Design and Implementation of an Atmospheric Dispersion Compensator/Corrector for the Gemini Multi-Object Spectrograph

Kei Szeto[*a], C. Morbey[a], C. Mayer[b], D. Crampton[a], M. Fletcher[a],
R. Murowinski[a], J. Stilburn[a], P Taylor[b], R. Wooff[a]
[a]National Research Council of Canada, Herzberg Institute of Astrophysics,
5071 West Saanich Road, Victoria, B.C. V9E 2E7, Canada
[b]Observatory Sciences Ltd., William James House, Cowley Road,
Cambridge, CB4 0WX, United Kingdom

ABSTRACT

The Gemini Multi-Object Spectrograph (GMOS) was delivered and commissioned at the Gemini North Observatory and it has been in regular science use since November 2001. While GMOS-North met all its reliability and performance requirements on flexure, image quality and throughput, the high velocity precision (2 km/sec) mode will not be implemented until the Atmospheric Dispersion Compensator/Corrector (ADC) is delivered and commissioned. The ADC optical design incorporating two bonded prism pairs and two corrector lenses is described along with its opto-mechanical and software control design considerations as related to the overall system requirements including: image quality, error budget, optical mounting, opto-mechanical packaging, mechanism control, handling, deployment and telescope observational control considerations.

Keywords: atmospheric dispersion compensator, multiobject spectrograph, optical design, opto-mechanical design, software control

1. INTRODUCTION

Among the first suite of the scientific instruments planned for the Gemini telescopes are two Gemini Multi-Object Spectrographs[1,2] (GMOS). They are workhorse optical spectrographs designed to satisfy a wide range of observational needs, including optical imaging, and long slit, multislit and integral field spectroscopy. In particular, GMOS is designed to exploit the exquisite image quality expected of the Gemini telescopes and capable of the high spatial resolution with velocity measurement accuracy to 2 km/sec. The first of two GMOSs was successfully commissioned at the Gemini Northern Observatory and has been in regular science use since November 2001. While the integration, test and commissioning of GMOS-North and its optical and stability performance are documented elsewhere in these proceedings[3,4,5], the high velocity precision (2 km/sec) mode cannot be implemented until the Atmospheric Dispersion Compensator/Corrector (ADC) is delivered and commissioned. This is currently planned for early 2003.

The GMOS ADC is optimized for the 0.37-1.1 μm wavelength region and for zenith angles up to 60°, and designed for minimal distortion over a 5.5 x 5.5 arcmin. field. In addition, the ADC is also provides partial field correction in order to compensate for the differences between the curved focal plane of the telescope and the flat input object plane of the spectrograph. In the following sections, the various aspects of the GMOS ADC design are presented and the state of development is also described.

[*] Kei.Szeto@nrc.ca; phone 1 250 363-0059; fax 1 250 363-0045; Herzberg Institute of Astrophysics, National Research Council of Canada, 5071 West Saanich Road, Victoria, B.C., Canada, V9E 2E7

2. OPTICAL DESIGN

2.1 Design Considerations

Atmospheric dispersion is a well-known phenomenon to those needing sub arc-second images. Light from stars arrives at the Earth's atmosphere at some angle and since the refractive index of the denser air increases from that of space, the light becomes dispersed and its angular deviation is dependent on the zenith angle. Compensation for the atmospheric dispersion requires that an equal and opposite dispersion be applied to the incoming beam of light. The best place to locate such a compensator would be at a pupil since all regions of the field would be treated the same way. For large reflecting Ritchey Crétien telescopes such as the Gemini this is really not feasible because there is no relatively small diameter imaged pupil before the focal surface. The Gemini spectrograph requires the correction before the slit mask location at the telescope focal surface and so the location of the ADC must be in the converging beam. Such a requirement imposed a further complexity for the ADC design: not only atmospheric dispersion needed to be compensated but the aberrations resulting from prisms in a converging beam also needed to be reduced. And because the prism would be close to the focus they would need to have more power than otherwise. Thicker prisms and/or higher refractive indices for the prism glasses conspire to reduce the throughput.

Another more subtle complexity is the differential refraction across the field, which cannot really be corrected. The reason is that different parts of the beam go through different amounts of different glasses. Resulting prismatic aberrations are complex (Wynne, 1986)[6]. The effect of these aberrations is to cause differential spot shifts over the field as the zenith distance varies and the counter-rotation angles of the prisms change. Normally this "distortion" is small for small prism angles in a slow beam but when the prisms must be close to the focus (therefore more prism leverage required), the effects are significant even in an f/16 beam. The main effect is an overall cylindrical distortion of an object grid when viewed at an appreciable zenith angle as opposed to no zenith angle at all. Wynne suggested the possibility of adding slight cylindrical surfaces to the outer faces of each doublet prism but he admitted that such surfaces would be difficult to manufacture. However, the introduction of cylinder is not likely to help because the prismatic astigmatism is more complicated when a converging beam is considered.

