Plate	Optical Tube Assembly	1	Machined Plate, 19mm thick	5142	Aluminum	2.71	30.7	Y	N
34	Actuation Motor Support, Dispersion	Optical Tube Assembly	1	Machined Bar Stock	82	Aluminum	2.71	0.5	Y	N
35	Actuation Motor Support, Rotation	Optical Tube Assembly	1	Machined Bar Stock	146	Aluminum	2.71	0.9	Y	N
36	Actuation Motor	Optical Tube Assembly	2	Galil DC Servo Motor #50-1000		Motor	3.85	5.2	Y	N
37	Timing Belt, Dispersion	Optical Tube Assembly	1	Kevlar Reinforced Elastomer	102	Nylon	1.13	0.3	Y	Y
38	Timing Belt, Rotation	Optical Tube Assembly	1	Kevlar Reinforced Elastomer	102	Nylon	1.13	0.3	Y	Y
39	Translating Prism Leadscrew Nut	Optical Tube Assembly	3	Commercial leadnut	20	Plastic	1.06	0.1	Y	Y
40	Shutter	Replacement Shutter Assy	1	Machined Plate, with Special Coating	700	Aluminum	2.71	4.2	Y	N
41	Guide	Replacement Shutter Assy	1	Welded and machined	250	Aluminum	2.71	1.5	N	N
42	Actuator	Replacement Shutter Assy	1	Commercial Pneumatic Cylinder	300	Aluminum	2.71	1.8	Y	N
43	Actuator Mount	Replacement Shutter Assy	1	Machined	100	Aluminum	2.71	0.6	N	N
44	Motor Controllers	Electronics						22.0	N	N
45	Sensors, Encoders, Cables	Electronics						4.4	Y	Y
							Total>	$\boxed{799.1\ lb}$	317 lb - static 482 lb - traversing 243 lb - ADC rotate	

Moments:

1. Maximum Moment along LRIS Z-axis, relative to main LRIS bearing, that will need to be passively corrected **774 pounds X 52 inches = 3,354 lb-ft**
2. Maximum Radial Moment around LRIS Z-axis: **Counterbalanced to within +/- 10 lb-ft**
3. Uncorrected moment along Z-axis, as a result of motion of dispersion prism: **+/- 75 lb-ft**

6.0 Electronics

The control electronics for the ADC will consist of a Linux-based PC containing Galil brand servomotor controllers. The controllers feed Galil power amplifiers that will, in turn, drive the stage motors. It is anticipated that the power amplifiers will be associated with connector panels that will also house the extra I/O. This is the same model as used with ESI and DEIMOS. Each servomotor will have an associated interconnect box that will break out connections for limits, fiducial, and encoders. The Linux PC will communicate with the control computer via a network connection. The power and physical volume required for the electronics has not yet been determined.

7.0 Software

7.1 For Phase A, we have presumed the primary goal is to derive a best estimate of the run-out costs for the ADC software. This requires that we identify the areas needing support from the software staff, to determine the level of expertise needed for the software tasks, and to estimate the amount of labor required to complete them.

We have identified the following areas needing significant software support:

1) control software to move the ADC
2) modified slitmask software that accounts for expanded options with the ADC
3) custom in-house software to assess optical performance
4) custom modeling software to predict PSF and spatial distortions of the atmosphere with and without the ADC for use by observers, guider, telescope pointing model, etc.)

The costs and requirements for the control software are the most well defined at this time and include the greatest detail, and are ready for the PDR. The other three areas will be fleshed out with more details during the Preliminary Design phase, so the listed tasks and costs are only rough estimates at this time.

7.2 Control Software Requirements, Tasks, and Costs

- 7.2.1 summarizes the draft software requirements.

- 7.2.2 lists the motors, encoders, and other elements of the ADC that are monitored and/or controlled by computer.

- 7.2.3 summarizes a strawman keyword service that would provide an interface to the control system.

- 7.2.4 estimates the time required to implement the baseline control system

- 7.2.5 describes and justifies a variety of options offering different levels of functionality and rough costs estimates

This section is largely based on the 30 Aug 2002 email memo from William Deich at UCO/Lick.

7.2.1 Software Requirements for Control Software

The following need consideration for the control software:

1) Compatibility with current Keck Telescope interface (DCS)
2) Instrument interface (ADC control shall use KTL keywords)
3) User interface (integrated into existing one for observers and staff, including hand control from a paddle)
4) Documentation (conform to Keck standards)

7.2.2 Computer-Monitored and/or Controlled Elements of the ADC

This section summarizes the components of the ADC Phase A design concept that must be computer-controlled and/or monitored. The goal is to provide a sufficiently detailed list to allow a meaningful estimate of the software implementation costs.

A. Traverse motors:

    1) Two motors (one slaved to the other) for driving the ADC unit into and out of the light path
    2) One linear encoder tape and encoder
    3) One home index
    4) Two limit switches, one at the ends of travel
    5) Two sensors for detecting if ADC unit runs past a primary limit and into a secondary limit, thereby cutting power to motors

B. Rotation motor:

    1) One motor
    2) Some kind of encoder
    3) One home index
    4) Nominally rotary, but actually needs limits because the triple leadscrews will have encoders implying wires

C. Dispersion adjust (triple leadscrew) motor:

    1) One motor
    2) Three auxiliary encoders, one per leadscrew
    3) One home index

4) At least two limit switches, perhaps more
5) Secondary limits and sensor for same

D. Active counterweight motor (to balance the weight of the optics as they are moved into or out of the light path) :

1) One motor
2) One encoder plus tape
3) One home index
4) Two limit switches

(This may not be a distinct element to control if a counterweight is part of the traverse drive and is mechanically driven in the opposite direction of the ADC optics.)

E. Hand paddle:

1) Auto/manual switch
2) Select among traverse motor, rotation motor, dispersion adjust motor
3) Pushbuttons for jogging the selected motor
4) Rotary switch "+" button to move to a numbered position
5) LEDs for indicating limit switches' state, attachment-truss-open

F. Hatch:

Not managed by ADC.

G. Environment control and sensors:

1) One temperature sensor
2) One glycol flow sensor
3) One fan switch
4) Attachment-truss-open switch

7.2.3 Keyword Service

The monitor-and-control software for the system summarized in 7.2.2 will provide a keyword service as its interface to the outside world. The following table lists the keywords for a strawman version of this service; as above, the purpose is to provide a sufficiently detailed list to allow a meaningful cost estimate. Additional keywords can be easily added later, including those for different modes of operation (OUT-MODE, FULL-MODE, etc.).

TRAVPOS	(r/w)	Traverse position, mm
TRAVENC	(r/w)	Traverse position, encoder counts

TRAVNAM	(r/w)	Named traverse locations (e.g., STOW and INPATH)
TRAVORD	(r/w)	Ordinal locations corresponding to TRAVNAM
TRAVRAW	(r/w)	Raw (encoder) locations corresponding to TRAVNAM
CWPOS	(r)	Counterweight position, mm
CWENC	(r)	Counterweight position, motor encoder units
CWLIM	(r)	Limit switch status
PA	(r/w)	Position angle of the prisms, degrees
PAENC	(r/w)	Position angle of the prisms, encoder counts
PALIM	(r)	Limit switch status
SEP	(r/w)	Separation between prisms, in mm, along leadscrew #1
SEPENC	(r/w)	Separation between prisms, encoder counts, along leadscrew #1
AIRMASS	(r/w)	Separation between prisms, represented as the corrected air mass
SEPLIM	(r)	Limit switch status.
SEP12	(r)	Diff between leadscrew encoders #1 and #2, in mm
SEPENC12	(r)	Diff between leadscrew encoders #1 and #2, in encoder cts
SEP13	(r)	Diff between leadscrew encoders #1 and #3, in mm
SEPENC13	(r)	Diff between leadscrew encoders #1 and #3, in encoder cts
TRACKDCS	(r/w)	Enable/disable tracking DCS-specified angle (Boolean) Affects both Rotation and Dispersion motors
ROTERR	(r)	Tracking error of rotation motor when TRACKDCS=true
DISPERR	(r)	Tracking error of dispersion motor when TRACKDCS=true
ADCCAL	(r/w)	Home all motors, or report state of same
CONTROL	(r)	State of auto/manual control switch on hand paddle
TEMPR	(r)	Temperature, raw volts
TEMPC	(r)	Temperature, Celsius
COOLFLOW	(r)	Rate of coolant flow, or Boolean value indicating rate is OK
FAN	(r/w)	Fan's off/on state

7.2.4 Control Software Cost for Baseline Functionality System

The baseline, lowest-cost system would be based entirely on existing Lick instrument technology, using Galil motor controller(s) on PCI cards in a Linux- based PC. It would be controlled from a stand-alone user interface that is not tightly integrated into the LRIS interface.

The existing LRIS software will be unmodified, so this is a very safe development path that will have least impact on ongoing LRIS use.

The software tasks include:

1) Working with electronics engineers in specifying and purchasing motor controllers (2 weeks)

2) Writing the motor control code and its associated keyword control interface (6 weeks for W. Deich; 10 weeks for another person: this estimate is based on modifying W. Deich's rotator code; if another person did the work, it would probably take an extra month to learn the rotator code well enough to modify it correctly.)

3) Low-level testing of motor controls (2 weeks)

4) Writing the environment controls (temperature monitoring, fan control, etc) and their keyword interface (2 weeks)

5) Exercising all motor stages (so-called k-tests) (2 weeks)

6) High-level keyword-based testing of integrated system (2 weeks)

7) Development of GUI (1 wk)

Total time cost: about 14-18 weeks.

Actual elapsed time: If W. Deich is the person doing the work, probably six months, because he expects to provide about half his time to Mt. Hamilton projects. Less time will be required if someone other than Deich can work full time on the ADC software.

7.2.5 Additional Functionality Options Beyond Baseline

OPTION 1: An alternative motor controller.

Galil motor controllers have a number of drawbacks: when combined with a wiring interface panel, they are bulky; the associated cable bundles are large and hard to modify; PCs generate a lot of heat; and the Galil programming interface is clumsy and difficult to use.

A very brief survey of the market gives the impression that some companies provide better programming interfaces (software) than Galil, and that other companies offer better packaging (such as "smart" motors in which the motor controller has been miniaturized and resides in a tiny unit along with the motor itself).

The ADC project is reasonably simple, and would make a good test bed in which alternatives to Galil motor controllers are tested. Finding a better controller would have long-term benefits for both CARA and UCO/Lick, and perhaps one or both of these institutions would be interested in investing some non-ADC funds in investigating and testing non-Galil alternatives.

Increased software costs would result from the time required to implement motor control using an unfamiliar development system. The costs would include:

- two weeks to identify and select several alternative control systems
- one week per motor of electronics shop time to install and verify basic functionality
- up to one week per motor for software testing

In all, it would cost approximately 8 weeks of time to test three alternative controllers, plus hardware costs of perhaps $3000 - $6000. This translates to an additional cost of roughly $30K.

OPTION 2: Integrate new keywords with LRIS GUI.

To integrate new keywords into the existing LRIS GUI is a task that is difficult for the software team to estimate; that is a job for John Cromer at Caltech. This option will be a great deal more expensive than a stand-alone ADC GUI.

OPTION 3: Replace existing LRIS GUI.

Instead of integrating the ADC keywords into the existing LRIS GUI, the software team could entirely replace the existing GUI with a new one based on the "dashboard" tool utilized in the GUIs for ESI and DEIMOS.

The LRIS keyword library does not conform to current Lick/KTL keyword API standards. In particular, the LRIS keywords do not provide KTL's NOTIFY functionality (that is, they do not provide the ability to report when a command has been completed), and many do not broadcast but must be polled.

There are two solutions to this problem:

1) Provide a "wrapper" service. This program is conceptually simple to implement: it would poll LRIS for keyword values, and then rebroadcast those same keyword/values under a slightly different service name. (When a wrapper keyword is written, the wrapper sends the same write command to LRIS; if NOTIFY is requested, the wrapper uses polling to monitor LRIS's status and sends back the proper notification when a command completes.) Programs that

need to monitor LRIS keywords would use this wrapper service instead of the underlying "real" LRIS service.

Cost: 2-4 weeks.

2) Rewrite the LRIS keyword library, which might require substantial changes to low-level code on its control crates.

This course would be cleaner and easier to maintain, but much more expensive to implement: it would require extensive collaboration between John Cromer at Caltech and the Software Program Group at Lick; travel between CIT and UCSC, and travel to and from HI. In addition, the cutover to new code for LRIS could be disruptive and would require more engineering time.

Cost: hard to estimate; perhaps 12 weeks.
Upgrading the LRIS keyword service could be undertaken independently of the ADC upgrade, which might well proceed first. The ADC keywords could then be integrated later into a new, modern LRIS KTL service at very little cost.

7.3 Slitmask Software

The current LRIS system has two software packages that LRIS observers use to design slit masks. One is the official software AUTOSLIT developed by J. Cohen at Caltech (current version is AUTOSLIT3 developed by J. Cohen and P. Shopbell). The other is an unofficial software package developed by UCO/Lick staff astronomer A. Phillips that originally used AUTOSLIT as its foundation, but which has since evolved to an independent package. For purposes of estimating the budget in this Phase A report, the assumption is that Phillips will be modifying his package to accommodate the ADC. Due to the lack of an ADC, the mask position angle in the sky can be set close to the parallactic angle to avoid or minimize the loss of light due to chromatic dispersion by the atmosphere. The mask design software already accounts for some focal plane scale changes that result from atmospheric refraction, and the masks are generally designed for a specific hour angle east or west.

With the addition of the ADC, Phillips will need to modify the mask-making software to account for expanded options with the ADC. In principle, with an ADC that fully corrects for the refraction from the atmosphere, an observer would need to design only one mask at zenith. In practice, an ADC largely corrects for the atmospheric color dispersion and does not correct for spatial distortions. The latter can be somewhat ameliorated by use of small rotation corrections. Depending on the scientific needs of the observer (high resolution or not, accurate velocity measurement vs. minimal color dispersion, etc.), the mask design software might allow various options that optimize the accuracy of one type of measurement at the expense of another.

Who: Drew Phillips
Time: 2 weeks to make and document modifications
2 weeks during commissioning to test and debug the software

7.4 Optical Performance Software

Drew Phillips played a critical role during DEIMOS integration, testing, and commissioning by developing and using custom software to assess and understand the performance of the DEIMOS optical system. A similar role is seen to be essential for the LRIS ADC. The ADC optics will be far simpler than analyzing the entire DEIMOS optical train, but the thorough assessment of total end-to-end optics system of LRIS plus the ADC will still require considerable work.

