GEMINI · PROJECT
NEWSLETTER

THE GEMINI 8-METER TELESCOPES PROJECT is managed by the Association of Universities for Research in Astronomy for the National Science Foundation under an international partnership agreement.

January 1994 / Number 7

Gemini Project Overview

The end of the year is a good time both to review what has already been accomplished and to look forward to what must still be done. Much of the work that has been completed is described in the articles in this newsletter, but the highlights include the following:

1. Chile, Argentina, and Brazil signed Memoranda of Understanding indicating their intention to join the project, thereby providing the final 10 percent of the required funding.

2. All of the boules for the first meniscus primary have been manufactured by Corning. The option for the second meniscus mirror has been exercised. (Corning has also successfully fused the boules for the Subaru primary mirror.)

3. A contract for polishing of the primary mirrors has been negotiated, contingent on approval by AURA, the Gemini Board, and the NSF. As soon as those approvals have been obtained, we will announce the vendor. The polishing schedule is consistent with the overall project schedule, which calls for first light on Mauna Kea in 1998 and on Cerro Pachon in 2000.

4. Negotiations are well underway with the likely manufacturer of the enclosures.

5. The Conservation District Use Application, which must be approved before construction can begin on Mauna Kea, was submitted by the University of Hawaii on behalf of the project at the end of December.

6. A specific site (the so-called prime site) on Cerro Pachon was selected as the location of the southern Gemini telescope.

7. Contracts have been let for the design of the road and the power line to Cerro Pachon.

The next twelve months should see the commitment of all of the major outside contracts. The critical design review for the telescope mount will be held in the spring. The plan for instrumentation will be presented to the Gemini Board in May. And we hope to break ground for one — and possibly both — telescopes during this calendar year.

— ***Sidney Wolff***
Acting Project Director

TABLE OF CONTENTS

Project Manager Appointed

Richard Kurz has been appointed Project Manager for the Gemini telescopes project, and he assumed the position at the beginning of January. Dick was formerly at TRW, where he was most recently a proposal development manager. In this capacity he was responsible for new business proposals to government agencies, primarily NASA and the Department of Defense. Prior to that assignment, he was deputy project manager of a $200M project to design and build a spaceborne electro-optical system. Dick has a Ph.D. in physics from the University of California at Berkeley.

New Appointment to the AURA Corporate Office

AURA is pleased to announce the appointment of Mr. Richard N. Malow as Special Assistant to the President for International Relations.

Malow left his post as the Clerk of the VA, HUD, and Independent Agencies Subcommittee of the House Appropriations Committee in January. During his 21 years on Capitol Hill, Malow had responsibility for more than 70 appropriations accounts for 20 Federal agencies, including the National Science Foundation and NASA. Formerly, Malow served in management positions in the Department of Agriculture and the Overseas Development Council. Malow will join the AURA Corporate Office officially on April 1, 1994.

Preliminary Design Review of the Primary Mirror Assembly

The Preliminary Design Review (PDR) of the primary mirror assembly (PMA), which includes the mirror support and thermal control systems, was held in Tucson on December 6, 7, and 8. The design review was open by invitation, and about 50 people attended the review.

The executive summary of the committee's report reads as follows:

"The Gemini Project Primary Mirror Assembly (PMA) Preliminary Design Review Committee (PDRC) met December 6-8, 1993 to conduct a preliminary design review (PDR) of the Gemini Project Team's approach to attaining the scientific objectives of the Gemini Project with a thin ULE meniscus primary mirror. We find that the Gemini Project Team has made significant progress during the past 10 months on the evaluation and design of PMA to support the meniscus mirror, although some subsystems are not ready to proceed to the detailed design phase. We are unanimous in finding that the present design approach will lead to the successful development of a PMA that will enable the thin meniscus to achieve the scientific performance requirements specified by the Gemini Project Science Requirements Team under most observing conditions. The risk associated with most of the technologies to be employed is acceptable. Several proposed subsystems require prompt experimental evaluation. In some cases, alternative parallel paths should be pursued to a decision point well before the critical design review (CDR). We have identified actions required to bring

all subsystems to readiness for the detailed design phase, and believe that progress toward the goal of a CDR for all subsystems of the PMA about a year from now is encouraging.

Cost and schedule for the PMA were not presented by the Gemini Team at the PDR. Very careful cost evaluation and earnest consideration of simplifications to the base-line design will be required to fully assess the degree of risk in this area. We believe that cost containment requires adherence to a well defined schedule."

The committee was "*unanimous in finding that the present design approach will lead to the successful development of a PMA that will enable the thin ULE meniscus primary mirror blank selected by the Gemini Project to achieve the scientific performance requirements specified by the Gemini Project Science Requirements Team under almost all expected operating conditions. Many of the design approaches to be employed in the implementation of the PMA have been proven at some level in other operational telescope systems. Other approaches being considered have been used effectively in other scientific and engineering applications. The untried approaches that require further development can be promptly evaluated in limited research and development efforts that have already been initiated by the Gemini Team. In some cases, alternate parallel paths should be pursued to a decision point well before the critical design review (CDR).*"

The committee did, as do all design review committees, identify a number of action items for the project team. These had to do with such detailed engineering issues as the optimization and placement of the supports; possibilities for simplifying the design; the interface between the supports and the primary mirror; the completion of detailed modelling of the effect of temperature and CTE variations on surface shape; and the incorporation of adequate fail-safe systems to prevent damage to the primary mirror.

It is the practice of the Gemini project to respond to *all* issues raised by design review committees, and the project is currently carrying out the work necessary to respond to the questions raised in this review.

The project wishes to express its appreciation to Bob Gehrz, who chaired the review, and to the other members of the committee. The expertise and thoroughness that they brought to this review will be extremely helpful to the project as we proceed with the detailed design of the PMA.

— ***Sidney Wolff***
Acting Project Director

Gemini Board Members

The December meeting of the Board was the first to be attended by representatives of Argentina, Brazil, and Chile. Juan Forte represented Argentina, and Joao Steiner represented Brazil. Claudio Anguita, who served for many years on the AURA Board, is now the Chilean member of the Gemini Board.

The December meeting was the last to be chaired by Bob Bless. The project team is very grateful to Bob for his steady leadership during the difficult two years when the project was being established. Malcolm Longair (UK) will be the chair of the Board in 1994-1995. Alan Dressler (Carnegie) will replace Bob as one of the US representatives.

Gemini Board
— Action Items and Motions —

At its meeting in December, the Gemini Board took the following actions:

- Set the next meeting dates as May 23-24 in Santiago. The meeting will be preceded by a visit to Cerro Pachon.
- Approved the budget for 1994.
- Noted that the Project intends to exercise the option to order a second mirror from Corning.

Gemini Director Search

A search is in progress for a permanent Director of the Gemini Telescopes project. The search committee is chaired by John Huchra (Center for Astrophysics). Nominations of candidates are encouraged and should be sent directly to John.

— *Sidney Wolff*
Acting Project Director

- Noted and encouraged the Project's plans for systems level reviews.
- Noted and concurred with the general direction taken by the Project with respect to the polishing of the primary mirrors.
- Reaffirmed the intention of providing from time to time a silver coating on the primary of the Mauna Kea telescope.