A final requirement was that the focal surface should be as flat as possible. In-focus images over the field result in more uniform slit losses and creates a better spatial correlation between spectrographic and imaging modes of operation. Because the incident beam of GMOS is converging, at least some surfaces of the prism arrangement need to be powered, therefore additional powered elements were introduced to reduce the prism aberrations and to flatten the focal surface.

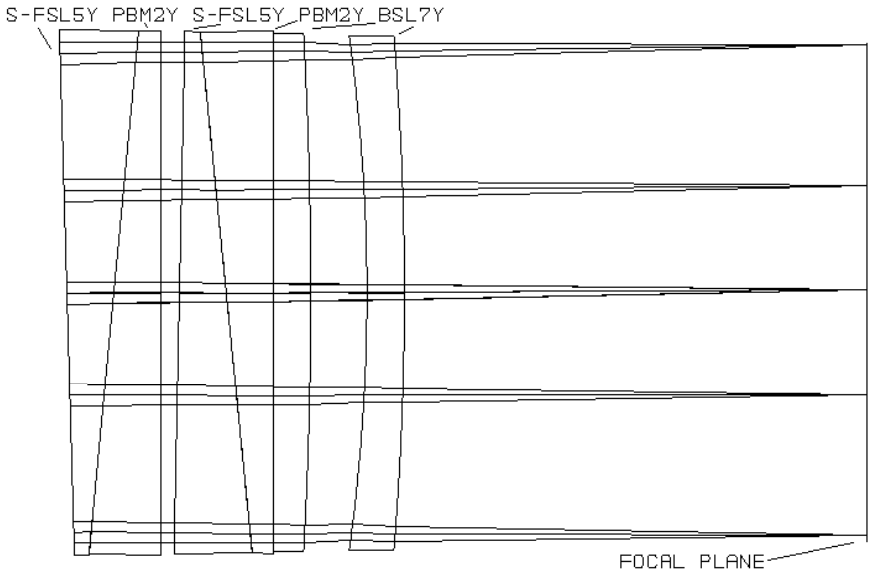

Figure 1 ADC Optical Design

2.2 ADC Design

An optimal solution for the GMOS ADC is comprised of two counter-rotating prism pairs, one element of one pair having a powered surface, and a separate singlet, which helps flatten the focal surface. Such an arrangement is shown in Figure 1. The glass types are specified at the top of the figure. Note that the rightward surface of both prism pairs is perpendicular to the middle ray at zero field angle. Such an arrangement allows the two prism pairs to be counter-rotated concentrically. Note also the placement of the two "powered" singlets: one adjacent the second prism pair and the other, to the right of it. This nearly doubles the radius of curvature of the focal surface and helps reduce prism aberrations. However, the ADC optical design also causes a 46.83 mm shift in the spectrograph focus.

Figure 2 shows image spot diagrams for the telescope without and with the ADC at zenith angles (0,15,30,45,52, and 60 degrees). Each group of 3 spots shows the image sizes (microns) on axis, and 1.5 and 3.5 arc minutes radius off-axis. The top 2 diagrams (without ADC) show the images for the perfect on-axis focus and for the compromise-images-over-the-field focus. The bottom 2 diagrams are the similar cases including the ADC. Note the asymmetric superposition of images resulting from a range of zenith angles (0 - 60 degrees).