This assessment will occur during the testing and integration phase at Santa Cruz, in Hawaii upon integration with LRIS, and at the telescope with sky images during commissioning. The performance assessment task will be made more challenging than it may appear at the surface (2 prisms) by adding the effects of variable seeing, assessing a wide wavelength range, the potential interplay of effects due to new guider software, modified rotation model for the telescope tracking, etc.

Using either a test bed in Santa Cruz (support for the ADC, light source with various wavelengths, camera to record the images), or LRIS and the light source in Hawaii, tasks to test the optical performance of the ADC span a wide range. Most of these tasks involve image analysis that often requires custom software to extract and present the information. As part of deliverables of the ADC to CARA, such software will be useful for continued calibration of the LRIS ADC system in the future by performing the following checks:

- alignment of the ADC with the optical axis
- throughput of the ADC at all wavelengths
- image quality at all wavelengths
- ADC correction vs. wavelength vs. prism separation
- stability of image quality and flexure under rotation
- variations with temperature of the ADC
- vignetting by the ADC at different prism separations
- ghosts and scattered light at different positions

Who: Drew Phillips
Time: 4 -10 weeks for UCSC and Waimea testing phase
2 – 4 weeks for commissioning phase work
2 – 4 weeks for documentation for use by CARA staff

The range is an indication of uncertainty; the higher number includes contingency at some level.

7.5 Modeling Software to Predict PSF and Spatial Distortions

As described in the optical section of this Phase A study, the effects of atmospheric refraction on the positions and shapes of images as a function of zenith distance and spectral range (not to mention temperature, humidity, pressure of the air, and seeing) can be quite complex and subtle. Adding the optical distortions of an ADC makes the problem more complicated: This was explicitly stated by J. Allington-Smith, one of the builders of GEMINI's GMOS (which includes an ADC), while discussing the complications of assessing the spatial distortions and whether to use the ADC in full tracking mode or to use it in a mode locked to a given position during an exposure:

"In practice it will be necessary for the investigator to preplan the observations with the aid of a software tool that simulates both types of non-chromatic distortion and the chromatic atmospheric dispersion as the source tracks across the sky."
In addition to allowing astronomers to optimize the data during an exposure, subsections of such a software tool may also be essential to determine the optimal guider tracking corrections and telescope rotation model.

This software is not essential to operate and use the ADC, but without it users may not be able to take full advantage of the ADC for optimal data gathering.

Who: Drew Phillips
Time: 4 – 8 weeks depending on exact features and functions and level of detail in the documentation

7.6 Summary

The software needs of this ADC project go well beyond providing instrument control and interfaces to the Keck control system, and the high cost of software and testing phases in the budget reflects this reality. Custom software will likely be needed for testing the performance of the ADC before and during commissioning, for calibration of the ADC, for proper design of slit masks, and for users to preplan their observations. New software is also an area that can easily expand, i.e., to accommodate more functionality, some of which may not be absolutely essential. Though not critical, some software is still important enough to merit serious consideration due to its role in improving the performance of or optimizing the use of the ADC.

8. Cost Estimate

ADC Preliminary Cost Estimate
Core Costs

Area	Item	Notes	Labor Time	Rate	PDR	CDR	Fab & Assy	Cost ($)	Sub-Total
Optics (CORE)									
	Optical Design Analysis (Drew)	Includes 4 weeks of testing during fab.	9.0 man-wks	$70/hr	4.0 man-wks	1.0 man-wks	4.0 man-wks	$25,200	
	Optical Material	(ref 4.12)					$64,250	$64,250	
	Materials & Supplies	(ref 4.12)					$5,000	$5,000	
	Fabrication Labor	(ref 4.12)	9.0 man-wks	$90/hr			9.0 man-wks	$32,400	
	CONTINGENCY (Drew only)		4.0 man-wks	$70/hr			4.0 man-wks	$11,200	
	CONTINGENCY (fabrication)		2.5 man-wks	$90/hr			2.5 man-wks	$9,000	
									$147,050
Electronics (CORE)									
	Materials						$13,576	$13,576	
	Labor		27.6 man-wks	$65/hr	4.0 man-wks	4.0 man-wks	19.6 man-wks	$71,760	
	CONTINGENCY						$12,176	$12,176	
									$97,512
Software (CORE)									
	Labor (Will Deich's group)	(ref 7.2)	24.0 man-wks	$65/hr	4.0 man-wks	16.0 man-wks	4.0 man-wks	$62,400	
	Slitmask Design Software (Drew)	Generates distortion model (ref 7.3)	1.0 man-wks	$70/hr			1.0 man-wks	$2,800	
	CONTINGENCY (Deich)		4.8 man-wks	$65/hr			4.8 man-wks	$12,480	
									$77,680
Mechanical Fab. (CORE)									
	Fabrication Material				$1,000		$1,700	$2,700	
	Gear Broaching (outside vendor)						$1,500	$1,500	
	Labor (Shop)		16.5 man-wks	$65/hr	6.0 man-wks	1.0 man-wks	9.5 man-wks	$42,900	
	Commercial Parts				$2,000		$5,240	$7,240	
	CONTINGENCY						$7,935	$7,935	
									$62,275
Mechanical Eng. (CORE)									
	Labor (Lee)		27.0 man-wks	$70/hr	11.0 man-wks	9.0 man-wks	7.0 man-wks	$75,600	
	CONTINGENCY		5.4 man-wks	$70/hr			5.4 man-wks	$15,120	
									$90,720
Reviews (CORE)									
	Labor		27.0 man-wks	$60/hr	9.0 man-wks	9.0 man-wks	9.0 man-wks	$64,800	
	Consulting Fees			$150 /hr	$0	$0	$0	$0	
	Travel				$0	$0	$0	$0	
									$64,800
Miscellaneous (CORE)									
	Travel				$5,000	$2,500	$2,500	$10,000	
	Project Management		10% total hours	$70/hr	$10,640	$11,200	$23,268	$45,108	
	Electronics Documentation		10.0 man-wks	$70/hr			10.0 man-wks	$28,000	
	Performance/Calibration Software Docs.	Drew's time (ref 7.4)	4.0 man-wks	$70/hr			4.0 man-wks	$11,200	
	LRIS Modifications		4.0 man-wks	$65/hr			4.0 man-wks	$10,400	
	CONTINGENCY (general)						$7,000	$7,000	
									$111,708
Commissioning (CORE)									
	Labor	Includes 4 weeks Drew's time (ref. 4.12)	11.0 man-wks	$65/hr			11.0 man-wks	$28,600	
	Instrument Transport						$11,200	$11,200	
	Travel						$23,375	$23,375	
	CONTINGENCY		2.2 man-wks	$65/hr			2.2 man-wks	$5,720	
									$68,895
				Labor:	$110,640	$115,400	$275,128	$501,168	
				Materials:	$3,000	$0	$91,266	$94,266	
				Expenses:	$5,000	$2,500	$37,075	$44,575	
				Contingency:	$0	$0	$80,631	$80,631	
									Total
				Total:	$118,640	$117,900	$484,100		$720,640

ADC Preliminary Cost Estimate
Optional Costs

Area	Item	Notes	Labor Time	Rate	PDR	CDR	Fab& Assy	Cost ($)	Sub-Total
Optics (OPTIONAL)									
	Optical Design Analysis	Represents further design exploration (ref 4.11 & 4.12)	4.0 man-wks	$70 /hr	3.0 man-wks	1.0 man-wks		$11,200	
	* Optical Coatings	* Potential savings ONLY if Lawrence					$80,000	$80,000	
		Livermore Labs does for free							$91,200
Electronics (OPTIONAL)		Radial Traverse Stage							
	Materials						$3,394	$3,394	
	Labor		4.9 man-wks	$65 /hr			4.9 man-wks	$12,740	
	CONTINGENCY		0.5 man-wks	$65 /hr			0.5 man-wks	$1,274	
									$17,408
Software (OPTIONAL)									
	Labor (Deich)	(ref 7.2)	24.0 man-wks	$65 /hr	4.0 man-wks	16.0 man-wks	4.0 man-wks	$62,400	
	User Interface / Calibration software (Drew)	(ref 7.5)	8.0 man-wks	$70 /hr			8.0 man-wks	$22,400	
	Redesign Slitmask Tool (Drew)	(ref 7.3 & 7.5)	2.0 man-wks	$70 /hr			2.0 man-wks	$5,600	
	CONTINGENCY for above item		2.0 man-wks	$70 /hr			2.0 man-wks	$5,600	
									$96,000
Mechanical Fab. (OPTIONAL)		Covers Radial Traverse Mechanism							
	Fabrication Material						$300	$300	
	Shop Labor		2.0 man-wks	$65 /hr			2.0 man-wks	$5,200	
	Commercial Parts						$5,500	$5,500	
									$11,000
Mechanical Eng. (OPTIONAL)									
	Labor	Radial Traverse Mechanism	10.0 man-wks	$70 /hr	2.0 man-wks	2.0 man-wks	6.0 man-wks	$28,000	
	CONTINGENCY		2.0 man-wks	$70 /hr			2.0 man-wks	$5,600	
									$33,600
Miscellaneous (OPTIONAL)									
	Project Management		10% of total	$70 /hr	$2,520	$5,320	$8,372	$16,212	
									$16,212
Commissioning (OPTIONAL)									
	Labor for further characterization (Drew)		3.0 man-wks	$70 /hr			3.0 man-wks	$8,400	
									$8,400
			Labor (OPTIONAL):		$26,920	$55,320	$89,912	$172,152	
			Material (OPTIONAL):		$0	$0	$89,194	$89,194	
			CONTINGENCY (OPTIONAL):		$0	$0	$12,474	$12,474	
									Total
			Total:		$26,920	$55,320	$191,580		**$273,820**

ADC Preliminary Cost Estimate
Core and Options

Area	Item	Labor Time	Rate	PDR	CDR	Fab & Assy	Cost ($)	Sub-Total (CORE)	Sub-Total (OPTIONAL)
Optics (CORE)									
	Optical Design Analysis (Drew)	9.0 man-wks	$70/hr	4.0 man-wks	1.0 man-wks	4.0 man-wks	$25,200		
	Optical Material					$64,250	$64,250		
	Materials & Supplies					$5,000	$5,000		
	Fabrication Labor	9.0 man-wks	$90/hr			9.0 man-wks	$32,400		
	CONTINGENCY (Drew only)	4.0 man-wks	$70/hr			4.0 man-wks	$11,200		
	CONTINGENCY (fabrication))	2.5 man-wks	$90/hr			2.5 man-wks	$9,000		
								$147,050	
Optics (OPTIONAL)									
	Optical Design Analysis	4.0 man-wks	$70/hr	3.0 man-wks	1.0 man-wks		$11,200		
	* Optical Coatings					$80,000	$80,000		
									$91,200
Electronics (CORE)									
	Materials					$13,576	$13,576		
	Labor	27.6 man-wks	$65/hr	4.0 man-wks	4.0 man-wks	19.6 man-wks	$71,760		
	CONTINGENCY					$12,176	$12,176		
								$97,512	
Electronics (OPTIONAL)									
	Materials					$3,394	$3,394		
	Labor	4.9 man-wks	$65/hr			4.9 man-wks	$12,740		
	CONTINGENCY	0.5 man-wks	$65/hr			0.5 man-wks	$1,274		
									$17,408
Software (CORE)									
	Labor (Will Deich's group)	24.0 man-wks	$65/hr	4.0 man-wks	16.0 man-wks	4.0 man-wks	$62,400		
	Slitmask Design Software (Drew)	1.0 man-wks	$70/hr			1.0 man-wks	$2,800		
	CONTINGENCY (Deich)	4.8 man-wks	$65/hr			4.8 man-wks	$12,480		
								$77,680	
Software (OPTIONAL)									
	Labor (Deich)	24.0 man-wks	$65/hr	4.0 man-wks	16.0 man-wks	4.0 man-wks	$62,400		
	User Interface / Calibration software (Drew)	8.0 man-wks	$70/hr			8.0 man-wks	$22,400		
	Redesign Slitmask Tool (Drew)	2.0 man-wks	$70/hr			2.0 man-wks	$5,600		
	CONTINGENCY for above item	2.0 man-wks	$70/hr			2.0 man-wks	$5,600		
									$96,000
Mechanical Fab. (CORE)									
	Fabrication Material			$1,000		$1,700	$2,700		
	Gear Broaching (outside vendor)					$1,500	$1,500		
	Labor (Shop)	16.5 man-wks	$65/hr	6.0 man-wks	1.0 man-wks	9.5 man-wks	$42,900		
	Commercial Parts			$2,000		$5,240	$7,240		
	CONTINGENCY					$7,935	$7,935		
								$62,275	
Mechanical Fab. (OPTIONAL)									
	Fabrication Material					$300	$300		
	Shop Labor	2.0 man-wks	$65/hr			2.0 man-wks	$5,200		
	Commercial Parts					$5,500	$5,500		
									$11,000
Mechanical Eng. (CORE)									
	Labor (Lee)	27.0 man-wks	$70/hr	11.0 man-wks	9.0 man-wks	7.0 man-wks	$75,600		
	CONTINGENCY	5.4 man-wks	$70/hr			5.4 man-wks	$15,120		
								$90,720	
Mechanical Eng. (OPTIONAL)									
	Labor	10.0 man-wks	$70/hr	2.0 man-wks	2.0 man-wks	6.0 man-wks	$28,000		
	CONTINGENCY	2.0 man-wks	$70/hr			2.0 man-wks	$5,600		
									$33,600
Reviews (CORE)									
	Labor	27.0 man-wks	$80/hr	9.0 man-wks	9.0 man-wks	9.0 man-wks	$64,800		
	Consulting Fees		$150/hr	$0	$0	$0	$0		
	Travel			$0	$0	$0	$0		
								$64,800	
Miscellaneous (CORE)									
	Travel			$5,000	$2,500	$2,500	$10,000		
	Project Management	10% total hours	$70/hr	$10,640	$11,200	$23,268	$45,108		
	Electronics Documentation	10.0 man-wks	$70/hr			10.0 man-wks	$28,000		
	Performance/Calibration Software Docs.	4.0 man-wks	$70/hr			4.0 man-wks	$11,200		
	LRIS Modifications	4.0 man-wks	$65/hr			4.0 man-wks	$10,400		
	CONTINGENCY (general)					$7,000	$7,000		
								$111,708	
Miscellaneous (OPTIONAL)									
	Project Management	10% of total	$70/hr	$2,520	$5,320	$8,372	$16,212		
									$16,212
Commissioning (CORE)									
	Labor	11.0 man-wks	$65/hr			11.0 man-wks	$28,600		
	Instrument Transport					$11,200	$11,200		
	Travel					$23,375	$23,375		
	CONTINGENCY	2.2 man-wks	$65/hr			2.2 man-wks	$5,720		
								$68,895	
Commissioning (OPTIONAL)									
	Labor for further characterization (Drew)	3.0 man-wks	$70/hr			3.0 man-wks	$8,400		
									$8,400
			Labor (CORE):	$110,640	$115,400	$275,128	$501,168		
			Labor (OPTIONAL):	$26,920	$55,320	$89,912	$172,152		
			Materials (CORE):	$3,000	$0	$91,266	$94,266		
			Material (OPTIONAL):	$0	$0	$89,194	$89,194		
			Expenses (CORE):	$5,000	$2,500	$37,075	$44,575		
			CONTINGENCY (CORE):	$0	$0	$80,631	$80,631		
			CONTINGENCY (OPTIONAL):	$0	$0	$12,474	$12,474		
								Total (CORE)	Total (OPTIONAL)
			Total:	$145,560	$173,220	$675,680		$720,640	$273,820