The Board also passed the following resolution:

"The Gemini Board has received a very favorable preliminary report from Dr. Gehrz on the outcome of the primary mirror PDR. This report has strongly endorsed the approach adopted by the project to the solution of the many problems imposed by the ambitious design specifications of the Gemini Telescopes. The performance of the Project Team and its collaborators in the partner countries was outstanding throughout the review, and the Board unanimously passes on its warmest congratulations to all concerned."

— *Sidney Wolff*
Acting Project Director

Project Scientist's OUTLOOK

In preparation for the Primary Mirror PDR, the Gemini Science Committee set up the Science Working Group (SWG) to undertake a thorough review of the performance of the primary mirror system being proposed for the Gemini telescopes. This group met twice in Tucson, September 10-11, 1993 and November 18-19, 1993 and attended the PDR on December 6-7, 1993. During this time the SWG reviewed a broad range of written and presented material and had extensive discussion with the Gemini Project team. The following is a summary of our deliberations and conclusions from the PDR.

Error Budget

As the Gemini Telescopes are complex systems, the individual contributions to the final 0.1 arcsecond focal plane image quality are broken down into a hierarchical error budget. The 2.2 micron 50% encircled energy error budget is shown in ***Table 1***. The relevant entries for the primary mirror have been highlighted. The error budget tracks and quantifies individual contributions from the optics, active control system, wind buffeting, and tracking; from image quality degradations induced by the telescope structure and enclosure; and from temperature differences between the ambient air and optical surfaces. At 2.2 microns both the 50% and 85% encircled energy diameters are tracked individually. Each contribution to the total error

Title	Error Budget				
Level	1	2	3	4	5
1.0 Image Quality	**0.100**				
1.1 Static Image Quality		0.093			
1.1.1 Optical Design			0.065		
1.1.1.1 Diffraction Size				**0.065**	
1.1.1.2 Field Angle Position				0.000	
1.1.2 Surface Errors			0.043		
1.1.2.1 Primary				**0.036**	
1.1.2.1.1 Polishing Residuals					**0.015**
1.1.2.1.2 Support Residuals					**0.010**
1.1.2.1.3 Thermal Distortion					**0.005**
1.1.2.1.4 Wind Buffeting					**0.030** (.005 low wind)
1.1.2.1.5 Coating Thickness					**0.004**
1.1.2.2 Secondary				0.021	
1.1.2.2.1 Polishing Residuals					0.015
1.1.2.2.2 Support Residuals					0.010
1.1.2.2.3 Thermal Distortion					0.005
1.1.2.2.4 Wind Buffeting					0.010
1.1.2.2.5 Coating Thickness					0.003
1.1.2.3 Active Control				**0.010**	
1.1.3 Alignment of Optics			0.017		
1.1.3.1 Secondary Decenter				0.010	
1.1.3.2 Secondary Defocus				0.010	
1.1.3.3 Secondary Tilt				0.010	
1.1.4 Self Induced Seeing			0.049		
1.1.4.1 Enclosure				0.045	
1.1.4.2 Telescope (thermal seeing)				0.018	
1.1.4.2.1 Primary Mirror Delta T					**0.010** (.04 low wind)
1.1.4.2.2 Decondary Mirror Delta T					0.004
1.1.4.2.3 OSS Structure Delta T					0.015
1.2 Dynamic Image Quality		0.018			
1.2.1 Dynamic Optical Alignment			0.015		
1.2.1.1 Pointing				0.010	
1.2.1.2 Primary Seondary Decenter				0.006	
1.2.1.3 Primary Secondary Tilt				0.001	
1.2.1.4 Primary Secondary Defocus				0.010	
1.2.2 Coma Induced by Atmos. Tilt Correction			0.010		
1.3 Image Smear		0.030 (.01 low wind)			
1.3.1 Wind Shake			0.028		
1.3.2 Measure Error			0.003		
1.3.3 Other Errors			0.011		

Table 1. The Gemini error budget for the f/16 focus at 2.2 microns for the 50% encircled energy diameter.

budget is quantified by the quadratic difference from the 2.2 micron diffraction limited profile, expressed in arcseconds on the sky. This allows the overall error budget to be expressed as the quadratic sum of the differences from diffraction — 0.065 arcseconds. In the diffraction limited regime at 2.2 microns, this procedure is recognized as an approximate method for tracking optical errors. However in most cases the Project did do a full diffraction calculation and used the quadratic difference from diffraction as a convenient 'house keeping' tool. Simulations using the full diffraction calculations of the optical design program CODE V for representative optical telescope errors show that at the level of 0.01 arcseconds this methodology gives acceptable results.

Given the above discussion the SWG accepted this approach to quantifying the individual error contributions to the final 2.2 micron image quality requirement as long as both the 50% and 85% encircled energy contributions were always considered.

A key assumption of the error budget is that the telescopes are operated in an active mode.

In this 'active mode' wavefront tip/tilt, which results from wind shake, wind buffeting and atmospheric turbulence, will be taken out by rapidly articulating the secondary mirror at 10 - 40Hz using a fast guiding loop. Slow wavefront errors with frequencies less than 0.003 Hz, resulting from optical misalignments and distortions of primary and secondary mirrors due to flexure, wind buffeting and thermal gradients, will be measured and corrected using an active optics loop. A wavefront sensor will provide this information by monitoring a star in the periphery of the Cassegrain guide field.

The error budget tracks only residual errors after correction. Consequently, allowance for wavefront sensor measurement errors, servo loop bandwidth, and lag effects inherent in tip/tilt and the active optics corrections are explicitly included in the Gemini error budget.

In general the SWG accepted that the project had allowed a reasonable distribution of image quality errors in the various error budget categories.

Wind Buffeting

A principal concern inherent in the meniscus mirror approach is the effect of wind buffeting of the primary mirror while the telescopes are operating on windy sites like Mauna Kea and Cerro Pachon. Primary mirror wind buffeting is allocated 0.03 arcseconds in the Gemini error budget.

The science requirements call for the telescope to meet the image quality in winds up to 11 m/s (24.75 mph) outside the enclosure. The telescope is housed in an enclosure which is designed to protect the mirror from the free stream wind. However, the telescope must observe through an open slit, often at quite low elevations in arbitrary directions. In addition, as will be discussed in more detail later, the enclosure must allow a certain amount of wind flushing of both the enclosure and primary mirror surface to reduce the effects of 'dome' and mirror seeing.

Given that the enclosure can provide a certain level of wind attenuation, a key concern of the SWG was to establish the limiting velocity for operation within the error budget.