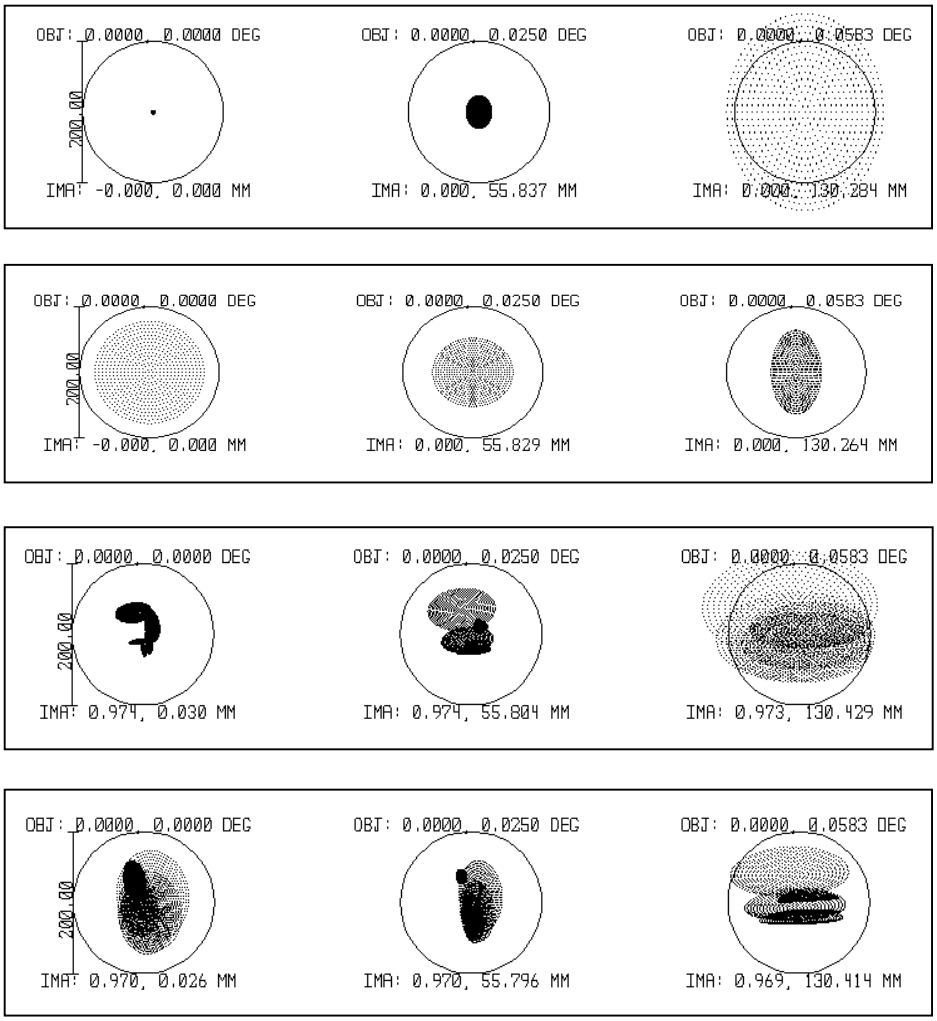

Figure 2. Telescope Image Spot Diagram

Table 1 is a comparison of the ADC performance in terms of the predicted encircled energy diameter (EED) with the pre-slit error budget specifications. These figures assume an overall optimal focus, which brings the design closest to the

specifications. Obviously, different field regions can be improved by an alternative focus. For the most part the 85% EEDs are noticeably better than the specifications.

Table 1. ADC Image Quality

Image quality, in arc sec, compared with specifications, in ()				
	wavelength (micron)	0.37	0.55	1.00
	encircled energy			
on-axis	50% EED	0.07(0.07)	0.07 (0.07)	0.07 (0.06)
	85% EED	0.12 (0.18)	0.13 (0.15)	0.14 (0.13)
off-axis	50% EED	0.09 (0.09)	0.08 (0.07)	0.08 (0.06)
	85% EED	0.14 (0.20)	0.13 (0.18)	0.14 (0.15)

Figure 3 shows the ADC distortion calculated for 6 zenith angles (0,15,30,45,52, and 60 degrees) at 9 field positions. The offsets have been magnified for clarity and should be compared to the size of the 0.25 arcsec (150 microns) slit in the upper right. For each field position and zenith angle, the locations for the no-ADC case are shown shifted to the right. Offsets within 30 degrees are similar in magnitude with and without the ADC, but below 45 degrees the offsets become large and clearly any high precision velocity work should be carried out closer to the zenith. To achieve the highest possible accuracies, the slit masks will need to be designed for a specific ADC configuration. For proper calibration, images taken before and after the spectrographic exposures will be necessary. Velocity offsets can then be calculated from the measured locations of objects within the slits.