Grand Total
$994,460

9. Schedule

LRIS ADC -Core Project

Tue 10/29/02

Milestones

ID		Task Name	Duration	Start	Finish	Predecessors
38		Phase A Review	0 days	Mon 12/2/02	Mon 12/2/02	
41		PDR	0 days	Wed 4/9/03	Wed 4/9/03	40
44		CDR	0 days	Wed 7/16/03	Wed 7/16/03	43
47		PSR	0 days	Mon 2/16/04	Mon 2/16/04	46
52		First Light	0 days	Mon 4/12/04	Mon 4/12/04	51

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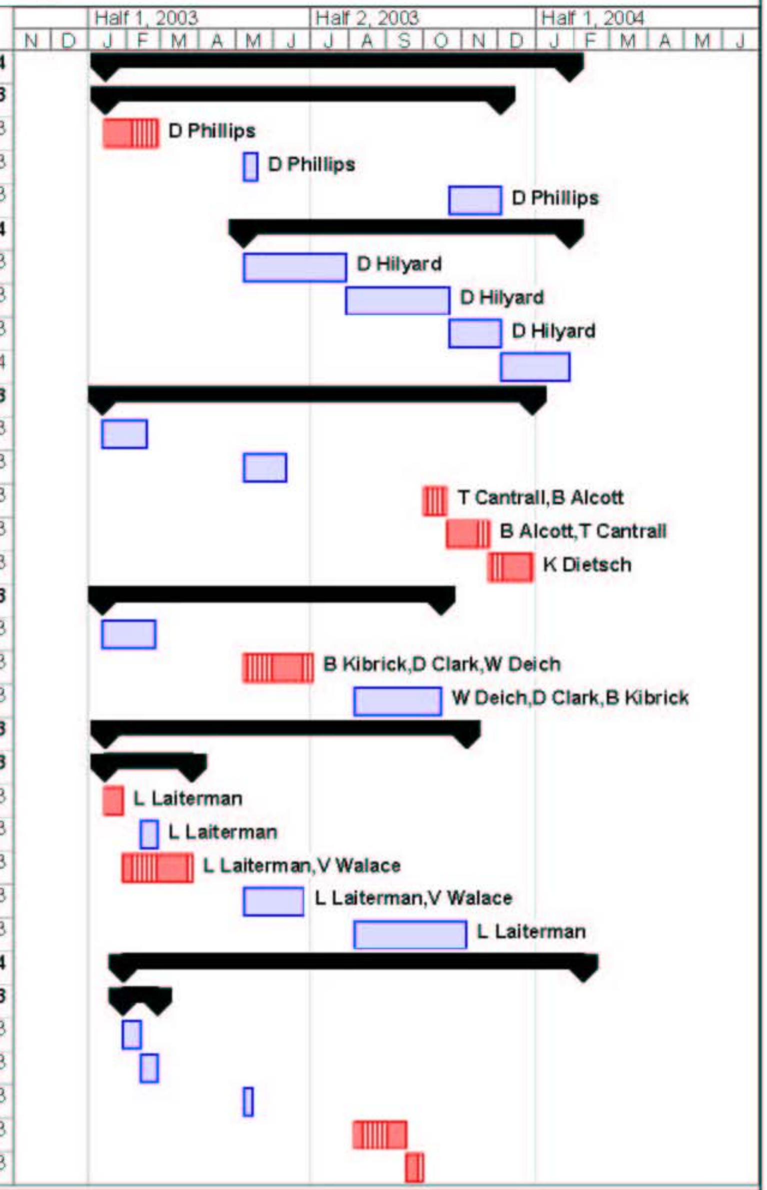
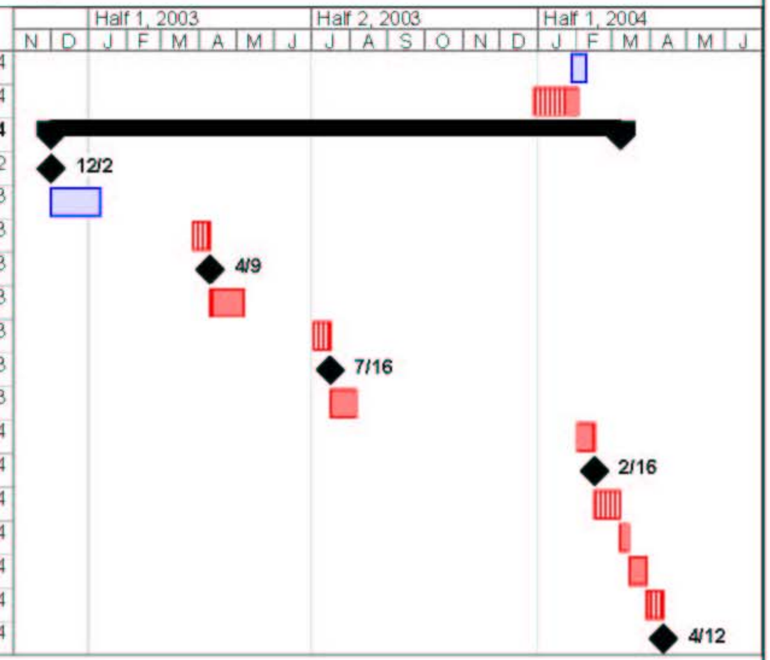
LRIS ADC -Core Project

ID		Task Name	Duration	Start	Finish
1		**Optics**	**270 days**	**Wed 1/15/03**	**Wed 1/28/04**
2		**Optical Design Analysis**	**230 days**	**Wed 1/15/03**	**Wed 12/3/03**
3		Optical Design-PDR	6 wks	Wed 1/15/03	Wed 2/26/03
4		Optical Design-CDR	1.5 wks	Thu 5/8/03	Mon 5/19/03
5		Optical Testing Analysis	6 wks	Thu 10/23/03	Wed 12/3/03
6		**Optical Fabrication**	**190 days**	**Thu 5/8/03**	**Wed 1/28/04**
7		Optical Materials Order/delivery	12 wks	Thu 5/8/03	Wed 7/30/03
8		Optical Fabrication	12 wks	Thu 7/31/03	Wed 10/22/03
9		Optical Acceptance Testing	6 wks	Thu 10/23/03	Wed 12/3/03
10		Optical Coatings	8 wks	Thu 12/4/03	Wed 1/28/04
11		**Electronics**	**249.5 days**	**Mon 1/13/03**	**Mon 12/29/03**
12		Electronics-PDR investigations	5 wks	Mon 1/13/03	Mon 2/17/03
13		Electronics-CDR investigations	5 wks	Thu 5/8/03	Wed 6/11/03
14		Electroinic mountings	2.5 wks	Thu 10/2/03	Mon 10/20/03
15		General wiring	5 wks	Mon 10/20/03	Mon 11/24/03
16		Initial Electronics testing	5 wks	Mon 11/24/03	Mon 12/29/03
17		**software**	**197 days**	**Mon 1/13/03**	**Wed 10/15/03**
18		Software-PDR level investigations	6 wks	Mon 1/13/03	Mon 2/24/03
19		Software-CDR investigations	8 wks	Thu 5/8/03	Wed 7/2/03
20		Software-Coding/code check	10 wks	Thu 8/7/03	Wed 10/15/03
21		**Mechanical Engineering**	**210 days**	**Wed 1/15/03**	**Wed 11/5/03**
22		**ME-PDR level design**	**50 days**	**Wed 1/15/03**	**Wed 3/26/03**
23		Design of a weighted test fixture	2 wks	Wed 1/15/03	Wed 1/29/03
24		Flexture test of rotator bearing	2 wks	Thu 2/13/03	Wed 2/26/03
25		Design updates of ADC	8 wks	Thu 1/30/03	Wed 3/26/03
26		ME-CDR level design	7 wks	Thu 5/8/03	Wed 6/25/03
27		ME-Frabrication supervision	13 wks	Thu 8/7/03	Wed 11/5/03
28		**Mechanical Fabrication**	**267.5 days**	**Thu 1/30/03**	**Mon 2/9/04**
29		**MF-PDR investigations**	**20 days**	**Thu 1/30/03**	**Wed 2/26/03**
30		Fabrication of test fixture	2 wks	Thu 1/30/03	Wed 2/12/03
31		Flexure testing in HI	2 wks	Thu 2/13/03	Wed 2/26/03
32		MF-CDR investigations	1 wk	Thu 5/8/03	Wed 5/14/03
33		MF-fabrication	6 wks	Thu 8/7/03	Wed 9/17/03
34		MF-Assembly	2 wks	Thu 9/18/03	Wed 10/1/03



LRIS ADC -Core Project

ID	Task Name	Duration	Start	Finish
35	MF-Initial Mechanical Testing	1.5 wks	Thu 1/29/04	Mon 2/9/04
36	Pre Shipping Tests	5 wks	Mon 12/29/03	Mon 2/2/04
37	**Reviews**	**319.5 days**	**Mon 12/2/02**	**Mon 3/8/04**
38	Phase A Review	0 days	Mon 12/2/02	Mon 12/2/02
39	Post Phase Period	4 wks	Mon 12/2/02	Fri 1/10/03
40	Prep for PDR	2 wks	Thu 3/27/03	Wed 4/9/03
41	PDR	0 days	Wed 4/9/03	Wed 4/9/03
42	Post PDR Period	4 wks	Thu 4/10/03	Wed 5/7/03
43	Prep for CDR	2 wks	Thu 7/3/03	Wed 7/16/03
44	CDR	0 days	Wed 7/16/03	Wed 7/16/03
45	Post CDR Period	3 wks	Thu 7/17/03	Wed 8/6/03
46	Preparation for PSR	2 wks	Mon 2/2/04	Mon 2/16/04
47	PSR	0 days	Mon 2/16/04	Mon 2/16/04
48	Post PSR Period	3 wks	Mon 2/16/04	Mon 3/8/04
49	Shipping	5 days	Mon 3/8/04	Mon 3/15/04
50	Assembly and Commissioning	2 wks	Mon 3/15/04	Mon 3/29/04
51	Testing on LRIS	2 wks	Mon 3/29/04	Mon 4/12/04
52	First Light	0 days	Mon 4/12/04	Mon 4/12/04



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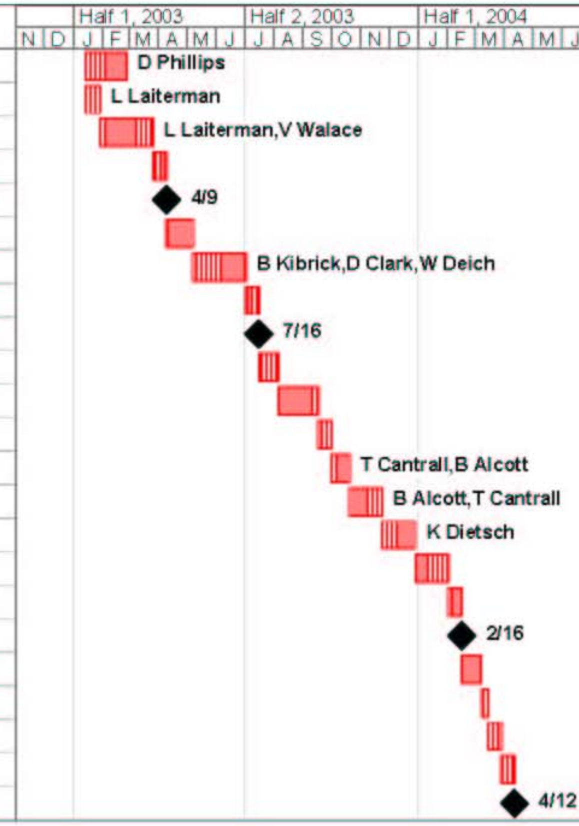
LRIS ADC -Core Project

Critical

ID		Task Name	Duration	Start	Finish	Predecessors
3		Optical Design-PDR	6 wks	Wed 1/15/03	Wed 2/26/03	
23		Design of a weighted test fixture	2 wks	Wed 1/15/03	Wed 1/29/03	39,3SS
25		Design updates of ADC	8 wks	Thu 1/30/03	Wed 3/26/03	23
40		Prep for PDR	2 wks	Thu 3/27/03	Wed 4/9/03	3,22,25
41		PDR	0 days	Wed 4/9/03	Wed 4/9/03	40
42		Post PDR Period	4 wks	Thu 4/10/03	Wed 5/7/03	41
19		Software-CDR investigations	8 wks	Thu 5/8/03	Wed 7/2/03	18,42
43		Prep for CDR	2 wks	Thu 7/3/03	Wed 7/16/03	26,13,19,4
44		CDR	0 days	Wed 7/16/03	Wed 7/16/03	43
45		Post CDR Period	3 wks	Thu 7/17/03	Wed 8/6/03	44
33		MF-fabrication	6 wks	Thu 8/7/03	Wed 9/17/03	32,45
34		MF-Assembly	2 wks	Thu 9/18/03	Wed 10/1/03	33
14		Electroinic mountings	2.5 wks	Thu 10/2/03	Mon 10/20/03	34
15		General wiring	5 wks	Mon 10/20/03	Mon 11/24/03	14
16		Initial Electronics testing	5 wks	Mon 11/24/03	Mon 12/29/03	15
36		Pre Shipping Tests	5 wks	Mon 12/29/03	Mon 2/2/04	16
46		Preparation for PSR	2 wks	Mon 2/2/04	Mon 2/16/04	36
47		PSR	0 days	Mon 2/16/04	Mon 2/16/04	46
48		Post PSR Period	3 wks	Mon 2/16/04	Mon 3/8/04	47
49		Shipping	5 days	Mon 3/8/04	Mon 3/15/04	48
50		Assembly and Commissioning	2 wks	Mon 3/15/04	Mon 3/29/04	49
51		Testing on LRIS	2 wks	Mon 3/29/04	Mon 4/12/04	50
52		First Light	0 days	Mon 4/12/04	Mon 4/12/04	51