The Gemini mirror support system resists the dynamic wind buffeting (at frequencies > 0.003 Hz) by supporting the mirror on a passive hydraulic whiffletree, coupling the mirror to a stiff steel mirror cell through six zones on the whiffletree. Slow ($f < 0.003$) 'quasi-static' wind-induced distortions are corrected by active optics force actuators, which work in series with the passive hydraulic supports. To model the behavior of the Gemini mirror, two aspects of 'wind buffeting' must be addressed - the temporal and spatial wind-induced pressure fluctuations on the mirror surface. The Gemini Project approached this modeling in two ways:

Modeling the mirror and support system as a static system

A key issue is the form of the wind input spectrum (both spatial and temporal). Little real wind data has been measured in the vicinity of primary mirrors in real telescopes. In addition, it is a fairly challenging task to collect reliable data for pressure variations from 0.003 Hz through ~ 30 Hz with sufficient dynamic range. Consequently, Earl Pearson constructed a model for the wind pressure spectrum at the primary mirror. This model assumed a Kolmogorov spectrum for frequencies 0.01Hz - 1Hz exterior to the enclosure and an acoustic spectrum for frequencies greater than 1 Hz. The influence of the enclosure at the mirror surface was modeled assuming simple geometric attenuation for the quasi-static pressures less than 0.01 Hz and conservation of energy for frequencies > 1Hz, using a logarithmic interpolation for intermediate frequencies. Earl also included an 'organ pipe' wind resonance at 8.8Hz to account for standing waves set up between the primary mirror and the interior of the enclosure.

Two data sets the project did obtain are plotted in ***Figure 1a***, which compares torque measurements made at the MMT, converted to pressure spectral density, and pressure measurements made at the surface of a dummy mirror inside the NNT enclosure by ESO. Both sets show reasonable agreement with the Gemini wind model.

An essential step in the calculations was to find a way of separating the temporal calculations from the spatial calculations to simplify the analysis. To give some measure of the complexity of this problem, a full three dimensional hydrodynamic calculation of the static distributions of

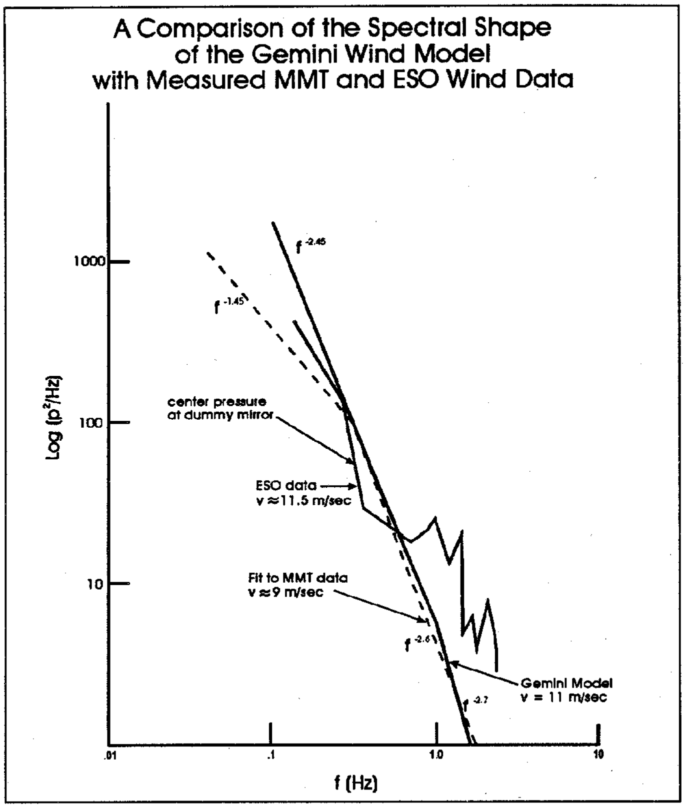


Figure 1a.

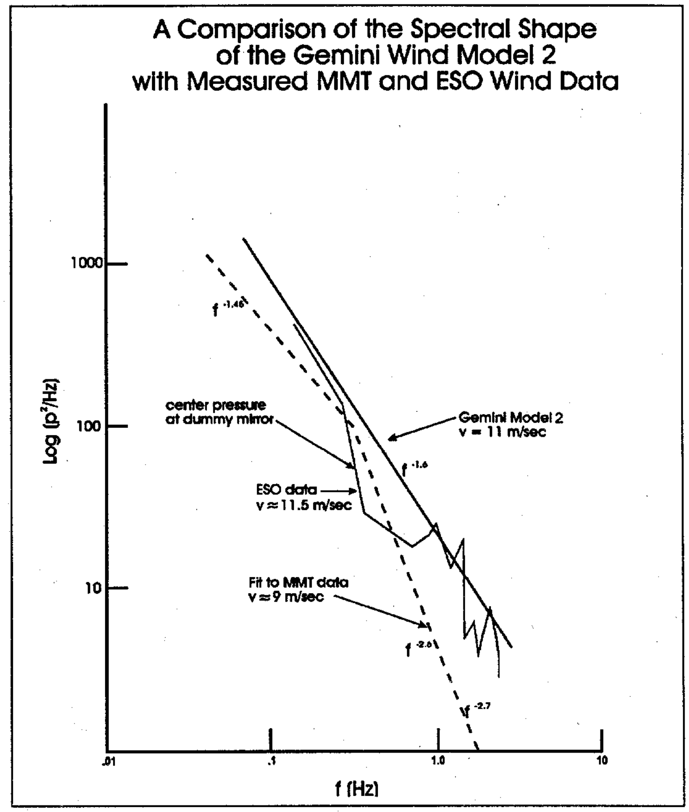


Figure 1b.

pressure on an inclined disc (9 metres in diameter and with 3meter thickness) in a 11 m/s wind was done by Dave De Young (NOAO) — each inclination took 5 hours of CPU time to compute on a Cray (***see Figure 2***).

Finite element analysis (FEA) established that the first elastic resonance of the mirror on its support system is a focus mode at 26Hz (on a six zone whiffletree), the next two being astigmatic modes at 31 Hz and the fourth at 41 Hz. Using the model wind spectrum as an input and applying this to the FEA mirror support model, the dynamic response of the mirror surface was found to be within a few percent of simple static calculations. This is because the model wind spectrum at the primary mirror has over 95% of the wind energy below 10Hz, a common characteristic of measured wind spectra (***see Figures 1a and 1b***).

A simple way to visualize this result is to look at the response of a simple damped oscillator. If a major fraction of the excitation energy is at frequencies well below the resonant frequency of the oscillator, the deflection $\hat{\mathbf{x}}$ of the spring will be very close to the value resulting from a constant (static) force. For example, for a forcing function F(ω);

$$\frac{F(\omega)}{m} = \ddot{x} + \gamma\dot{x} + \omega^2 x\,,\ \hat{\mathbf{x}}\ \mathit{at}\ 10\,Hz \approx 1.17\hat{\mathbf{x}}\ \mathit{at}\ 0\,Hz,$$
$$\textit{with a resonant frequency of } 26Hz$$
$$\textit{for damping values between } 0.01 \le \gamma \le 10$$

A closer look at the measured ESO wind spectrum in *Figure 1* shows a possible high frequency "tail". To confirm that there was not sufficient energy in this type of "tail", even if real, to excite the first resonant frequency of the mirror on its support, a second model (***Figure 1b***) was used to drive the primary mirror surface. For a range of viscous damping values from 1% - 10%, the dynamic mirror deflections were again within a few percent of the simpler static deflections.