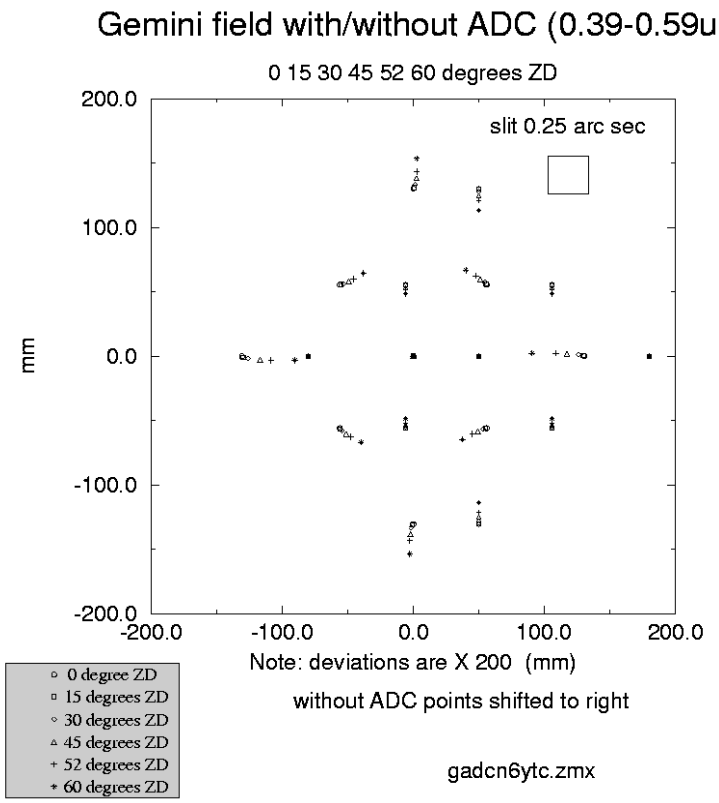

Figure 3. ADC Field Distortion

2.3 Throughput Consideration

A major problem with any refractive optics is the light beam throughput. The ADC uses a total of about 150 mm thickness of 3 glass types selected partly for high transmittance. To maximize the throughput on air/glass surfaces between the lens groups, it was decided to make use of the new sol-gel coating application procedure[7] developed at the National Research Council of Canada. The resulting exceptional throughput predicted is shown in Figure 4.

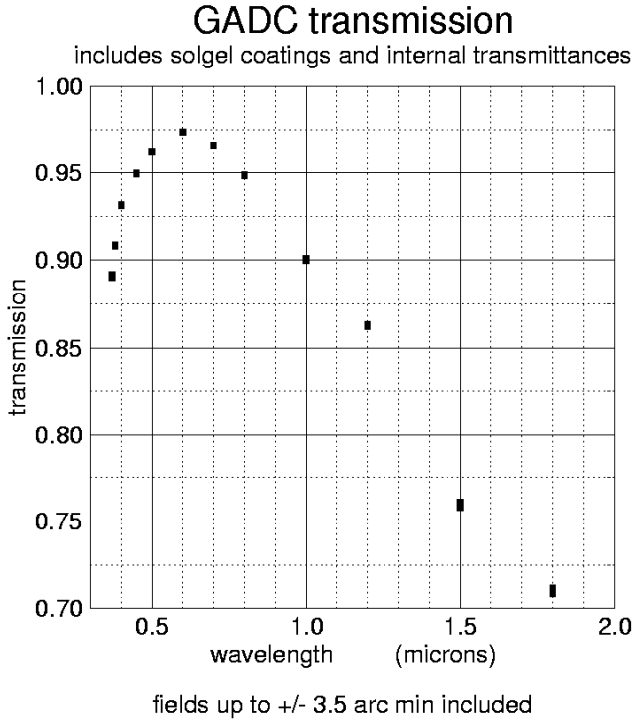

Figure 4. ADC Throughput Prediction

2.4 Fabrication Tolerance

Fabrication tolerances were computed in the normal fashion using the Zemax optical design program. Table 2 listed below is a summary.

Glass refractive index	+/- 0.0005
Glass inhomogeneity	+/- 2.0 x 10^{-6}
Glass bubble content	< 0.25 mm^2 / 100 cc
Glass Abbe number	+/- 0.8%
Glass striae	Ohara Grade A
Prism flatness	< 3 fringes
Prism wedge error	< 3 arc min
Surfaces irregularity	< 4 fringes variation @ 632.8 nm
Axial separations	+/- 0.15 mm
Radii of curvature (lenses)	+/- 2 mm
Decentration (lenses)	< 0.1 mm
Surface quality	60/40

Table 2. ADC Optics Fabrication Tolerance

3. OPTO-MECHANICAL DESIGN

The major opto-mechanical design considerations for the GMOS ADC are:

- Deployment
- Mounting of optics
- Opto-mechanical packaging

3.1 Deployment

Since GMOS is required to operate with and without the ADC, remote deployment was considered at the preliminary design phase. However, remote deployment was deemed to be impractical for introducing the ADC into the optical path especially when it extends the spectrograph focal plane by 48.63 mm from the nominal cassegrain focus[**] of the Gemini telescope. Moreover, the optical design required that the front surface of the first prism group to be 380 mm in front of the focal plane. As a result, this requires the front part of the ADC to be "inserted" inside the Instrument Support Structure (ISS) science port when GMOS is deployed with its ADC. (The science port is the centre opening on the ISS in Figure 5.)