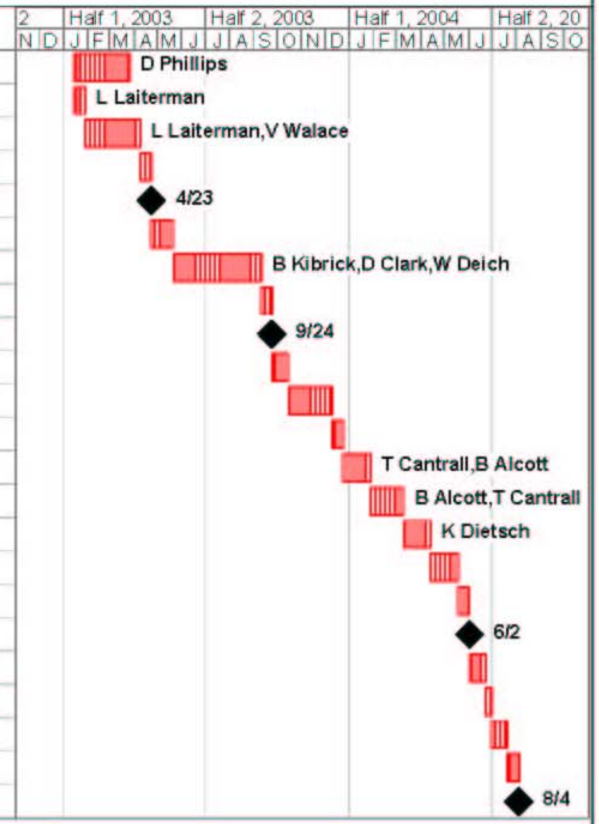


Tue 10/29/02

LRIS ADC -Full Project

Critical

ID		Task Name	Duration	Start	Finish	Predecessors
3		Optical Design-PDR	10 wks	Wed 1/15/03	Wed 3/26/03	
23		Design of a weighted test fixture	2 wks	Wed 1/15/03	Wed 1/29/03	3SS,39
25		Design updates of ADC	10 wks	Thu 1/30/03	Wed 4/9/03	23
40		Prep for PDR	2 wks	Thu 4/10/03	Wed 4/23/03	3,22,25
41		PDR	0 days	Wed 4/23/03	Wed 4/23/03	40
42		Post PDR Period	4 wks	Thu 4/24/03	Wed 5/21/03	41
19		Software-CDR investigations	16 wks	Thu 5/22/03	Wed 9/10/03	18,42
43		Prep for CDR	2 wks	Thu 9/11/03	Wed 9/24/03	26,13,19,4
44		CDR	0 days	Wed 9/24/03	Wed 9/24/03	43
45		Post CDR Period	3 wks	Thu 9/25/03	Wed 10/15/03	44
33		MF-fabrication	8 wks	Thu 10/16/03	Wed 12/10/03	32,45
34		MF-Assembly	2 wks	Thu 12/11/03	Wed 12/24/03	33
14		Electroinic mountings	5 wks	Thu 12/25/03	Wed 1/28/04	34
15		General wiring	6 wks	Thu 1/29/04	Wed 3/10/04	14
16		Initial Electronics testing	5 wks	Thu 3/11/04	Wed 4/14/04	15
36		Pre Shipping Tests	5 wks	Thu 4/15/04	Wed 5/19/04	16
46		Preparation for PSR	2 wks	Thu 5/20/04	Wed 6/2/04	36
47		PSR	0 days	Wed 6/2/04	Wed 6/2/04	46
48		Post PSR Period	3 wks	Thu 6/3/04	Wed 6/23/04	47
49		Shipping	5 days	Thu 6/24/04	Wed 6/30/04	48
50		Assembly and Commissioning	3 wks	Thu 7/1/04	Wed 7/21/04	49
51		Testing on LRIS	2 wks	Thu 7/22/04	Wed 8/4/04	50
52		First Light	0 days	Wed 8/4/04	Wed 8/4/04	51



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10. Management Plan

10.1 Project Direction

CARA's Instrument Program Manager will oversee this project as part of the new instrument development program being instigated by CARA.

10.2 Project Management: David Cowley

- Monthly reports to CARA (due 20th each month), including Current Status, Project Concerns and Issues, a budget report, and a schedule report.

- PDR, CDR, and Pre- Ship reviews

- A detailed Gantt project schedule will be developed for each phase of the project. The schedule will be developed from a task list.

- Project will be tracked against a baseline schedule, re-set at time of PDR, CDR, and Pre-Ship review.

- Budgets will be tracked against the overall approved total. Budget amounts in each category (tracked with a cost code) will be revised as the project progresses to show the current estimated cost to complete within the established total budget.

10.3 Project Engineering/Project Lead: Lee Laiterman

Lee is the lead person for this project, and will carry out the mechanical engineering tasks, with support from UCO/Lick Engineering staff. His main engineering tasks during the PDR phase will be to work with the optical designer to accommodate refinements and changes in optical design of the ADC. He will also be involved with the construction and installation onto LRIS of a simulated ADC test fixture, correctly weighted and balanced, for determining potential flexure effects.

The plan is for Lee to work on this project through commissioning in Hawaii

10.4 Optical Design: Drew Phillips

The Optical Designer at the PDR phase is planned to be Drew Phillips. He has the necessary computer programs and the time available.

10.5 Optical Fabrication: David Hilyard

The plan is for David Hilyard to fabricate the prisms required for this project in the Optics shop at Lick Observatory. He has the time, experience, and facilities to perform this function. The plan will be re-evaluated at the PDR and CDR reviews.

10.6 Software: Drew Phillips and Bob Kibrick/Will Deich

Drew Phillips, who has extensive astronomical and technical software experience, will be the lead for technical software development required for this project. Bob Kibrick will lead the efforts of UCO/Lick's Scientific Programming Group (SPG). Servomotor and keyword control are expected to be very similar to other instruments built for Keck by Lick Observatory.

10.7 Mechanical Fabrication:

The plan is to fabricate this instrument at Lick Observatory, although this can be re-assessed at the PDR and CDR reviews. The test fixture required for the PDR phase is planned for fabrication at Lick. Instrument shop staff is available to work on this project in the PDR phase.

10.8 Electronics: Barry Alcott

Barry will lead the electronics portion of this project. Lick has the personnel to carry out this part of the project.

10.9 Instrument Testing:

We plan to thoroughly test ADC functionality before the Pre-Ship Review. If possible, we will run it with a Keck Telescope DCS simulator, and remotely using DCS commands directly from the telescope in HI.

10.10 Accounting:

The project budget will be tracked and updated monthly, based on University records.

11. Outstanding Issues Needing Attention Before Start of Preliminary Design

Here we summarize the issues that need attention before or during the Preliminary Design phase of the LRIS ADC project.

1. Real-Time Removal of the ADC from LRIS Field of View: A decision is needed of whether to add the OPTION of the radially translating tracks that allows real-time moves of the ADC in and out of the LRIS FOV. This option will cost another $74K ($67K plus $7K contingency).

2. Zenith Distance Limit for ADC: Agreement that air mass 2.0 (60 degrees) will be the actual rather than the possible limit of air mass 3.2 (72 deg). See discussion in the Alternatives section.

3. Spec for Throughput: Agreement that the specification for the total throughput will be on the basis of "best" effort, i.e., within the constraints of using the most transmissive fused silica available from industry; most effective and long-lasting broadband anti-reflection coatings – probably hardened Sol-gel; maximum space available for the ADC in front of LRIS during storage and satisfying the ZD limit; and without significantly increasing the vignetting of the LRIS guider FOV. An ideal and more specific target would otherwise be 90% end-to-end through the ADC for the full 0.32 to 1.1 μm range, but this may not be reachable in practice.

4. LRIS Modifications - Hatch and Front Shroud: The current hatch opens outward and would interfere with the new ADC. A conceptual design is in place for its replacement by a sliding door. The design also indicates a small interference between the proposed ADC support frame and two of the corners of the current front shroud of LRIS; this will have to be remedied. Agreement needs to be made on funding of the project; and how and by whom it will be managed and carried out. Possibilities include Caltech, Lick, and CARA.

5. CARA Requirements and Specs: As mentioned in the specification section, the LRIS ADC will be designed to meet Keck standards for weights, safety, maintenance, operation, user GUI software, etc. These need to be explicitly provided by the PD phase.

6. Keck Telescope Modifications: To take full advantage of the gains in image quality by use of LRIS ADC, software changes or additions will be needed for the guider, for any focus routines (MIRA or new ones), for the pointing or rotation model used by Keck I, and for optimization of the image quality for the full LRIS field or portion thereof. As yet undetermined are who will be planning the functional requirements for these upgrades, who will be doing the work, how the project will be coordinated with the efforts of the LRIS ADC, and the sources of funding.

7. LRIS Software Upgrade: As discussed in more detail in Section 7.2.5 concerning software tasks, the existing LRIS software can use some major upgrades to bring it to

the standard of other Keck instruments that use “Dashboard” and have a NOTIFY mode. Early decision about whether this will be done, by whom, and with what funding is important in determining the schedule and costs for the LRIS ADC software.

8. Motor Control Upgrade: As discussed in more detail in Section 7.2.5, the existing Galil controllers have drawbacks that may have cost-effective solutions available, including “smart motors” in which the controller has been miniaturized and resides beside the motor itself. If Lick and CARA concur that upgrading to these motors is desirable, who will fund the effort? Will the LRIS ADC with its small number of motors be a good pathfinder for this effort? Does this issue need further exploration during the PD phase? If the upgrade is to be implemented, these questions will need to be addressed by the CD phase.

9. Fast Track Option for LRIS ADC: To fast-track the project, but with added risks for problems, CARA and SSC may want to consider having the project explore options for reducing the time needed for completion of the project. To achieve speedups, UCO/Lick may add personnel or, if this is not practical, and if the requisite quality can be assured, some of the ADC work can be out-sourced to commercial firms. The preliminary design phase can be used to check the feasibility of fast-tracking the LRIS ADC and to assess the cost/benefits of this option. The cost of adding personnel or out-sourcing to commercial firms has not been determined.

Acknowledgements

Acknowledgement of thanks to Judy Cohen (CIT), Chuck Steidel (CIT), Jeremy Allington-Smith (Durham University), Bryan Miller (Gemini), and Bill Mason (Keck), who helped with the study but have not been listed as contributors

Appendix A

Atmospheric Dispersion Correctors for the Keck Telescopes

Jerry Nelson and Terry Mast
DRAFT September 2002

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1. Introduction

During the initial design of the first Keck telescope we envisioned using atmospheric dispersion correctors (ADC). Harland Epps created designs for prime focus correctors that included ADCs (Nelson, Faber, and Mast, Figure 4-3, 1985). For the f/15 foci Epps investigated three possible designs (Figure 4-8), two with finite deviation and one with zero-deviation. For reasons of cost none of these designs were implemented.

In October of 1998 the Science Steering Committee funded a Phase A study proposed by Nelson for ADCs for the Keck f/15 foci. This report is part of that Phase A study.

The proposed design uses an Amici prism pair (Nelson and Sutin, 1998). An Amici prism pair is two identical prisms rotated about the optical axis with respect to each other by 180 degrees. A ray passing through the pair is not changed in direction ("zero deviation") and is displaced by an amount that depends on the wavelength and prism separation. The ADC corrects for atmospheric dispersion by changing the prism separation as the telescope zenith angle changes. This design is referred to as a "linear ADC."

At z = 60 degrees, atmospheric dispersion causes the images at wavelengths 0.4 and 1.0 μm to be separated by about two arcsec on the sky. The ADC eliminates most of this separation.

Nelson and Sutin suggested fused silica for the prism material to provide excellent UV transmission. They assumed the prism angle was 2.5 degrees. A prism separation of 1.4 meters is required for correction at a zenith angle of 60 degrees. In this report we emphasize a design with a prism angle of 5 degrees requiring a prism separation of about 0.7 meters at a zenith angle of 60 degrees.

We analyze the performance using the commercial ray-tracing program ZEMAX. A draft image quality error budget is given in Section 4. A linear ADC design has also been studied for the VLT (Avila, Rupprecht, and Beckers, 1997).

2. Atmospheric Dispersion and Correction

Atmosphere

Nelson (1994) gives an analytic approximation for the index of refraction on Mauna Kea

$$n_{atmo}(\lambda) - 1 = 10^{-8}\,(17020 + 93.2\,\lambda^{-2.102}) \quad (\lambda \text{ in microns}) \qquad (1)$$

For example:

$$n_{atmo}(\lambda = 0.4\mu m) - 1 = 1.7660 \times 10^{-4}$$

$$n_{atmo}(\lambda = 1.3\ \mu m) - 1 = 1.7074 \times 10^{-4}$$

Figure 1 shows $n(\lambda)$ for the atmosphere at Mauna Kea.