ESO have provided Gemini with data taken from thirteen pressure sensors across a dummy mirror placed at various orientations in the NTT and ESO 'inflatable' NTT enclosures. The pressure patterns are characterized as static

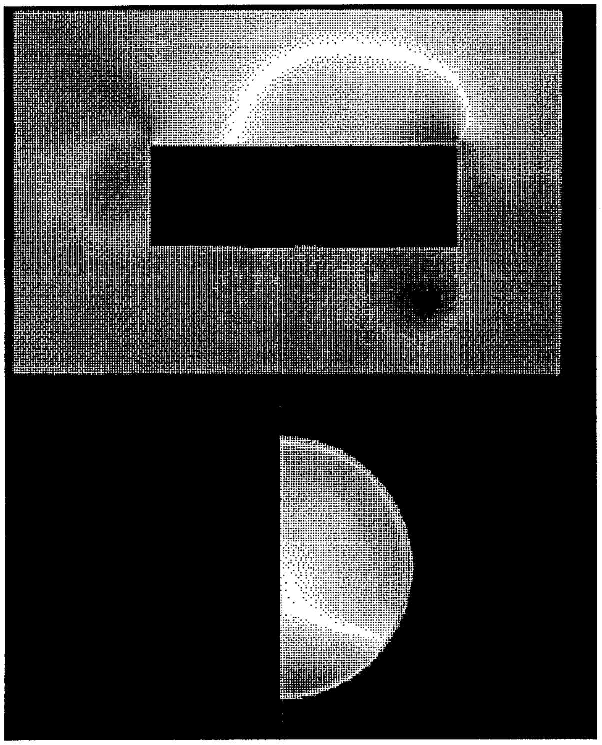


Figure 2. Results of a three-dimensional hydrodynamic calculation of the static pressure variations across a simulated Gemini mirror and cell at a zenith angle of 60 degrees in a 11 m/s wind. The upper figure shows the cross sectional view of the pressure variation around the mirror and cell with the wind impinging on the top surface at an angle of 60 degrees from the right. The bottom view shows the calculated pressure variations across the front of the mirror and is similar to the patterns measured by ESO.

pressure variations (f < 0.02 Hz) and rms pressure variations for f > 0.02 Hz. These spatial patterns have a qualitative similarity to the static calculations of Dave De Young, (*see Figure 2*). With the worst orientation of both the static and dynamic patterns, the Gemini mirror and support system could withstand the rms pressure fluctuations equivalent to wind velocities up to ~ 3-4 m/s across the primary mirror and remain within the 0.03 arcsecond error budget. The bulk of the deflections come from focus errors. A fast focus correction with the secondary mirror at f ~ 3Hz would move the most significant deflections up to the astigmatic modes with excitation frequencies at ~ 30 Hz.

An independent dynamic model

As a cross check of this method, a completely independent and novel FEA approach was developed by Earl Pearson. Using tapes of the original ESO data sets from the 13 pressure sensors across the dummy mirror, wind pressure patterns as a function of x, y, and t were applied to the mirror. The spatial and temporal response of the mirror could then be simultaneously quantified every 1/50 second for a complete 80-second run. Using the data from the fully open (inflatable) enclosure experiments showed that the Gemini mirror could resist wind buffeting for pressure variations ~2-3 Pascals and not exceed the error budget of 0.03 arcseconds. Scaling this from the measured ESO wind velocities, showed a Gemini mirror could tolerate winds across the primary mirror surface of 6 - 10 m/s depending on mirror elevation angle. Again the most significant response was from the azimuthally symmetric defocus mode.

In summary the SWG concluded the project had demonstrated that in the frequency range ~0.01Hz to ~2Hz the Gemini Primary Mirror support system would give satisfactory resistance to wind buffeting. To fill in the "frequency gap" between where the data sets stop at ~ 0.02 Hz and where active optics becomes effective at ~ 0.003 Hz a Davenport spectrum was used (reference Quart.J.Roy.Met.Soc 87, 194 [1961]) assuming no enclosure attenuation.. At these low frequencies, even at 11 m/s wind speed, we are looking at spatial wavelengths ~ 550m - 3.7km, so within an enclosure behind a 10m slit this is a fairly conservative assumption. These wavelengths are also too large to excite any "organ pipe" resonances within the 30 meter diameter Gemini enclosure. Examining the enclosure design and watching an extract from the water tunnel tests it was reasonable to assume that the exterior wind velocities up to 20 m/s could be attenuated to 3-5 m/s in the vicinity of the primary mirror. This gives the Project significant margin in meeting the science requirements up to 11 m/s wind speed outside the enclosure.

Mirror Seeing and Thermal Control System

The second principal scientific concern of the meniscus mirror approach is the accuracy to which the front surface of the mirror can follow changes in the ambient air temperature. Temperature differentials at the mirror surface can cause convective eddies, and the resulting turbulent

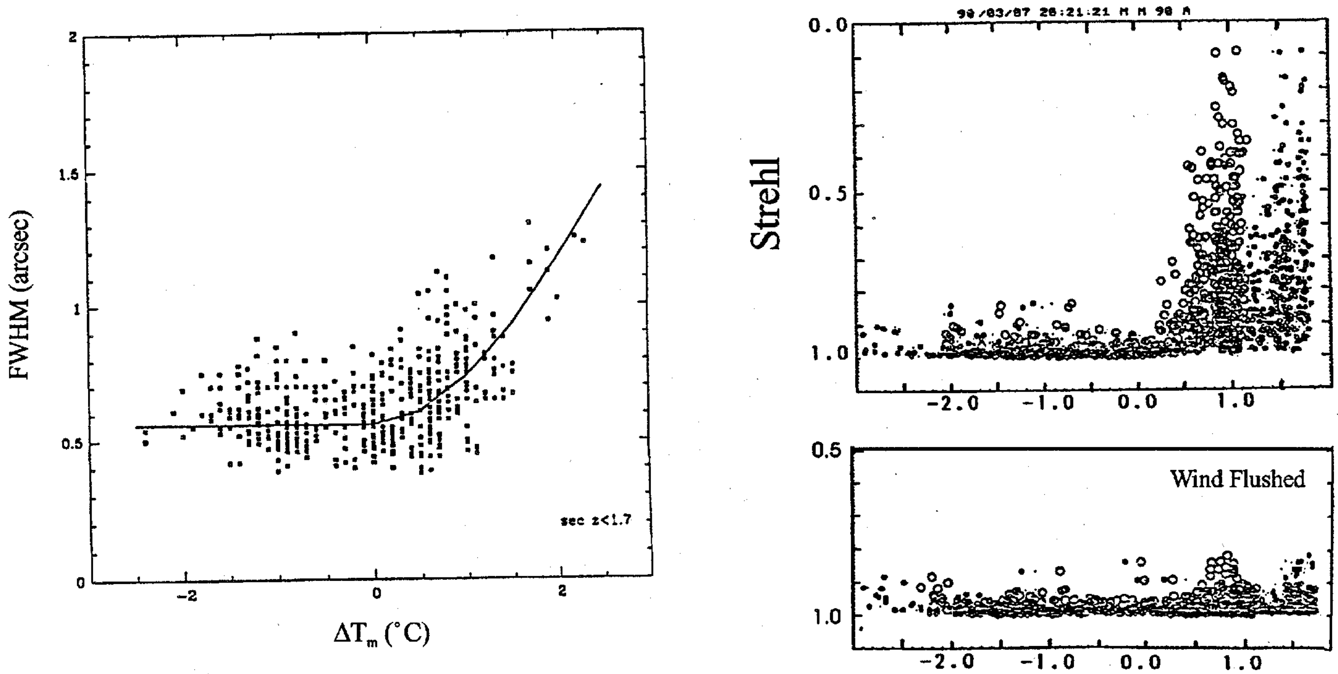


Figure 3. Mirror seeing data taken from Racine (Ref. 1) and Iye (Ref. 2). Racine plots FWHM (arcseconds) as a function of mirror temperature difference from ambient taken from CFHT measurements. Iye uses Strehl Ratio (plotted 1.0 - 0.0) as a function of mirror temperature difference from ambient found during laboratory experiments using a 62 cm mirror and a Shack-Hartmann sensor. Both data sets suggest weak dependence on visible seeing when the mirrors are cooler than ambient air.