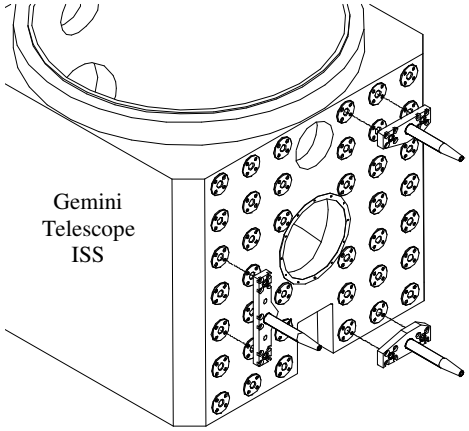

Figure 5. GMOS Locating Pins on the Instrument Support Structure

Given the opening of the science port is 400 mm in diameter, the possibility of collision during instrument mounting due to the small clearance between the lens cell that contains the 305 mm diameter optics and the science port must be considered. The position of GMOS on the telescope is defined by the three locating pins, as shown in Figure 5. When mounting GMOS on the ISS, the locating pins are attached first and GMOS is then mounted by "inserting it on the pins". Features between the ISS mounting face, the pins and three mounting blocks of GMOS control and maintain the positional repeatability, as shown in Figure 6. The radial clearance between the locating pin and the corresponding bore in the mounting block is smaller than the radial clearance between the ISS science port and the ADC lens cell thus eliminating any possibility of collision.

[**] The nominal focus position is 300 mm as defined from the instrument mounting face on the telescope instrument support structure.

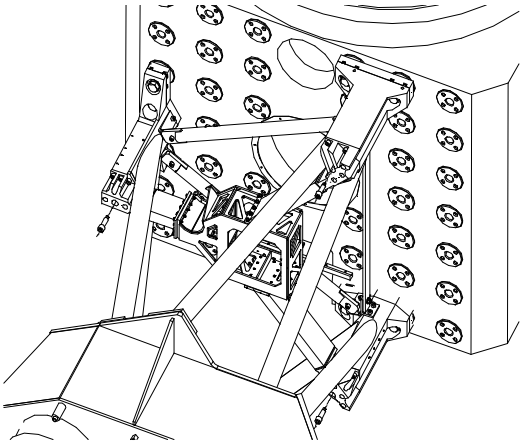

Figure 6. Mounting of GMOS – Mounting Blocks through the Locating Pins

Not shown in Figure 6 is the actual ADC assembly. The ADC assembly that consists of the ADC housing, the triangular structural frame and the spacer frame is shown in Figure 7. The framework matches the three mounting blocks, and the ADC is attached to the front of GMOS prior to mounting on the telescope. Since the ADC assembly is attached to GMOS on the same telescope mounting blocks, i.e. through the same load path, therefore the flexure characteristic of GMOS is preserved. GMOS with ADC is mounted the same way as illustrated in Figure 6. The ADC space frame's 48.63 mm "thickness" provides the required amount of focus shift and the framework also has the same features as the mounting face of the GMOS exterior frame which provides light sealing when mounted on the telescope.