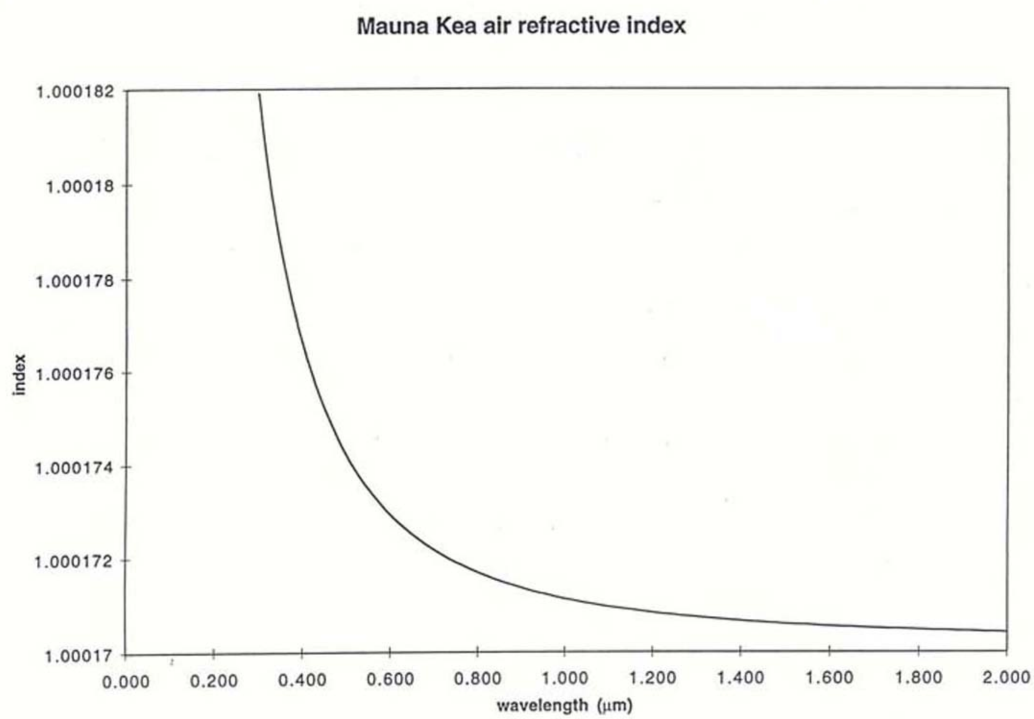

Figure 1

The atmosphere's index of refraction causes a change in the direction and thus a change in apparent zenith angle.

$$\delta z_{atmo}(\lambda) \equiv z_{apparent}(\lambda) - z_{true} = -\tan z\,[\,n_{atmo}(\lambda) - 1\,] \qquad (2)$$

For two wavelengths, λ_0 and λ, the zenith angle separation is

$$\delta z_{atmo}(\lambda) - \delta z_{atmo}(\lambda_0) = -\tan z\,[\,n_{atmo}(\lambda) - n_{atmo}(\lambda_0)\,] \qquad (3)$$

Figure 2 shows the image separation, $\delta z_{atmo}(\lambda) - \delta z_{atmo}(\lambda_0)$, versus zenith angle z (degrees) for $\lambda_0 = 0.4$ μm and various values of λ.

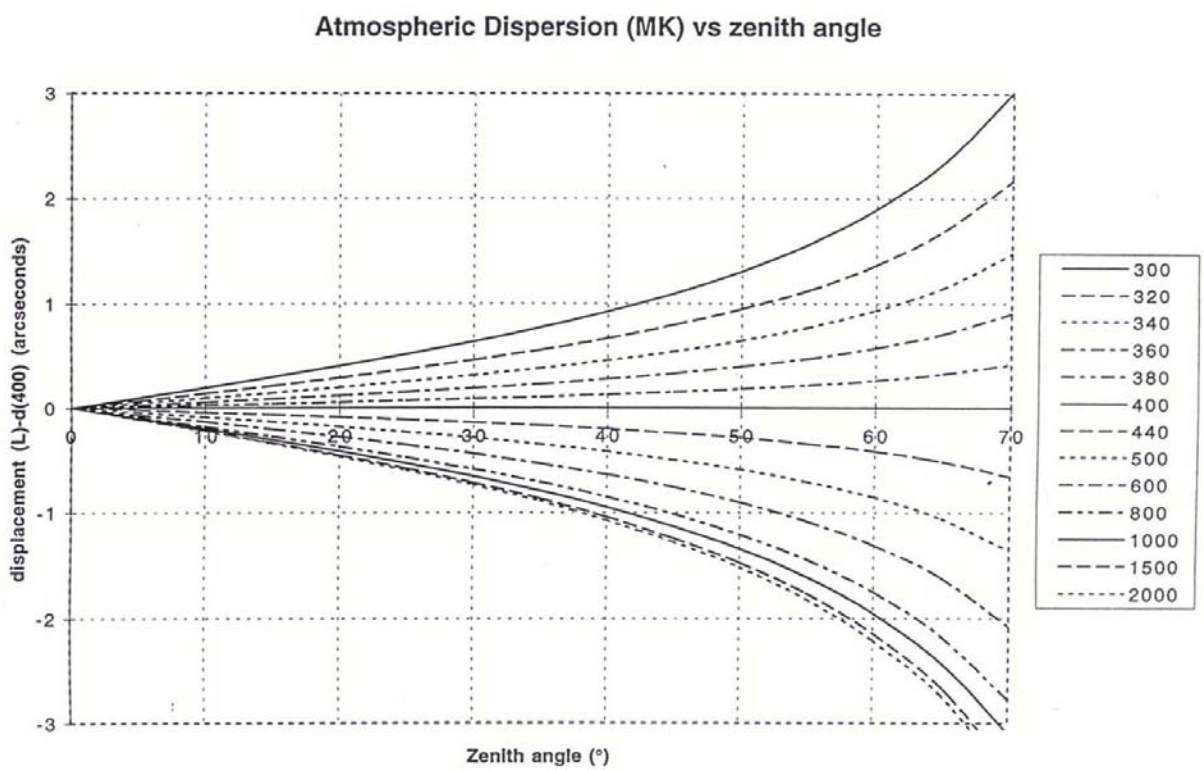

Figure 2

For example, for λ = 1.3 μm and z = 60 degrees,

$$\delta z_{atmo}(\lambda) - \delta z_{atmo}(\lambda_0) = 2.10 \text{ arcsec}$$

Prisms

For an Amici prism pair the chief ray leaving the prism pair is

1) unchanged in direction, and
2) displaced perpendicular to its original direction by

$$D = +\theta \frac{n-1}{n} t + [-\gamma (n-1)] d \tag{4}$$

where γ is the prism opening angle, t the two-prism thickness, and θ the angle of incidence which in our application depends of the field angle and any prism-pair rotation.

This displacement translates the image in the telescope focal surface and corresponds to a change in sky angle

$$\delta z_{adc} = \frac{D}{f} \qquad \text{where f is the telescope focal length} \tag{5}$$

For two wavelengths, λ and λ_0, the zenith angle separation (radians) is

$$\delta z_{adc}(\lambda) - \delta z_{adc}(\lambda_0) = \frac{t}{f} \theta \left[(n_{adc}(\lambda)-1) / n_{adc}(\lambda) - (n_{adc}(\lambda_0)-1) / n_{adc}(\lambda_0) \right] - \gamma \frac{d}{f} \left[n_{adc}(\lambda) - n_{adc}(\lambda_0) \right] \tag{6}$$

For the Keck telescopes the maximum field radius (10 arc minutes) results in a maximum θ = 0.0219 radians (= 1.25 degrees). For practical designs and a zenith angle about 60 degrees, the first term of Equation 6 is only about 1% of the second.

For the modeling below we have assumed the prisms are made of fused silica. Figure 4 shows the index of refraction for fused silica. For example:

$$n_{adc}\,(\lambda = 0.4\ \mu m) = 1.46994$$
$$n_{adc}\,(\lambda = 1.3\ \mu m) = 1.44672$$

For f = 150 m, γ = 5 degrees, d = 1.0 m, $\delta z_{adc}(1.3) - \delta z_{adc}(0.4) = 2.79$ arcsec.

Atmosphere and Prisms

Selection of Prism Separation d

Neglecting the first term in Equation 6 and equating the atmosphere (Equation 3) and ADC (Equation 6) zenith separations gives the desired distance between the prisms in order to have the images at λ_{lo} and λ_{hi} coincide.

$$d = \frac{f}{\gamma} \tan z \; R(\lambda_{lo}, \lambda_{hi})$$

$$\text{where } R(\lambda_{lo}, \lambda_{hi}) \equiv \frac{n_{atmo}(\lambda_{hi}) - n_{atmo}(\lambda_{lo})}{n_{adc}(\lambda_{hi}) - n_{adc}(\lambda_{lo})} \tag{7}$$

Table 1 shows some values of R assuming the ADC is fused silica. R times 10,000 is shown for various λ_{lo} and λ_{hi} (microns).

Table 1. R x 10,000

λ_{hi} =	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
λ_{lo}										
0.3	2.62	2.75	2.78	2.77	2.76	2.73	2.69	2.66	2.61	2.57
0.4		3.07	3.04	2.98	2.92	2.85	2.77	2.69	2.61	2.52
0.5			2.97	2.88	2.79	2.68	2.57	2.46	2.35	2.24
0.6				2.75	2.62	2.49	2.35	2.22	2.09	1.97
0.7					2.44	2.28	2.13	1.98	1.84	1.71
0.8						2.08	1.92	1.76	1.62	1.48
0.9							1.72	1.56	1.42	1.29
1.0								1.39	1.25	1.13
1.1									1.10	0.99
1.2										0.87

A fundamental tradeoff to be made in the design parameters is between the prism angle γ and the maximum required displacement, d. For a larger prism angle γ, the required range of d is smaller; however, the prisms are thicker, reducing their transmission and increasing their weight.

Residual Dispersion After Correction

If the shapes of $n_{atmo}(\lambda)$ and $n_{adc}(\lambda)$ were the same, then for a single value of d the image centroids would match at all wavelengths. However, the different shapes of $n_{atmo}(\lambda)$ and $n_{adc}(\lambda)$ give an image separation that can be set to zero at λ_{lo} and λ_{hi} , but will be non-zero for other wavelengths.

The residual image separation S(λ) =

$$- \tan z \left\{ [\, n_{atmo}(\lambda) - n_{atmo}(\lambda_0) \,] - \frac{n_{atmo}(\lambda_{hi}) - n_{atmo}(\lambda_{lo})}{n_{adc}(\lambda_{hi}) - n_{adc}(\lambda_{lo})} [\, n_{adc}(\lambda) - n_{adc}(\lambda_0) \,] \right\}$$

or

$$S(\lambda) = - \tan z \left\{ [\, n_{atmo}(\lambda) - n_{atmo}(\lambda_0) \,] - [\, \gamma\, d / (f \tan z) \,] [\, n_{adc}(\lambda) - n_{adc}(\lambda_0) \,] \right\} \qquad (8)$$

Figures 3 and 4 show the residual image separation versus λ for a fused silica ADC using (λ_{lo} , λ_{hi}) equal to (0.3,2.0) μm and (0.4,1.8) μm, respectively. Similar curves need to be calculated for the final design material and wavelength range.

FS, 0 at 0.3, 2 μ

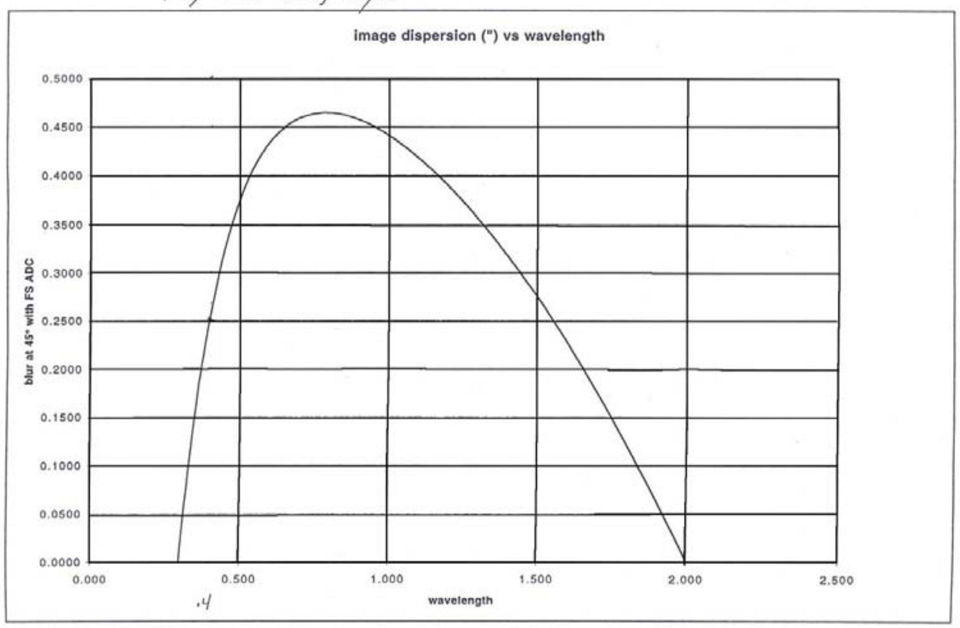

Figure 3

FS, 0 at 0.4, 1.8 μ

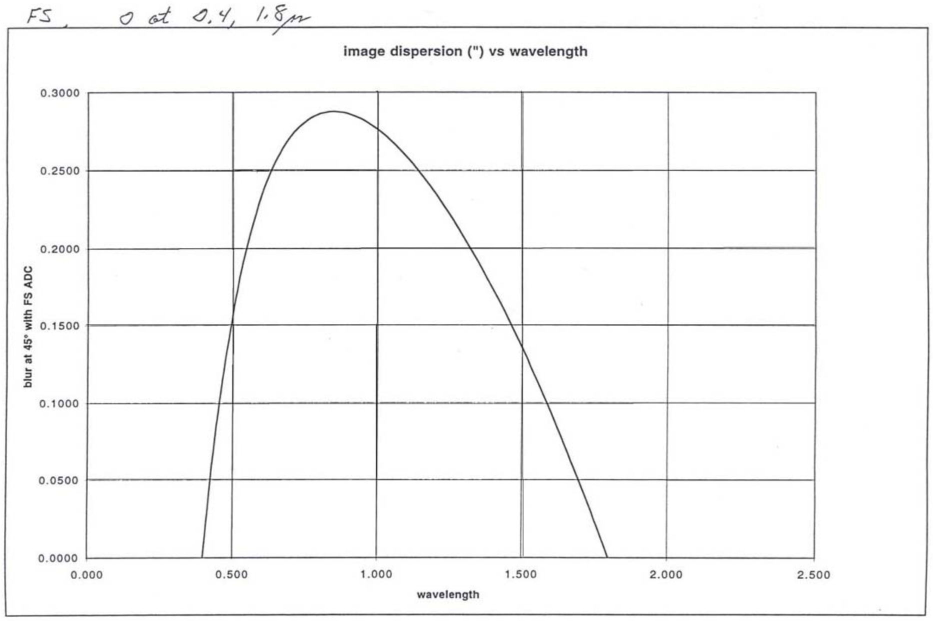

Figure 4

The sensitivity of the residual image separation to an error in the prism separation d,

$$\partial S/\partial d = [\,\gamma / (f \tan z)\,]\;[\,n_{adc}(\lambda) - n_{adc}(\lambda_{lo})\,] \qquad (9)$$

For γ = 5 degrees (0.0873 radians), f = 150 m, z = 60 degrees, λ_{lo} = 0.4 ,
and λ = 1.3 for a maximum $\partial S/\partial d$

$\partial S/\partial d$ = 1.61 arcsec / meter.

An error in d of 10 mm gives an error of 0.016 arcsec on the sky
(11.6 μm in telescope focal surface).

3. Ray-Trace Analysis of Performance

We have used the ray-tracing program ZEMAX to analyze the performance of various design configurations. A configuration is defined by four angles and one distance.