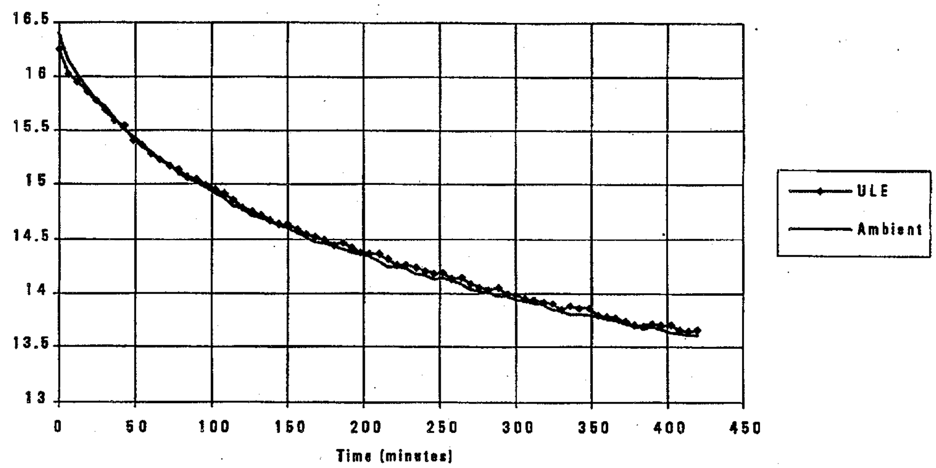
behavior of the temperature structure above the mirror surface can degrade the final optical image quality through 'mirror seeing'. The enclosure and telescope structure can also contribute to thermal seeing effects through similar differentials. For example, to reduce 'enclosure seeing', the enclosure has been designed to have a low thermal time constant so it can be flushed effectively either by the wind or active ventilation. The SWG accepted the 2.2 micron 0.04 arcsecond error budget allocation for primary mirror seeing in low winds.

Relating temperature differentials to mirror seeing values

The principal difficulty facing the SWG is that there is very little quantitative data at even the 3m - 4m scale to associate mirror surface temperature differentials with image quality degradation at the levels relevant to Gemini. Especially difficult is separating the effects of mirror seeing from enclosure seeing in conventional telescope enclosures. Two of the most recent data sets are shown in ***Figure 3***. There are no measurements at infrared wavelengths of mirror seeing.

After considerable discussion the SWG endorsed the Project's use of a temperature tolerance band for the mirror surface temperature difference between ambient of $-0.6°C < \Delta T < 0.2°C$, where $\Delta T = T_m - T_a$, which is the same range adopted by the ESO-VLT project. This assumes moderate flushing, and the Project proposes using the Zago curve (ESO Technical report) to scale the mirror seeing with wind flushing rate. The evidence that exists shows a weaker dependence on mirror seeing when the mirror is cooler than ambient, particularly for low wind flushing rates ***(see again Figure 3)***. To scale the optical relations to infrared wavelengths, the Project adopted the conservative approach of using the Kolmorogov 5/3 power law assuming the mirror turbulence is homogenous and isotropic — thermal seeing then scaling as $\lambda^{-1/5}$.

Temperature control achieved in test:



Primary mirror thermal management system PDR presentation
RJS Greenhalgh CEng M I Mech E, Engineering Division, RAL

Figure 4. Laboratory results from the coating heating experiments using a sample of 200mm thick ULE glass, which show the ambient and surface temperature as a function of time. The ULE was cooled from the back surface using a radiation plate with the front surface being controlled (using a simple commercial controller) through resistive heating of the reflective coating.

The proposed thermal control strategy

The Project plans to precondition the primary mirror to slightly below the next night's starting temperature and then during the night to slowly adjust the mirror surface temperature using a heating or cooling plate radiatively coupled to the back surface of the mirror. This is a design adapted from the ESO-VLT project. If additional margin in the control system is required, it appears practical to heat the mirror front surface by resistive heating. A prototype system under development in the UK is being used to evaluate this concept. Laboratory results using a sample of 200mm thick Corning ULE glass is shown in ***Figure 4***. The ULE was cooled from the back surface using a radiation plate with the front surface being controlled (using a simple commercial controller) through resistive heating of the reflective coating.

To assess the performance of these approaches, the Project in discussion with the SWG agreed to 'test' the control algorithms using a year's worth of Mauna Kea ambient air temperature and wind data. This would give a thorough statistical test of the ability to predict the forthcoming night's initial temperature and the subsequent ability of the control system to follow the nightly temperature changes in the presence of real wind and temperature data.

Results and recommendations

To bound the variations in prediction algorithms, the Project used two prediction simulations. The first assumed that the prediction was perfect, and the second, "carbon copy", used the previous night's temperature as the best guess, which gave an rms error of 1.2°C in the start temperature. ESO and initial work by the Project have shown prediction algorithms that can predict the next night's temperature on Paranal and Mauna Kea to 0.6°C rms and 0.8°C rms respectively. For Mauna Kea, the Project used data sets from the CFHT, which included wind data, and the NOAO site survey, which included good/bad night flags.

The results were assessed at 30 second intervals throughout the year — the time for which the mirror surface was within -0.6°C and 0.2°C between astronomical twilight and sunrise ranged from 50% - 80%. The variations depended on the data set and prediction algorithm used. The differences in the results between the CFHT and NOAO data sets, which were sampled and averaged in similar intervals, were as great as the variations produced by the two prediction algorithms. For example, in the NOAO data sets, the temperature variations between simultaneous measurements from sensors at heights of 11m and 27m had an rms of 0.6°C. It was also noted that for nights flagged as good in the NOAO data set (cloud cover < 30%), there was a significant improvement in the system performance, with results changing from 65% to 73% for the amount of time the mirror surface was within $-0.6°C < \Delta T < 0.2°C$.

With a mirror surface heating model, (using two different models to simulate non-uniformity effects) the time the surface was within the temperature tolerances rose to 80 - 90% depending on the data set and prediction algorithm used.

There are real uncertainties in relating temperature differences to infrared mirror seeing values. Examples are:

(a) Uncertainties in defining an appropriate 'ambient temperature' and hence a real uncertainty in relating temperature differentials to mirror seeing values.