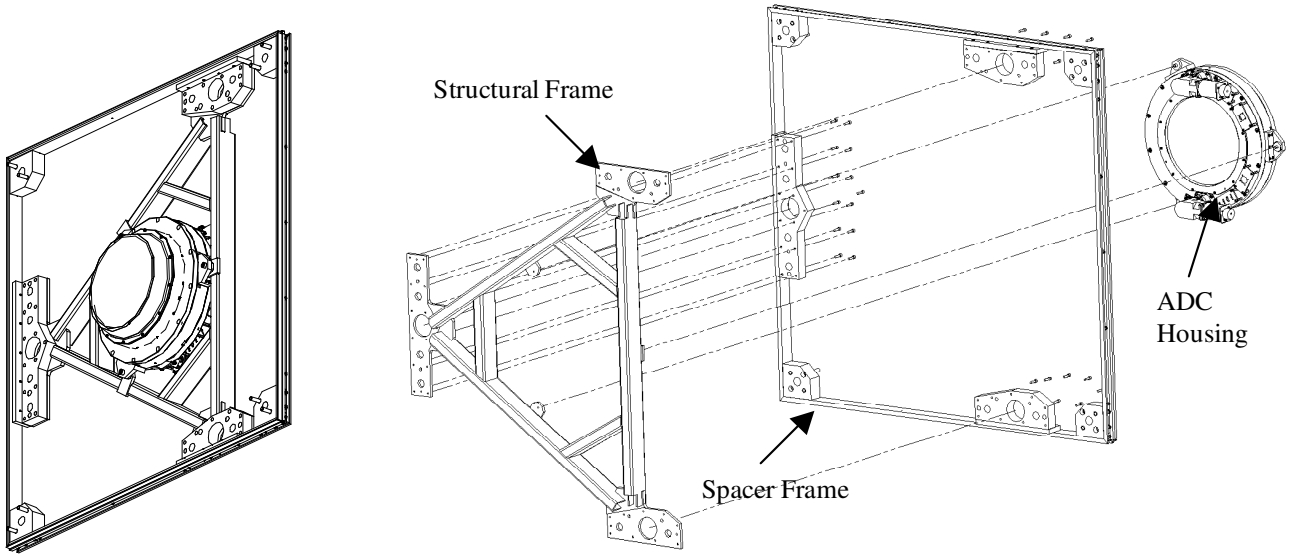

Figure 7. ADC Assembly (Left) and ADC Assembly Exploded View (Right)

3.2 Mounting of Optics

As mentioned that the optics of the ADC is 305 mm in diameter, mounting of large optics is the next design consideration. Figure 8 shows the cross-section of the opto-mechanical layout of the ADC housing. The first prism pair, the second prism group (the second prism pair plus the first singlet) and the second singlet are mounted as three lens groups. Each group is attached to its lens cell by tangential flexures which compensate for the differences in coefficient of thermal expansion between the glasses and the corresponding steel lens cells. Axial athermalization of the lens groups are not required. The mechanical design of the lens mounting is discussed by Bond[8] and by Murowinski[4] in this conference. However, instead of using an optical couplant, the internal air/glass interface between lenses in each prism group is eliminated by bonding the optical elements together with a Norland optical adhesive. The new sol-gel antireflection coating[7] is applied to all external air/glass surfaces to maximize throughput. The thermal stress induced at the boned interface, between 50 °C to –40 °C (survival condition), was found to be at a safe level based on the results from finite element analysis. The actual prisms were temperature cycled between 20 °C to –10 °C (operating condition) in our cold testing facilities and no adverse effect was observed between the bonded interfaces.