γ = the opening angle of each prism
$\alpha,-\alpha$ = the angle of prism1, prism2 with respect to the z-axis
β = the angle of the second prism with respect to the first
ε = the angle of the pair of prisms with respect to the z-axis
d = the distance between the two inner prism surfaces along the z-axis.

The angles α, β , ε are rotations about the x-axis.

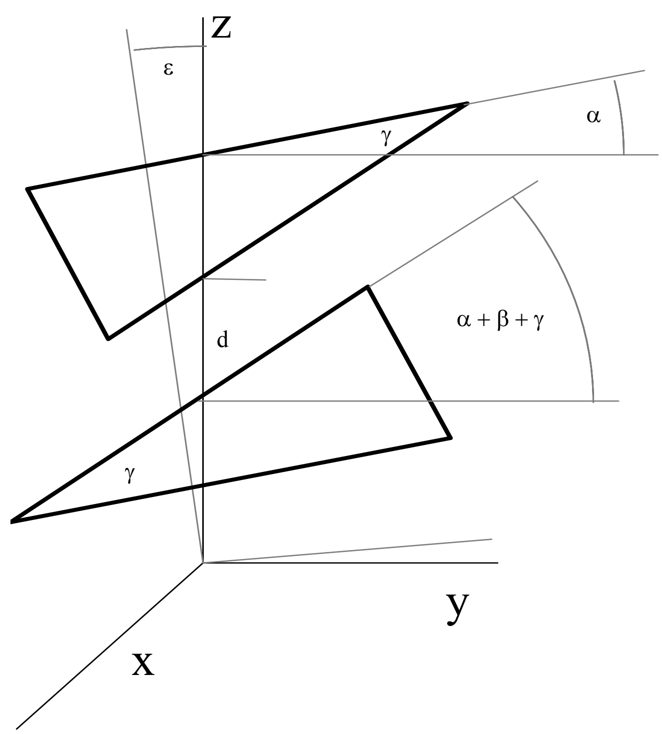

Figure 5. The parameters used to define a design configuration.

Figure 5 illustrates these parameters. The angles α and β are shown for $\varepsilon = 0$.

The distance d is varied to achieve the atmospheric dispersion compensation. The angle β cancels focal plane tilt.

ZEMAX uses a model atmosphere based on Seidelmann, Ed. (1992) and Hohenkerk and Sinclair (1985). We have assumed an observer height = 4160 meters, temperature = 275°K, pressure = 600 millibars, and relative humidity = 0.

Spreadsheet 1 ("Results from keckadc_S.zms") gives a list of some of the configurations explored. Two sets of field points are defined; Keckadc_A and Keckadc_B.

For this model we assumed $\gamma = 5.0$ degrees, and a prism thickness of 50 mm along the telescope optical axis.

For the model we assumed fused silica prisms with the following indices of refraction at 2°C.

wavelength (microns)	index
0.400	1.469938
0.500	1.462149
0.600	1.457861
0.700	1.455115
0.800	1.453138
0.900	1.451570
1.000	1.450228
1.100	1.449009
1.200	1.447851
1.300	1.446716

Spreadsheet 2 ("ZEMAX model - Keckadc_S") shows the full ZEMAX model surface definition. We defined two sets of field points, (keckadc_A and keckadc_B). The field points and the wavelengths are listed at the bottom of the spreadsheet.

At the beginning of 1999 Brian Sutin made ray-trace studies of candidate Keck ADC designs. The results of these studies are contained in an email dated 16 Apr 1999. The studies are for prism angle (γ) = 5 degrees, wavelength (λ) = 0.55 μm, and zenith angles (z) = 0 and 60 degrees (Sutin refers to these as "power = 0" and "power = 1"). He calculated images for three field angles. He used a prism spacing (d) = 27.5 inches (= 0.6985 m) for zenith angle (z) = 60 degrees. Additional details of the model are not available.

Sutin calculated image sizes [rms diameter (= 2 x rms radius), and enclosed energy diameters [80%, 90%, 100%] for no ADC and for six cases: $\alpha = -5.0, -2{,}5, 0.0$ degrees at z = 0, 60 degrees.

We have compared our ZEMAX results with Sutin's for these cases (spreadsheet "Compare ZEMAX & Sutin," not included in this report). There is overall agreement in the image sizes. Where there is not complete agreement, it is most likely due to different assumptions in the models. We used a circular aperture; Sutin most likely used a hexagonal or a full-segmented aperture for the primary mirror. We used a “secondary” baffle; Sutin probably did not. There are small differences in the optimized focal-surface position.

Given the overall agreement and the complete independence of the models, we conclude that the ZEMAX model is correctly configured.

Optimal Prism Spacing

There are two different categories of criteria one might use to establish the exact prism spacing. Given a wavelength range one might minimize the image centroid position variation (range or rms) over the wavelength range. Alternatively one might minimize the combined-wavelengths image size (rms image radius or 100% enclosed energy diameters).

We have used ZEMAX to compare these different criteria at z = 60 degrees, for the wavelength range 0.4 to 1.3 μm, and averaged over the keckadc_B field points.

The plate scale at the telescope focal plane is 727 μm per arcsec on the sky.

The range of centroid positions in minimized for d = 683, and changes by 10 μm for Δd = ± 5 mm.

The maximum image radius is minimized at 299 μm for d = 670 m, and the maximum image radius is degraded by 2% for Δd = ± 46 mm.

The rms image radius is minimized at 146 μm for d = 650 m, and the rms image radius is degraded by 2% for Δd = ± 50 mm.

We adopt a value of d = 680 mm for the remainder of our analysis.

Optimization of Geometry

We have varied the configuration parameter α to find the prism configuration that minimizes the rms image radius. The results are given in spreadsheet "Results from keck adc_S,zmx." and are summarized in the Table 2 below.

Table 2.

Wavelength (microns)		0.4	1.3	0.4	1.3
Field point #		4	4	5	5
Field point y (degrees)		0.167	0.167	-0.167	-0.167
	α				
rms image radius (microns)	0.0	240	246	261	250
rms image radius (microns)	–2.5	195	206	208	196
rms image radius (microns)	–5.0	160	177	153	147

The optimal geometry is α = −5.0 degrees, corresponding to parallel inner faces of the prisms.

At α = -5.0 we varied β (the angle of prism 2 with respect to prism 1) and considered the ratio of image size from field points 4 and 5 (Y_field = ± 0.167 degrees) for both rms image radius and maximum image radius. There is no overall image size-ratio improvement by making β non-zero.

We made a similar study varying the tilt of the Amici pair as a whole with respect to the telescope optical axis and concluded $\varepsilon = 0$ was optimal.

Summary

Based on this study we adopt for a baseline configuration

γ = the opening angle of each prism	= 5.0 degrees
$\alpha,-\alpha$ = the angle of prism1, prism2 with respect to the z-axis	= −5, 5 degrees
β = the angle of the second prism with respect to the first	= 0.0 degrees
ε = the angle of the pair of prisms with respect to the z-axis	= 0.0 degrees
d = the distance between the two inner prism surfaces along the z-axis	= 680 mm for a zenith angle = 60 degrees

This gives rms image radii of ~ 150 to 180 μm over the field and λ = 0.4 to 1.3 μm.

Image Quality

For the modeled design (α =−5 degrees, β = 0, ε = 0, d = 680 mm, fused silica at z = 60°) Table 3 gives image sizes (rms image radius about the chief ray) for the 12 field points and for λ = 0.4, λ = 1.3, and all wavelengths between 0.4 and 1.3 combined. The weighted rms ("wtd rms" is weighted to approximate an array of field points that is uniform over the full field. For a Gaussian point spread function, the FWHM is $2.35/\sqrt{2}$ = 1.66 times the rms radius.

Table 3. RMS image radii about the chief ray (microns)

field pt	field_x (deg)	field_y (deg)	wavelength (microns) = 0.4	1.3	all
1	0	0	68	85	96
2	0	0.0833	104	124	130
3	0	-0.0833	51	48	72
4	0	0.1667	159	177	181
5	0	-0.1667	162	147	159
6	0.0833	0.0000	89	102	112
7	0.1667	0.0000	174	178	185
8	0.0589	0.0589	66	70	87
9	0.0589	-0.0589	101	120	126
10	0.1179	0.1179	168	161	171

11	0.1179	-0.1179	166	181	185
12	-0.1667	0.0000	174	178	185
		ave =	123	131	141
		stdev =	48	47	42
		wtd rms =	130	137	145

Vignetting

Figure 6 shows the footprint of the beam on the first prism. Using ZEMAX and field points Keck_A we calculated the vignetting of the first prism as a function of field angle for prism radii of 450, 475, and 500 mm. Figure 7 shows the results. A vignetting of 0.94 for the secondary baffle has been divided out. For 500 mm radius prism, there is no vignetting up to a field angle of 8 arcmin. At a field angle of 10 arcmin the vignetting is 0.94.

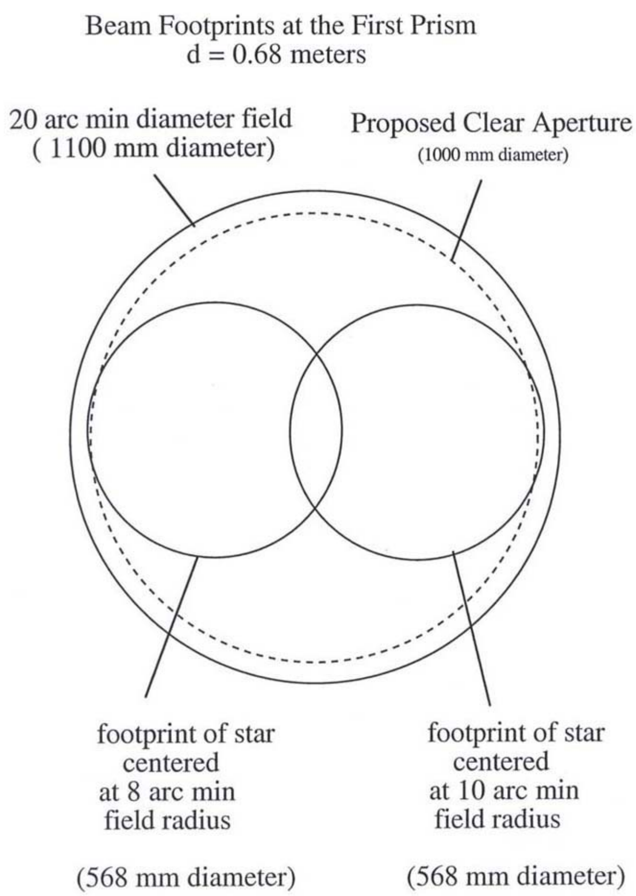

figure 6

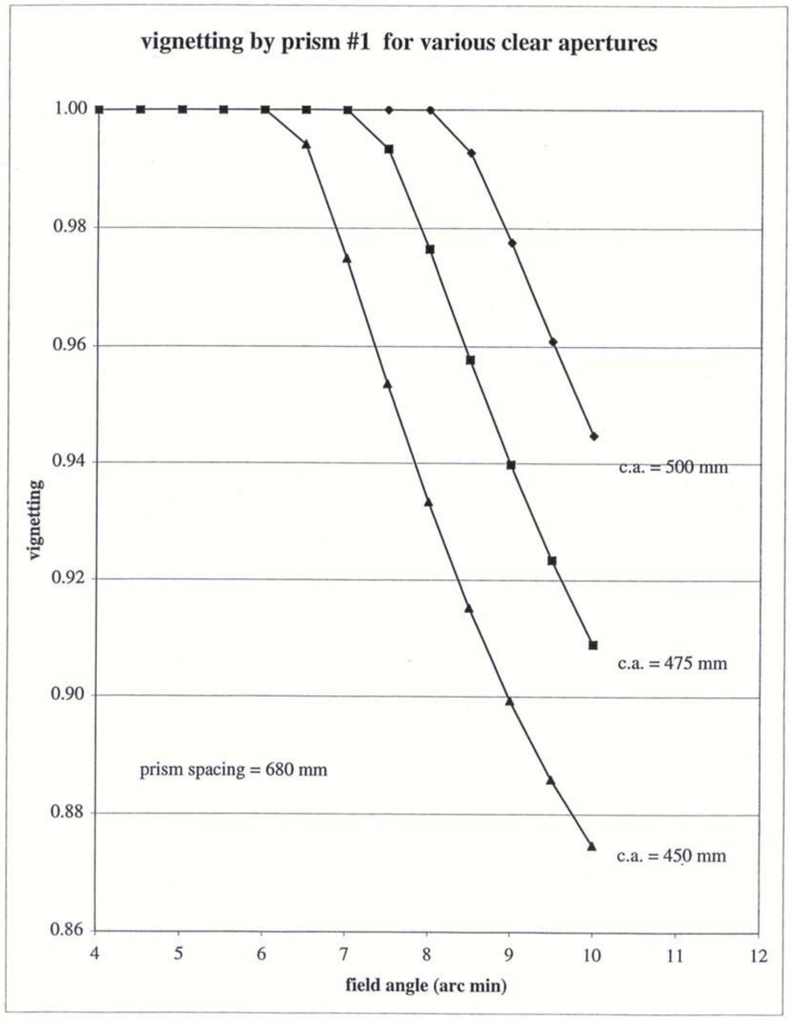

Figure 7

Reflections

Two reflections from the prism faces have the potential of creating a ghost at the telescope focal surface. Possible reflection pairs are (S2 / S1 and S3 / S1), (S4 / S3 and S4 / S2) , and (S4 / S1).
For the first two groups the beam after the double reflection is at 10 degrees to the telescope optical axis. For the third group the beam is at 5 degrees to the optical axis.

If we assume the ADC is about 4 meters above the primary and the telescope focal surface is 2.5 meters behind the primary, then the 5 degree ghost beam center lands (6.5 m x 5/57.3) ~ 0.57 meters from the center of the telescope focal surface. The 20-arcmin field of view has a radius of 0.44 meters. We conclude that ADC will not induce ghost images.

Transmission

For prism angle (γ), extra radius beyond the clear aperture (s), a minimum edge thickness (tmin), and a clear aperture radius (R) the total thickness of both prisms is

$$t_{total} = 2 \, (\text{tmin} + (R + s) \, \gamma) \quad (9)$$

Assume tmin = 10 mm, R = 550 mm, γ = 5 degrees , s = 10 mm

$\Rightarrow \quad t_{total} = 118$ mm

For 10 mm of fused silica the transmission τ (10 mm) = 0.99. This implies τ (118 mm) = 0.89.

We do not know τ (10) mm to higher precision. A range of τ (10) = 0.985 to 0.995 implies τ (116 mm) = 0.839 to 0.944.