(b) The difficulties of separating mirror effects from enclosure effects when considering measurements of thermal seeing made in conventional telescope enclosures.

(c) When a mirror is cooler than ambient, mirror seeing may be a much weaker phenomena than assumed by the project. When surfaces are cooled, a real asymmetry in the heat transfer rates occurs since the direction of the buoyancy force (associated with convection) is reversed and acts with gravity to increase the pressure on the surface layer. The data of Iye et al. (1991, ***Figure 3***) shows a dramatic asymmetry in the **measured** Strehl ratios resulting from the turbulence from a warmed surface compared to a cooled surface (both in the flushed and non-flushed cases). SUBARU, for example, are assuming this to be the case and are using a range of $-2.0°C < \Delta T < 0.0°C$ for their primary mirror. Recent measurements taken on the 4.2-m WHT may give further credence to this view — mirror seeing values of 0.006 - 0.012 arcseconds were calculated from the measured structure function when the mirror was 2°C cooler with moderate flushing (Jenkins et al. in prep.).

(d) When the mirror is cooler than ambient and inclined from the horizontal, or when wind flushing rates across the mirror > 2 m/s, hydrodynamic calculations show that the turbulent layer is confined to a thin layer on the mirror surface. It is likely that this turbulent layer is the source of 'mirror seeing'. An essentially two-dimensional layer would have a disproportionately smaller affect on the 2.2 micron 50% encircled energy diameter than the more conservative 5/3 homogenous and isotropic Kolmogorov scaling law would predict from optical measurements. Initial measurements of microturbulent structure above the WHT mirror show a structure function shallower than Kolmogorov (Jenkins et al., in prep.).

The SWG concluded that the proposed thermal control system for the Gemini primary mirror will allow sufficient control of the Primary mirror surface to meet the Science Requirements. Given the large uncertainties in the input data, physics, and results from the modeling, the SWG recommended that the mirror heating development be continued since it gives the control system a substantial added level of capability to control the surface temperature of the primary mirror to meet the requirements. In addition, as a cautionary note, for 5% of the time on Mauna Kea the dewpoint is within 1^{0} C of the air temperature which could cause dewing of the mirror if it is cooled substantially below ambient. The resistive surface heating could be used to protect the mirror surface in conditions of high humidity and avoid the potential loss of 17 observing nights/year on Mauna Kea.

Mirror Cell Modeling and Manufacture

Since the Gemini mirror is coupled to the mirror cell by an over-constrained support, distortions in the cell can be coupled to the mirror surface. However, the Project demonstrated by using simple symmetry arguments that a six zone support can only bend the mirror in two astigmatic modes and a trefoil mode. The total error budget for all these effects (support residuals) is 0.01 arcseconds.

Gravitational flexure

In going from zenith pointing to horizon pointing the Gemini mirror cell will flex. Using a 4 bipod support system to couple the mirror cell to the telescope structure, FEA results show that in the current design the total mirror cell flexure from zenith to horizon is 40 microns peak-to-valley.

A detailed FEA model was used to show that for the worst tracking rate (declination = 14 degrees on Mauna Kea) at the worst elevation angle (El = 30 degrees), the total effect on the mirror surface without any form of look-up-table correction produced mirror bending at a rate of 4nm (rms)/min. This would be equivalent to tracking for 5 minutes without using look-up-tables before needing any active optics correction. Based on experience with other large welded structures, the Gemini Control Group predicts that by using look-up-table corrections, a wavefront sensor measurement would be required only once every 15 - 20 minutes for the worst case tracking trajectory.

CASE NUMBER	MIRROR DEFORMATION IN FIVE MINUTES (nm RMS)				TOTAL HEAT INPUT IN EACH CASE (watts)
	SS	AA	SA	TOTAL	
Thermal 3	1	0	0	1	
Thermal 4	12	0	0	12	30
Thermal 5	1	0	0	1	50
Thermal 6	0	0	0	0	375
Thermal 7	1	0	0	1	192

Table 2. Results of the three-dimensional thermal FEA analysis of the Gemini mirror cell, showing the distortion rates of the mirror surface for a number of thermal disturbances discussed in the text. The results are in nanometer (nm) rms figure errors after five minutes for symetric-symetric (SS), antisymetri-antisymetric (AA) and symetric-antisymetric bending modes of the mirror. For these modes 25 nm rms is roughly equivalent to 0.01 arcseconds of error.

The SWG and PDR Committee were given a fairly detailed presentation of how the mirror cell would be constructed and subsequently heat stress relieved to reduce hysteresis. Experience with equivalently large steel structures used on 4m telescopes and, far larger, radio telescopes, is that these affects were likely to be well within the capabilities of the Active Control system.

Thermal distortions

Unlike gravitational flexure, thermal distortions could be non-systematic and unpredictable. The SWG were keen to establish what level of thermal control was required for the mirror cell structure to ensure thermal distortions did not bend the mirror beyond the allowed error budget during operation.

A number of typical cases were run through a full three dimensional thermal model of the mirror and mirror cell. This model and the consequent affect on the mirror was assessed as a function of time. The results are shown in ***Table 2.***

Most of the thermal disturbances considered, such as heat leaking from the radiation plate (case 6), heating from the Cassegrain rotator motors (case 5), or differential cooling across the mirror cell due to wind (case 3) had fairly large scale effects with some degree of symmetry which had little effect on the mirror surface. The worst case considered was a 30 watt leak from a computer crate placed asymmetrically at the outer edge of the mirror cell (case 4) 10 minutes after it had been switched on.

The SWG accepted that the modeled thermal mirror cell disturbances were representative cases and well within the capabilities of the Active Control loop. However it recommended that all cooling systems and ancillary equipment always be placed in symmetric configurations about the mirror cell.

Predicted Open loop - Closed loop and Active Optics performance of the telescope

Crucial to the performance of modern large telescopes trying to deliver diffraction limited performance is the effectiveness of the Active Optics control loops. After some thorough discussion and debates with the SWG, two aspects of the Gemini control system were presented by the Project to the PDR Committee.

The performance of the wavefront sensor with atmospheric turbulence and full moon illumination

To assess the errors inherent in the wavefront sensing, as a function of atmospheric turbulence and sky brightness, Brent Ellerbroek of the Starfire Optical Range (SOR), has produced a full wavefront analysis of the proposed Gemini active optics system. The allowed error budget for Active Optics errors is 0.01 arcseconds.

Assuming a low order Shack-Hartmann sensor and based on the real experience and data gained from the Active and Adaptive optics work at the SOR, Brent had modelled the following error sources:

- S-H fitting error to typical Gemini mirror errors
- The S-H sensor noise errors from CCD read noise and sky brightness effect
- The inherent error in using a finite integration time while observing a star through a turbulent atmosphere

The most striking result from this analysis is that the dominant noise source is the residual errors that result from not fully averaging out the effects of high altitude atmospheric turbulence.