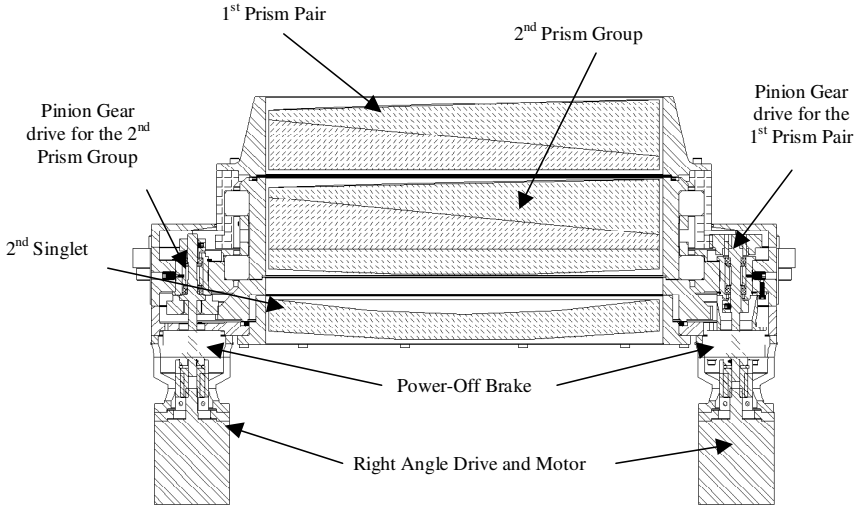

Figure 8. ADC - Cross-Section View

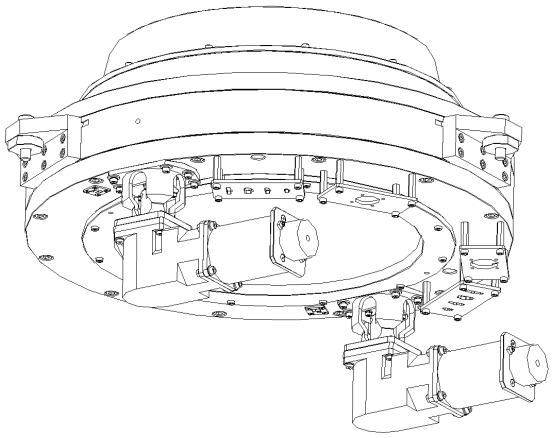

Figure 9. ADC - Isometric View

3.3 Opto-Mechanical Packging

Figure 9 shows the corresponding isometric view and Figure 10 shows the opto-mechanical packaging of the ADC. The space limitation dictates a compact design. Basically, a ring gear is attached to each prism group lens cell and it is driven by a pinion gear through a motor and a right angle gearbox. Rotation is maintained by custom-size Reali-Slim® Kaydon bearings, one per prism group. The pinion gear is mounted eccentrically on bushing such that the proper gear clearance can be adjusted. The first prism group is "stacked" on top of the second prism group. In addition to the 10:1 ratio between the ring gear and its pinion, each pinion is driven by a stepper motor through a right angle gearbox, with 40:1 ratio, the drive system provides more then sufficient angular resolution for each prism group. Moreover, the power-off brake attached to the pinion gear shaft holds the prism angular position, and allowing them to turn independently with respect to the stationary housing. The overall mass of the ADC housing is just over 100 kg.

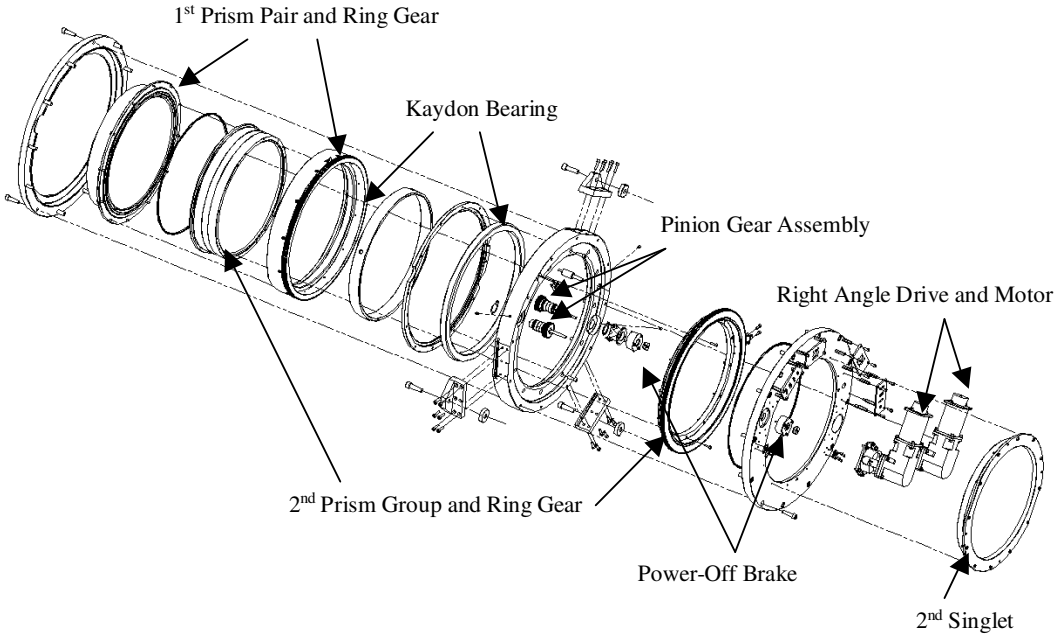

Figure 10. ADC - Exploded View

4. SOFTWARE CONTROL

Control of the GMOS ADC is coordinated through the instrument sequencer component of the GMOS control system. GMOS follows the pattern of a standard Gemini Instrument in that it consists of a separate Components Controller (GMOS CC) and Detector Controller (GMOS DC) together with an Instrument Sequencer (gmSeq) to tie the two Controllers together. The Components Controller and Detector Controller reside in separate VME crates and directly control their respective hardware. The Instrument Sequencer is a software component that runs within the Components Controller crate.

Overall control of GMOS and in particular its sequencing in relation to the Telescope Control System (TCS) is handled by the Observatory Control System (OCS). The hierarchy of control is illustrated in Figure 11.