The transmission versus wavelength is shown in Figure 8 for fused silica, F2, and PBL25Y. Fused silica has a severely reduced transmission around 1300 nm and maintains high transmission in the blue. Depending in availability we propose

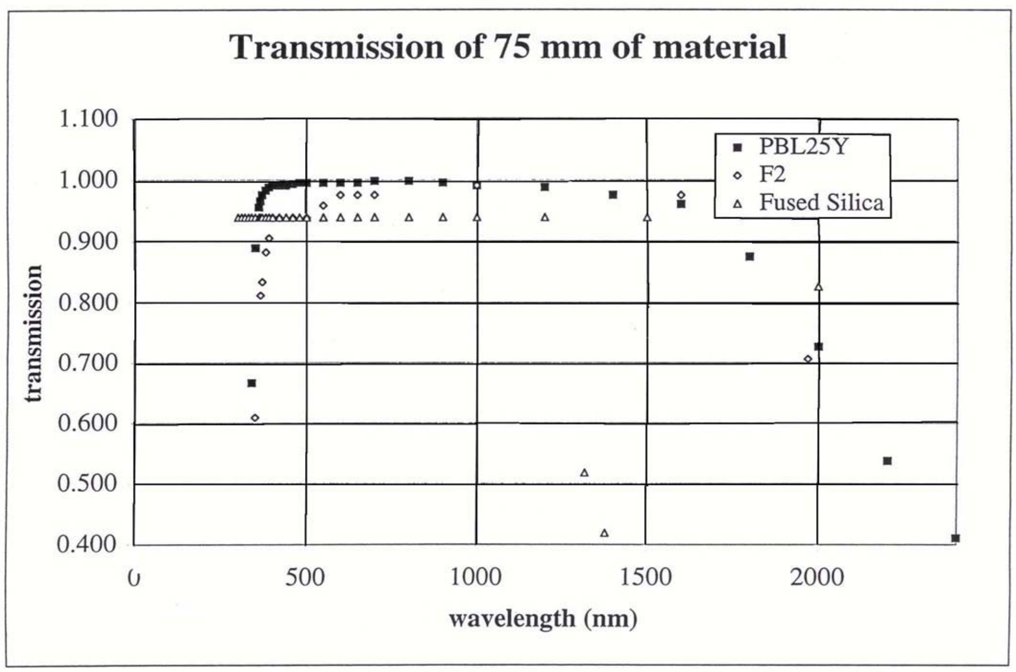

Figure 8

For Keck 1 blue optimized (LRIS B), use fused silica

For Keck 2 near-IR optimized (DEIMOS red), use PBL25Y or F2.

4. Image Quality Error Budget

Sensitivities

Using ZEMAX we have calculated the sensitivities to motions in the six degrees of freedom of each individual prism and the prism pair. These are summarized in the table below. The dispersion direction is Y. A rotation about the X axis is theta X, etc.

We list in Table 4 the amount of rms image radius that is to be added in quadrature to the unperturbed rms image radius. This is averaged over field points (weighted to give a uniform distribution of field points) and wavelength. The unperturbed rms image radius = 145 μm. For small perturbations this "addition" is proportional to the perturbation.

Table 4. Sensitivities. Quadrature additions to image sizes for perturbations in the positions and angles of the prisms.

		perturbation	"addition" to rms radius (microns)	spreadsheet filename
Amici Pair				
	delta X	20 mm	0	pp
	delta Y	20 mm	0	pp
	delta Z	20 mm	22	pp
	theta X	2 deg	56	pp
	theta Y	2 deg	58	pp
	theta Z	2 deg	13	pp

		perturbation	"addition" to rms radius (microns)	spreadsheet filename
prism #1				
	delta X	20 mm	0	pp
	delta Y	20 mm	0	pp
	delta Z	20 mm	0	pp
	theta X	0.1 deg	47	p4
	theta Y	0.1 deg	27	p5
	theta Z	0.1 deg	11	pp

Error Budget

Using the sensitivities in Table 4 we have assigned the errors in the following budget. As the design of the support and motion control develops, we expect this initial budgeting will be modified.

If we budget a 10% increase in rms image radius due to these motions, then the rms image radius to be added in quadrature = $145\,[1.1^2-1]^{1/2} = 145 * 0.458 = 66$ μm

Table 5. Prism Position and Angle Error Budget

	budgeted rms error		resulting rms image radius	
Amici Pair				
delta X	20	mm	0	microns
delta Y	20	mm	0	microns
delta Z	10	mm	16	microns
theta X	0.25	deg	20	microns
theta Y	0.1	deg	13	microns
theta Z	1	deg	9	microns
prism #1				
delta X	20	mm	0	microns
delta Y	20	mm	0	microns
delta Z	20	mm	0	microns
theta X	0.13	deg	54	microns
theta Y	0.05	deg	19	microns
theta Z	0.2	deg	16	microns
		rms =	66	

See Figure 5 for definition of coordinate system. The tolerances on translations are loose.

A 0.1 degree rotation corresponds 0.87 mm motion at the edge of a 0.5-meter-radius prism.

The above allowed rms perturbations need to be budgeted themselves to the potential sources: design, fabrication, assembly, calibration, and operations. We have made an initial budgeting in Table 6. Notes below describe the basis for the budgeting chosen.

The image blur is given in terms of contributions to rms image radius in microns at the telescope focal surface. For a Gaussian point spread function

FWHM = 1.66 rms image radius

80%-enclosed-energy diameter = 2.54 rms image radius

These yield

	Focal plane (microns)	angle on sky (arcsec)
rms radius =	159	0.219
FWHM =	264	0.364
80%-enclosed-energy diameter =	404	0.556

Table 6. ADC Error Budget

			rms image radius (microns)	Notes
1. Design			145	1
2. Fabrication				
Surface quality			4	2
Prism Angle			0	3
Index Non-homogeneity			10	4
3. Assembly				5
prism pair				
	θX	0.029 deg	2	
	θY	0.029 deg	4	
prism #1				
	θX	0.029 deg	11	
	θY	0.029 deg	12	
4. Calibration				
Prism Separation versus Zenith Angle			0	6
5. Operations				
Gravitational				7
Amici Pair				
	δX	20 mm	0	
	δY	20 mm	0	
	δZ	10 mm	16	
	θX	0.25 deg	20	
	θY	0.1 deg	13	
	θZ	1 deg	9	
prism #1				
	δX	20 mm	0	
	δY	20 mm	0	
	δZ	20 mm	0	8
	θX	0.13 deg	54	
	θY	0.05 deg	19	
	θZ	0.2 deg	16	
Thermal				9
ADC as a whole			0	
Individual prisms			0	
Motion Control Noise			0	10
			rms = 160 μm	

Notes:

1. Design

Includes Telescope and ADC averaged over field and $0.4 < \lambda < 1.3$

2. Surface quality

If we assume the surface error is dominated by astigmatism, the combined surface error from all four surfaces is 1 micron of C22, and the beam size at the ADC is ~ (600/1000) = 0.6 of the clear aperture (500 mm), then the resulting image blur will be

$$2 * (1\ \mu m / 0.5\ m) * (0.6)^2 * (1.45 - 1)/1.45) * 9\ m = 4\ \mu m$$

The surface errors are likely to be of higher spatial order, but are undoubtedly will be of significantly smaller than 1 micron.

3. Prism Angle

An error in the prism angle will have a small effect on the dispersion correction. The fractional correction of the dispersion is of order 0.1. We assume the fractional prism angle error will be an order of magnitude smaller than this, and thus the effect on the dispersion correction will be negligibly small.

4. Index Non-homogeneity

A typical value for index variations in fused silica is $\sigma\_n = 3 \times 10^{-6}$. If we assume the variations are on a spatial scale of 200 mm, then the wavefront slope is about ($\sigma\_n * t / 200$ mm), where t is the prism thickness (~ 100 mm). The resulting image radius is ($\sigma\_n * t / 200$ mm)* L, where L is the distance from the ADC to the telescope focal plane = ~ 9 meters). This gives a maximum image radius, assuming the rms radius is $\sqrt{2}$ smaller, of 10 μm.

5. Assembly

For all six degrees of freedom we assume rms dimensional assembly errors of 250 μm (~ 0.010 inches) For rotations we assume this applies at the edge of the prism and assume 500 mm radius. Thus 250 μm corresponds to a tilt of 0.029 degrees. The errors are scaled form Table 5.

6. Prism Separation versus Zenith Angle

7. Operations - Gravitational

8. Operations - Gravitational δZ

9. Operations - Thermal

For an assumed operating temperature range = ± 8 ^{o}C, and a steel (CTE = 12 x 10^{-6} / ^{o}C) structure providing a separation of 0.7 meters, $\delta d = \pm 70\ \mu m$. This has a negligible effect on the image, and so we assign all the errors in Table 6 to gravity.

10. Operations - Motion Control Noise

5. Prism Properties

We consider the prism angle, thickness, diameter, and material quality. Specification of these requires tradeoffs between these parameters as well as support and motion requirements, material availability, and cost.

Volume and Mass

For density (ρ), prism angle (γ), extra radius beyond the clear aperture (s), and a minimum edge thickness (tmin), the volume (V) and mass (M) for clear aperture radius (R) are

$$V = \pi (R + s)^2 (tmin + (R + s) \gamma)$$

$$M = V \ \rho$$

These are for a single prism.

Assume: fused silica $\rho = 2.2 \times 10^{-6}$ kg/mm^3
γ = 5 degrees
s = 10 mm
tmin = 10 mm

R (mm)	V(liters)	M (kg)
400	24.2	53.2
450	33.3	73.3
500	44.5	98.0
550	58.0	127.6

Material Quality

For transmission effects see page 9
Homogeneity -

Material Availability

The prism material, and hence the index of refraction, will be selected on the basis of

- the availability of materials in the required size and
- the different operating wavelength ranges expected for Keck 1 and Keck 2.

Fused silica (Corning 7040)
PBL25Y (Ohara 581408, an i-line glass) Ohara melts in volumes of 100 liters

Coating Limitations

A variety of anti-reflective coatings are possible including Sol-Gel, and multi-layer coatings. It is likely that the reflectivity per surface can be reduced to about 1% or better. The coating availability and limitations needs to be researched.

Polishing Limitations

Polishing of these large surfaces will need to be made by a commercial firm. Candidates include Kodak, Zygo, Brashear, and Tinsley.

6. Support Design

The prism support, prism motion control, and packaging rely on the details of the as-built configurations of the tertiary mirror module, the tertiary baffle, and the Cassegrain tower. This information is being assembled. The design will address issues associated with servicing, installation, removal, and stowing of the ADC.

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Appendix B

Atmospheric Dispersion Compensation for LRIS
Phase A Design and Tolerances

Terry Mast
June 2002

Contents

Overview

This report is an initial estimate of engineering tolerances for the LRIS ADC. It is based on "Atmospheric Dispersion Correctors for the Keck Telescopes" (Jerry Nelson and Terry Mast, DRAFT June 2002). In the next phase of the LRIS ADC design a ray tracing specific to the LRIS ADC will be made.

In most aspects the LRIS ADC is the same or similar to the design studied in the above report.

The LRIS ADC is closer to the focus

	prism #2 to telescope focal surface
Keck ADC	7050 mm
LRIS ADC	505 mm
Ratio	0.072

Since it is closer to the focus and samples only a portion of the telescope field, the prisms will be smaller in diameter; thus less costly to fabricate and support.

Unlike the Keck ADC, the LRIS ADC will sample only a portion of the telescope field. To track this portion it must be rotated about the telescope optical axis to maintain the same portion of the rotating field. This means that the prism pair must be rotated about its own axis to maintain the same orientation with respect to gravity (the atmospheric dispersion direction).

Although not a major concern for either design, the transmission will be better for the LRIS prisms since the central thickness is about 0.7 that of the Keck ADC.

Since the LRIS ADC is closer to the focal surface, I expect the non-chromatic part of the image blur in the Keck design to be reduced by the factor 0.072. Since it only samples that outer part of the telescope field, the field-averaged value used for the Keck ADC design is somewhat optimistic.

Design

A linear ADC design. Two prisms with a variable spacing that is adjusted as a function of zenith angle to partially correct the effect of atmospheric dispersion.

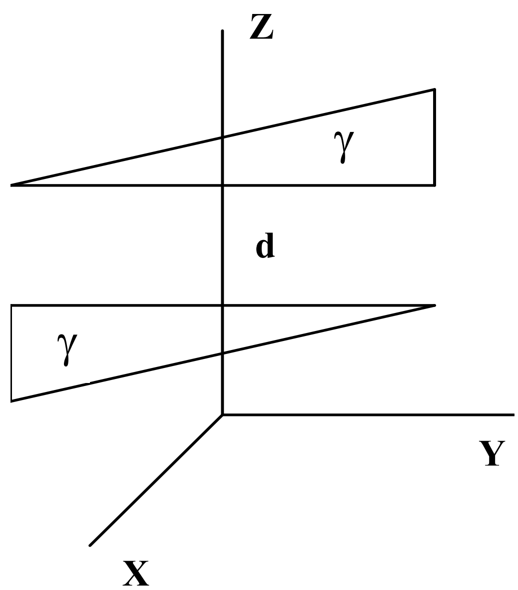

Figure 1 shows a cross section in the Y-Z plane. The design is symmetric ± X.

Each prism

material = fused silica
prism angle $\gamma = 5.0$ degrees
clear aperture diameter = 533 mm
physical diameter = 553 mm
central thickness = 34 mm
smallest edge thickness = 10 mm
mass = 18 kg
index of refraction
$\lambda = 0.4\ \mu m$ $n = 1.4699$
$\lambda = 1.3\ \mu m$ $n = 1.4467$
index homogeneity $\sigma_n < 5 \times 10^{-6}$

Prism Pair

prism orientation : inner surfaces parallel (Figure 1)
prism spacing between inner surfaces = d , varies from 4 mm to ~700 mm
The 4 mm is the minimum distance required because of the 0.5 degree zenith blind spot at Keck, and it also provides a safe separation between the prisms at closest approach.

The two-prism set rotates to maintain its orientation with respect to gravity as the instrument is rotated to maintain its off-axis section of the field.

For the Keck ADC design the rms image radius in the telescope focal surface for $z = 60$ degrees and averaged over the full 20 arc min diameter FOV = 145 μm (= 0.20 arcsec on the sky).

Atmospheric seeing will further increase the image size. For a FWHM = 0.5 arcsec image, the rms image radius in the telescope focal surface ~ 220 μm (= 0.30 arcsec on the sky).

Since it is closer to the focal surface, the LRIS ADC will create a smaller image blur than the Keck ADC design.