Using sky brightness measurements from the CFHT on Mauna Kea, the analyis shows that to minimize the resulting wavefront error, using:

- measured CCD properties, sensing in the 0.5 - 0.85 micron range,
- an 8x8 S-H lenslet array,
- in average seeing,
- 10 degrees from full moon, and
- a 18 magnitude star - which will give 99% sky coverage at the Galactic poles

requires at least a 60 second integration to give a reasonable residual wavefront error. This typically means that the Active Optics wavefront sensing loop can only correct errors with frequencies typically < 1/(5 x 60) = 0.003 Hz.

The SWG noted that if the high altitude winds at 4-5km were slow (~3 m/s) this would give a larger wavefront error than allowed by the error budget. However, examining the radiosonde balloon measurements for Mauna Kea shows that such low velocities are rare, and the inclusion of an adaptive correction of the atmospheric focus component using the secondary would reduce this error significantly.

Open loop - closed loop performance of the telescope

Having established the expected error contributions from the wavefront sensor optics and possible correction

3a.

Aberration	Total Range nm	Peak-Peak Range nm	LUT Capability %
Astigmatism	500	75	85
Coma	1,000	200	80
Spherical	400	100	75
Triangular coma	160	40	75
Quad. astigmatism	80	40	50

Table 3a shows the measured optical aberration from the NOT telescope in rms. The first column shows the total range of the aberration in tracking from zenith to horizon. The third column shows the predicted residual errors after application of look-up-tables (LUTs), giving the percentage of correction applied.

3b.

Effect	Integrated Effect 50% Energy	After LUT 50% Energy	LUT Capability %
Decenter	0.11	0.02	80
Tip/Tilt	0.07	0.01	80
Defocus	0.17	0.04	75
Higher Order	0.16	0.06	60

Table 3b gives the model predictions for Gemini, this time expressed as errors in the encircled energy diameters. Gemini is assuming it can achieve comparable levels of correction to the NOT Telescope.

GEMINI GROUP UPDATES

bandwidths, the Gemini Controls group was then able to fold these results into a full systems model of the Gemini telescopes.

Using the results from FEA models, power law disturbance functions and look up table predictions based on the Nordic Optical Telescope (NOT) on La Palma (***Table 3***), the predicted "open loop" performance can be calculated. The subsequent improvements gained by successively closing the slow guide loop, tip/tilt, fast focus and then Active optics loops can then be modelled using the dynamic models of the telescope, primary mirror (as discussed above) and the atmospheric results from Brent Ellerbroek.

The results were computed as the 50% encircled energy diameter degradation in image quality at 2.2 microns that could be expected on Gemini tracking at an elevation of 45 degrees after an hour of integration in a 11m/s wind. The error budget at this elevation is 0.122 arcseconds (including diffraction).

Using look up tables and a pointing map the predicted error was 0.45 arcseconds after an hour — comparable to what can be achieved on 4m class telescopes today. After closing the slow autoguiding loop and fast tip/tilt guiding loop, this error is predicted to be down to 0.13 arcseconds. With a fast focus and active optics wavefront sensor switched on, for median seeing conditions in a 11 m/s wind, the expected contribution from the telescope to the image quality after a one hour integration is reduced to 0.1 arcseconds.

— ***Matt Mountain***
Project Scientist

Telescope Structure, Building/Enclosure

Telescope Structure

Since the last Newsletter, Peter Hatton, Mark Warner and Mike Sheehan have been working on updating the design of the telescope structure in preparation for the telescope CDR in March 1994. The telescope mount base, columns, altitude trunnions, center section, altitude drive disks and the altitude and azimuth motor mounts have been designed and analyzed in depth with FEA. Areas still requiring detailed design and FEA include the primary mirror support frame, main trusses and top-end rings. The system level model is complete and is being used to predict the telescope performance under seismic events and wind excited loading.

The Gemini telescope design is shown in ***Figure 5***.

We have also investigated options for delivering a laser beam from the Support Facility to a laser launch telescope sited on the telescope structure.

Enclosure

The enclosure Design Requirements Document (DRD) has been completed, and discussions are underway with a contractor for the detailed design, fabrication and erection of the enclosures. The enclosure design is shown in ***Figure 6***. Significant features of the enclosure design include:

- Large ventilation gates, 10m high, all around the enclosure to allow rapid flushing of the enclosure. These gates can be gradually closed down as the wind increases.
- Active flushing for periods of low winds.
- An actively ventilated, low thermal time constant floor, which will track the ambient air temperature.

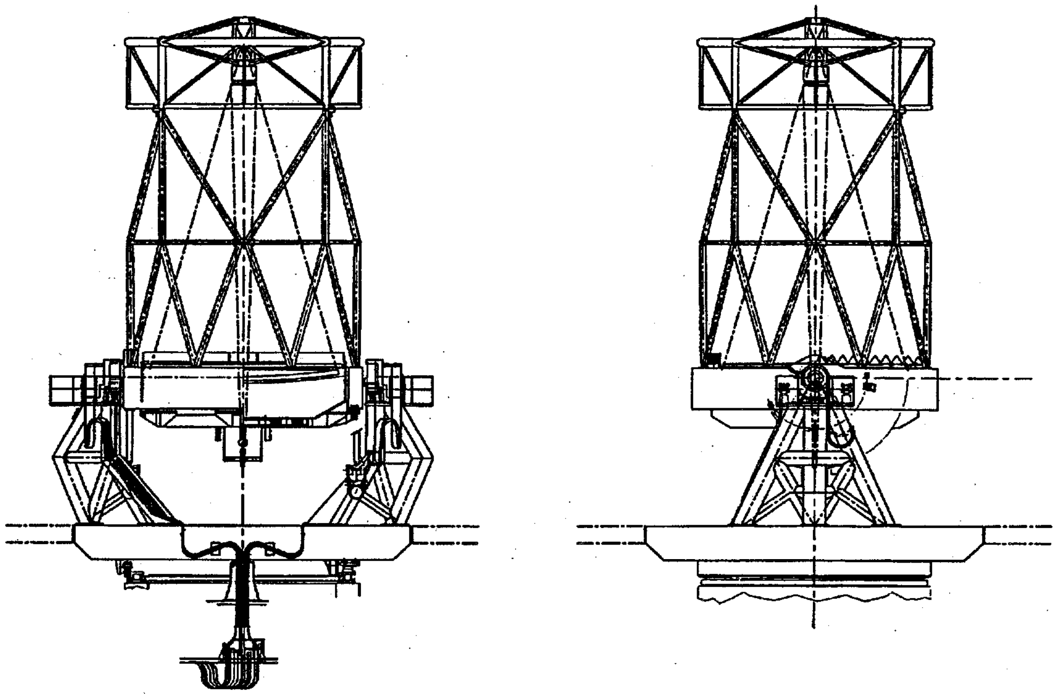


Figure 5. Gemini telescope design.

- A 120-ton capacity lift that will be used for transporting the primary mirror in its cell from the telescope to the coating chamber, and for transferring the top-ends from the enclosure base to the telescope.

Support Facility

The design requirements document for the Support Facility on Mauna Kea has been completed by Steve Hardash, Gordon Pentland and Bob Ford and passed to M3 Engineering to provide cost estimates for the construction. Following this exercise, modifications have been made to the Support Facility and the DRD modified. M3 started the construction documents in late October, and Mike Sheehen and Paul Gillett have evaluated the performance of several pier designs under wind loading. By March 1994, the construction documents will be completed and ready for bidding.