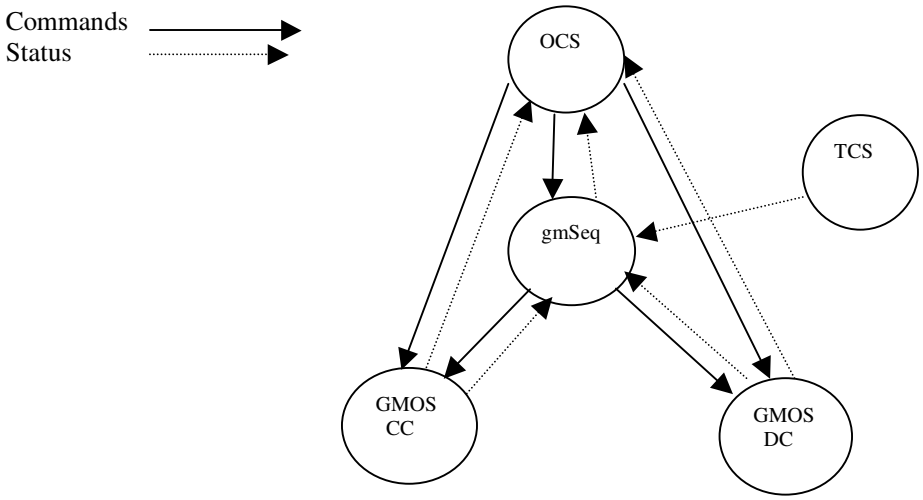

Figure 11. Control Hierarchy within GMOS

Commands flow down from the higher level systems to the lower levels and status flows back the other way. Depending on the command being sent from the OCS, it may go straight to the Component or Detector controller or may go via the Instrument Sequencer.

The normal operational mode of the ADC is to track. In this mode the relative orientation of the prisms within the ADC unit is continually adjusted to correct the dispersion introduced by the atmosphere. The adjustment is based on the zenith angle and refraction as a function of wavelength as computed by the TCS as well as the range of wavelengths over which the observer wants the dispersion corrected.

The formula currently used to compute the relative prism angles is

$$\Delta z = 0.572\left(\frac{1}{\lambda_2 - 0.23} - \frac{1}{\lambda_1 - 0.23}\right)\cos(\theta)$$

where Δz is the difference in refractive index in arcsec as computed by the TCS, and λ is the wavelength in microns.

This formula has been derived from fits to the predictions of the Zemax optical model over a range of different wavelengths.

As well as the relative orientation of the prisms as computed above, the absolute orientation of the ADC must also be continually adjusted to compensate for the changing angle of GMOS as projected on the sky as the telescope tracks the science target. The GMOS ADC software updates both the relative and absolute positions of the prisms every 30 seconds.

The GMOS user interface permits the operator to set the two wavelengths over which the dispersion is to be compensated and then enable the tracking mode. This command and its parameters are passed from the OCS to the instrument sequencer and the command checked for validity. In particular, consistency checks are performed on the parameters and the system checks to see that no interlocks are in place. Assuming there are no problems then the sequencer starts sending periodic updates to the components controller which, in turn, drives the prism motors. Once the system has been set into track mode and assuming the range of wavelengths to be corrected does not change, no further

interaction is needed from the operator. When slewing to a new target the new dispersion corrections are automatically retrieved from the TCS and the appropriate prism angles set.

5. SUMMARY

An ADC optical design that basically offers zenith-quality images at zenith angles down to 60 degrees for the Gemini Multi-Object Spectrograph is presented. However, it introduces some variable image distortion that will limit the zenith angles for which precision velocities can be obtained over the entire field. Similarly, it limits the field over which precision velocities can be measured and requires that slit masks be made for specific zenith angle configurations. For proper calibration, images taken before and after the spectrographic exposures will be necessary. Velocity offsets can then be calculated from the measured locations of objects within the slits.

Based on the optical layout, a corresponding opto-mechanical design is also developed. Because of the space limitation, part of the ADC assembly occupies part of the science port of the telescope instrument support structure when deployed. This introduces specific deployment and handling considerations that were incorporated into the overall system design initially. Consequently, identical telescope mounting and handling procedure have been developed for GMOS with and without ADC. Extra ballast weights are required when ADC is removed in order to preserve the overall mass and centre of gravity position of the spectrograph.

The internal air/glass interfaces of the optical elements are bonded together and external air/glass interfaces are sol-gel coated in order to maximize throughput. The lens groups are mounted to their lens cells via tangential flexures which compensate for differences in thermal expansion. Currently, both sets of ADC optics, one per each GMOS, have been procured (based on the fabrication tolerance outlined in Section 2.4), mounted and coated. One ADC housing has been assembled; and prism rotation was tested with both motors powered under low-level software control. Two ADC frameworks were fabricated and test fitted with the ADC housing and with the GMOS structure before GMOS-North was delivered.

Remaining work for the ADC-North is flexure and cold tests, and motion control test using the high-level software control described in this paper. In addition, validation of dispersion characteristics, image quality and throughput via direct laboratory measurements will be conducted. Acceptance test and delivery by the end of 2002 is expected.

ACKNOWLWDGEMENTS

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