Tolerances

For the Keck ADC design we assigned the following error budget for six degrees of freedom of the prism pair and for the six degrees of freedom of prism #1 with respect to prism #2.

Table 1. Keck ADC Prism Position and Angle Error Budget

Prism Pair		error	rms image blur
	δX	±20 mm	0
	δY	±20 mm	0
	δZ	±10 mm	16
	θX	±0.25 deg	20
	θY	±0.1 deg	13
	θZ	±1 deg	9
prism #1			
	δX	±20 mm	0
	δY	±20 mm	0
	δZ	±20 mm	8
	θX	±0.13 deg	54
	θY	±0.05 deg	19
	θZ	±0.2 deg	16

The tightest tolerances are for θX and θY.

An analysis of the Keck ADC sensitivities for θX and θY shows that about 30% of the rms image blur is from chromatic effects. For the LRIS ADC I assume the factor of 0.072 reduction in the distance to the focal surface will make the non-chromatic terms negligible, leaving only the 30% chromatic effects. Thus for an initial estimate I assume that the tolerances on θX and θY can be loosened by a factor of three. Similarly, an analysis of the θZ sensitivity suggests the tolerance can be loosened by a factor of 1.5. So I propose the following tolerances be used for the initial engineering of the LRIS ADC.

Table 2. LRIS ADC Prism Position and Angle Error Budget

Prism Pair		
	δX	±20 mm
	δY	±20 mm
	δZ	±10 mm
	θX	±0.25 deg
	θY	±0.1 deg
	θZ	±1 deg
prism #1		
	δX	±20 mm
	δY	±20 mm
	δZ	±20 mm
	θX	±0.4 deg
	θY	±0.15 deg
	θZ	±0.3 deg

The "Prism Pair" tolerances are with respect to the telescope focal surface. The "prism #1" tolerances are with respect to prism #2, where prism #2 is closest to the spectrograph.

A tolerance of ± 0.1 degrees for a prism with a diameter of 553 mm corresponds to an edge tolerance of ± 1 mm.

Appendix C
Draft Report – ADC Considerations
Drew Phillips, September 2002

C1.0 Abstract

The simple crossed-prism-pair ADC is considered and rejected for LRIS. The problems with such a system raise concerns about the design and operation of even zero-deviation ADCs in the case of multi-object spectrographs.

C2.0 Simple Crossed Prism Pairs

The classic ADC is simply a pair of matching thin prisms (of angle $\alpha/2$) that can be rotated to act as a single prism of prism-angle = 0 - α, at arbitrary orientation. This kind of system can work (at least to first order) in simple imaging systems, but is unsuitable for imaging spectrographs. To illustrate the latter case consider just the spectroscopic mode. We have a slit (at the focal plane of the telescope), a collimator, a dispersive element, a camera and a detector. These systems are usually constricted by the size of the dispersive element, and thus it is desirable to place a pupil there that fills the element. Let us consider the effects of the simple ADC on that requirement first:

Using the thin prism-approximation (in air), the angular deviation produced by a prism with angle α is

$$\delta = (n - 1)\alpha$$

Suppose this prism is located distance D in front of the slit, then the linear displacement at the slit, d, is simply

$$d = (n - 1)\alpha D$$

Now, consider that we want to use differences in $n(\lambda)$ to move atmospherically-dispersed images on top of each other. Suppose the monochromatic images have a separation Δ_{12} due to atmospheric dispersion, and then it is easy to see that

$$\Delta_{12} = (n_2 - n_1)\alpha D$$

Combined with the first equation, then, we find an average angular deviation of

$$<d>_{12} = \frac{\Delta_{12}}{D}\frac{(<n>_{12} - 1)}{(n_2 - n_1)}$$

As an example, at 60° zenith distance, an image at 0.35 μm is displaced about 2.2 arcsec from an image at 0.65 μm, or about 1.6 mm in the focal plane of the Keck telescopes. Fused silica has indices of refraction of about 1.477 and 1.456 at these two wavelengths, respectively. If we adopt a distance of 1 meter between the prism and focal plane, we find that the angular deviation is 2.0°.

What is the effect on the pupil placement at the grating? For LRIS, the distance from the slit to grating is roughly 4 meters -- so the pupil is displaced about 140 mm, i.e., a pupil diameter (141 mm). In short, we miss the grating.

However, there is a more compelling problem independent of the pupil placement. The position of an image formed on the detector is directly dependent on the angle of the collimated beam reaching it:

$$r = f_{cam} * \tan\theta,$$

where r is the distance off-axis. If θ changes by δ, there will be a large motion of the image. For example, f_{cam} (LRIS) is 307 mm, so an image that should have been on-axis would be displaced 10.9 mm, or over 450 pixels. Clearly, even a slight change in the orientation or magnitude of δ during an integration would destroy image quality.

C3.0 Considerations for Imaging Spectrographs

It is obvious from the above that *only* zero-deviation ADCs will work for *spectrographs*. This is because, simply, such instruments have not one but *two* focal planes --- that of the telescope and that of the detector --- that must be maintained in precise alignment with each other. Thus, it is not sufficient just to get the light through a slitlet, but it has to go through at very nearly the right angle, and the angle must be held constant to a high degree during an observation. (These constraints are valid even for imaging mode of imaging spectrographs, because guiding takes place in the focal plane of the telescope.)

Two ramifications appear from this:

1. During a long integration, the ADC may need to be in a fixed configuration.

2. The greater the distance from the ADC to the slit, the smaller any wavelength-dependent angular deviations produced by the ADC will be.

These issues must be carefully addressed in the design (and possibly operation) of the LRIS ADC. For LRIS, a deviation of 0.001° produces an image shift of 0.22 px. While holding the ADC configuration constant during an integration would prevent any degradation of image quality, it is clear that calibrations (arcs, possibly flat fields) would need to be acquired in each ADC configuration that caused angular deviations more than a few x 0.001°.

This raises an interesting and potentially troubling question: How small are the deviations in a "zero-deviation" ADC? They may be zero at a given wavelength, but the very nature of such a corrector is to vary the angles at different wavelengths. The truly zero-deviation ADC must precisely cancel out any wavelength-dependent angular deviations it introduces.

If the linear ADC were truly zero-deviation, and the rays simply translated different amounts at different wavelengths, then the angles we must worry about are merely those from the atmospheric dispersion. In the example above, we had a 2.2 arcsec dispersion. The angles entering the spectrograph are magnified by a factor of 7.?? (set by the telescope design), so the actual deviations would be around 16 arcsec, or 0.004° -- around 1 px displacement on the detector. This is at a level where we must be concerned, but the problems do not appear to be overwhelming.

Appendix D
Budget – Phase A Study

Keck Observatory — **Atmospheric Dispersion Corrector**
Budget Report — **For the Period 7/1/99 - 8/31/02**
Date Prepared: September 11, 2002
Prepared by: Marlene Couture

Description/Code	Budget	Hours	Labour	Materials	Balance	
November 1999		12.00	$ 613.51			(KADCXX)
October 1999		8.00	$ 426.06			(KCADCX)
December 1999		3.50	$ 186.40			(KCADCX)
January 2000		1.50	$ 80.18			(KCADCX)
August 2000		5.00	$ 267.26			(KCADCX)
September2000		11.50	$ 774.48			(KCADCX)
October 2000		5.00	$ 334.23			(KKADCX)
November 2000		33.00	$ 1,590.25			(KKADCX)
December 2000		45.00	$ 1,399.01			(KKADCX)
January 2001		4.00	$ 608.88			(KKADCX)
March 2001		118.50	$ 5,866.56			(KKADCX)
April 2001		34.50	$ 2,334.03			(KKADCX)
May 2001		21.50	$ 1,454.54			(KKADCX)
June 2001		32.00	$ 2,164.89			(KKADCX)
July 2001		3.00	$ 202.96			(KKADCX)
August 2001		8.00	$ 541.22			(KKADCX)
September 2001		16.00	$ 1,082.44			(KKADCX)
October 2001		11.00	$ 759.04			(KKADCX)
November 2001		6.00	$ 414.02			(KKADCX)
December 2001		14.00	$ 966.05			(KKADCX)
January 2002		3.00	$ 214.47			(KKADCX)
February 2002		87.00	$ 5,885.85			(KKADCX)
March 2002		53.50	$ 3,219.47			(KKADCX)
April 2002		137.00	$ 9,520.61			(KKADCX)
May 2002		96.00	$ 6,862.88			(KKADCX)
June 2002		32.00	$ 2,287.63			(KKADCX)
July 2002		101.00	$ 7,220.33			(KKADCX)
August 2002		30.00	$ 2,144.65			(KKADCX)
TOTAL LABOUR		932.50	59,421.90			
						(KKADCX)
Photograph y Services 10/99				$ 20.63		(KADCXX)
Dell Marketing 9/00				$ 4,074.85		(KCADCX)
Fry Steel Company 11/00				$ 73.34		(KCADCX)
McMaster-Carr 3/19/01				$ 267.85		(KKADCX)
Computing Services 11/01 - 1/31/02				$ 1,155.00		(KKADCX)
Computing Services 11/01 - 1/31/02				$ (1,155.00)		(KKADCX)
Laiterman/Travel/Keck 4/15/02				$ 2,351.98		(KKADCX)
Radovan/Travel/Keck 4/15/02				$ 1,938.49		(KKADCX)
Inner Mtn. Outfitters 3/18/02				$ 71.59		(KKADCX)
Lee Laiterman 2/28/02				$ 70.80		(KKADCX)
McMaster-Carr 2/27/02				$ 31.01		(KKADCX)
Payroll (R. Mercurio) 2/28/02				$ 765.38		(KKADCX)
Tax				$ 4.96		(KKADCX)
Feb. Long Distance				$ 1.26		(KKADCX)
Jan. Long Distance				$ 1.96		(KKADCX)
May Long Distance				$ 0.14		(KKADCX)
PURCHASE ORDER #85364	**$ 30,000.00**					
MODIFICATION #1	**$ 38,000.00**					
MODIFICATION #2	**$ 10,000.00**					
TOTALS	**$ 78,000.00**	932.50	$ 59,421.90	$ 9,674.24	**$ 8,903.86**	

Appendix E
Communication from CARA (30 Oct 2002)

CARA ME Group Action Items from 10/22/02 LRIS ADC Phase A Review

Note (1): **Per 10/23/02 phone conversation with Lee Laiterman, precise information not needed for Phase A Report. CARA shall enter information in ICD. This task is included in the .5 FTE LOE estimation for CARA mechanical support Information and Support Needed from CARA.**

1. Modification of front shroud and hatch on LRIS - section 2.3 #5, 2.7.4, 11
    a. Lick shall define the envelope for the shroud modifications and Keck shall design and implement the modification.
    b. Lick shall design the new hatch and CARA shall approve and implement the modification.
    c. CARA will assess LOE and modify the estimated amount in the proposal.

2. Coordination and support to install a correctly weighted dummy module on to LRIS
    a. Lick shall supply the module.
    b. CARA shall coordinate and support the effort.

3. Maximum practical weight that can be added to LRIS - 2.7.1
    a. The current estimate is that the ADC will increase the total weight of LRIS from 2425 kg to 3343 kg (230 kg heavier than ESI). This includes additional counter weights on the back side of the instrument. If that is the case, counterweights may have to be added near the secondary module.
    b. Lick shall make every effort to reduce the total weight added to the telescope.
    c. CARA will assist with this effort.
    d. See Note (1).

4. Max practical axial moment on LRIS that can be corrected with passive counterweights 2.7.1, BOM p37
    a. See Note (1).

5. Precision to which LRIS must be counterbalanced - axially and radially - 2.7.1, 5.2, BOM p37
    a. Axially: See Note (1).
    b. Radially: 10 ft-lbs.
    c. See Note (1).

6. Tolerances and true limits of dimensions depicted on CARA document SK-055(880) "Keck I and II Cassegrain Instrument Interface Envelope" - 5.2
    a. See Note (1).

7. Response to requiring a specific LRIS rotational orientation when hinging ADC away from LRIS - safety and maintenance considerations - 2.7.4, 2.9.4, 5.2, 11
    a. There is no preferred rotational orientation for maintenance considerations.
    b. CARA is concerned that there will be interference with the rails of the LRIS handler if the ADC hinges as shown in Sec. 5.3, Figure 5. Lee will investigate this with support from Drew. A different scheme may be required.
    c. See Note (1).

8. Operations/maintenance costs of not doing option A
    a. This action item is still being evaluated and requires input from Bill Mason and others on the CARA team. A best guess for now is 48 to 100 man-hours (8 to 16 man days) per year + a night or two per year lost observing time.
        1. According to an instrumentation technician, last year we removed the front cover about ten times for repairs. We typically change two calibrations lamps per year. If we have to use the jib crane to remove the ADC and park it on the other side of the elevator that means requiring dome restrictions. Using an estimate of 2 hours for two people to remove and replace the ADC, adds an additional (12 X 4Mh) 48 man hours per year.
        2. There is an additional concern. In the past, last minute (after initialization) slit mask jams have occurred. If you need a crane to remove the ADC you will probably **lose the night** or at least a significant portion of it.
        3. Finally - There are Gratings, Filters, and Slitmasks that are routinely changed. If ADC structure interferes with our traditional methods of doing this work, and we can't easily get it out of the way, costs could be significantly increased.

9. DEIMOS safety plan was emailed to Dave Cowley on Friday, 10/25/02.

Appendix F

LRIS-ADC Contact List

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Appendix G

Glossary / Acronyms

ADC	Atmospheric Dispersion Corrector
CARA	California Association for Research in Astronomy
CD(R)	Critical Design (Review)
Dashboard	software tool for creating a user interface
DCS	telescope control system used at Keck
DEIMOS	DEep Imaging Multi-Object Spectrograph
ESI	Echelette Spectrograph and Imager
FORS	Focal Reducer low dispersion Spectrograph
FOV	Field of View
Galil	manufacturer of motor/controller systems
GUI	Graphical User Interface
HIRES	High Resolution Echelle Spectrometer
LRIS	Low Resolution Imaging Spectrometer
LRIS-B	blue camera side of LRIS sensitive to UV (0.32 μm up)
LADC	Linear (or Longitudinal) ADC
MMT	Multiple Mirror Telescope
NIR	Near Infrared (1.1 μm - 5 μm)
NIRSPEC	Near Infrared Spectrograph
PD(R)	Preliminary Design (Review)
PI	Principal Investigator
PSF	Point Spread Function
SSC	Science Steering Committee
UCO	University of California Observatories
UV	Ultra-Violet
VLT	Very Large Telescope
ZD	Zenith Distance (distance in degrees from overhead towards horizon)
ZEMAX	Optical analysis software program