Mauna Kea Site

The Conservation District Use Application (CDUA) was submitted by the Institute for Astronomy (IfA) to the Hawaii State Department of land and Natural Resources (DLNR) on December 22, 1993. The DLNR, after receiving our application, should issue a Conservation District Use Permit (CDUP). This latter process takes approximately 8-10 months, and the CDUP, together with the applicable building permits, will allow the project access to the Mauna Kea site to start construction.

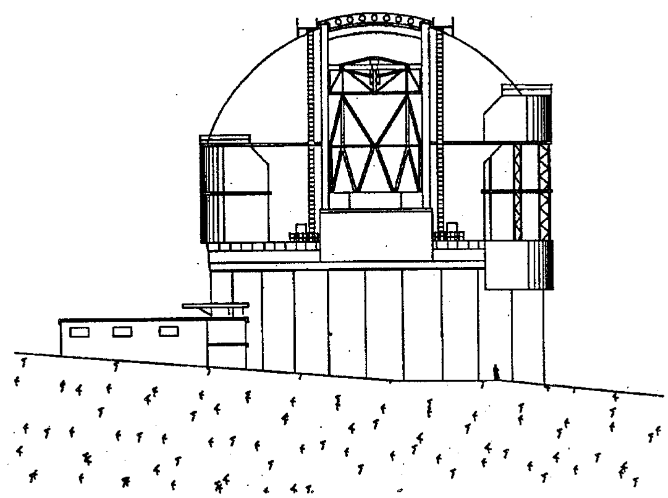


Figure 6. Gemini enclosure design.

GEMINI GROUP UPDATES

Paul Gillett is revising the schematics for relocation of the utilities on Mauna Kea following recommendations from, and requirements stipulated by, Helco.

In Chile

After evaluation of the wind measurements taken by Ruth Kneale, the computer numerical modelling of flow over the Prime and alternate West sites by Dave De Young, and logistic and geotechnical considerations, the Prime site has been selected for the Gemini telescope.

Contracts have been placed in Chile for the design of the road to Cerro Pachon, and for the design of the commercial power line from commercial tap-in to Cerro Pachon.

CTIO have formed a committee to advise the Project on the requirements for the facilities on Cerro Pachon and La Serena. It was encouraging to see the similarity of the committee's recommendations and the current schematics. The CTIO committee will be working closely with Paul Gillett to define the requirements for the facilities in Chile.

Protected Silver Coating

The second phase of the development and testing of protected silver coatings is now underway. In the first phase, Optical Data Associates (ODA) investigated the feasibility of developing protected silver coatings to meet the Gemini emissivity specifications. Computer simulations and a study of recent development work in the coating industry indicated that hafnia and silicon nitride offered the most promising options for protecting silver. In the second phase of this work, coatings will be optimized to meet the stringent 2% target emissivity specification. The coating optical properties, adhesion, abrasion resistance and environmental durability will be measured.

ODA has subcontracted the development of the silicon nitride coating to Airco Coating Technologies, (ACT), a firm with considerable experience developing silicon nitride protected silver coatings for commercial applications. Similarly, ODA has subcontracted to Deposition Sciences, Inc. (DSI) the optimization of hafnia-protected silver coating to benefit from their extensive experience in this area.

Coating Plant

An agreement has been reached with the Royal Observatories (RO) regarding the work scope, cost and schedule for a work package with the UK for the development, design and specification, procurement, assembly and commissioning of the Coating Plants. Brian Mack at the Royal Observatories will be managing this work with Ron Adams, David Jackson and others at the RO involved in the program. Brian Mack has been pioneering the application of the sputtering process for coating large astronomical mirrors for many years, and this program will build on this experience. He has already completed an initial program to investigate the effect of varying sputtering parameters on the emissivity of aluminum coatings. The sputtering coating process offers greater potential for depositing protected silver coating than the conventional evaporative technique.

— ***Keith Raybould***
Telescope Structure, Building/Enclosure Manager

Optics

Most of the activity of the Optics Group in recent months has been involved in preparations for the Primary Mirror Assembly Preliminary Design Review (PDR), which was held December 6-8, in Tucson. Many people worked very hard to make this review successful. I would specifically like to thank the Optics Group staff, Project Scientist Matt Mountain, acting Project Manager Jim Oschmann, staff members of the Controls, Instrumentation and Telescope Groups in Tucson, our colleagues at Rutherford Appleton Laboratory and Royal Greenwich Observatory in Great Britain, Brent Ellerbroek of Starfire Optical Range, the Science Working Group for the PDR, and particularly, PDR Committee Chair Bob Gehrz and the other PDR Committee members who devoted considerable time and effort to understand and critique our designs.

GEMINI GROUP UPDATES

As described at the PDR, the design of the mirror support actuators is progressing well at RGO. Brian Mack and his team have built and tested prototype support mechanisms, and are well along toward having designs that meet all of the specified requirements. They have also been working with load cell manufacturers to develop a variation on a commercially available design that has the required stiffness and resolution, and can be obtained at *normal commercial prices.*

Our colleagues at RAL have been developing the design of the primary mirror thermal management system. After looking at several options they have selected a design incorporating a radiation plate behind the primary mirror. This is very similar to the design currently planned by ESO for the VLT Project.

They have also been developing a design proposed by Chief Engineer Earl Pearson for a mirror front surface coating heating system. This system will increase the thermal response speed of the mirror front surface by an order of magnitude. Several prototype heated mirrors have been built at RAL up to one meter across and up to 20 cm thick, with both silver and aluminum coatings. The results of the prototype tests are:

1. Life cycle tests have shown no measurable degradation of the coating properties caused by the heating system.

2. Thermal uniformity tests show good uniformity of heating across the surface of the one-meter mirror.

3. Control tests show excellent ability to follow changing ambient temperatures with a 20-cm thick ULE™ mirror (the same thickness as the Gemini primary mirrors).

Eric Hansen, of the Tucson staff, has been doing detailed heat transfer modeling of the response of the primary mirror to the ambient air temperature, when controlled by this thermal management system. Thanks to the cooperation of the staffs at UKIRT and CFHT, we have several years' worth of temperature data from Mauna Kea. Even after weeding out cloudy nights, etc., we have hundreds of nights of data suitable for use in our simulations. This has given us a chance to develop algorithms for control of the thermal system. The results are quite good: using the radiation plate, the mirror surface is able to follow the air temperature within the specified range of +0.2° to -0.6° C for most of the hours suitable for astronomy in a given year. With the addition of the coating heating system, the mirror surface is able to follow the air temperature within the specified temperature range for 75% to 90% of hours suitable for Astronomy in a given year. As far as we know, no ground-based telescope project has ever performed such extensive thermal modeling to verify their system's mirror seeing performance over several years' worth of data.

Myung Cho has been performing finite-element studies relating to the support system. These studies include optimization of the support positions and forces, a detailed tolerance study of possible support system errors, analysis of potential modes of thermal distortion of the blank, and evaluation of the support system's active optics capabilities. The results of these studies show that the support system will be able to meet the error budget in all respects.

Brent Ellerbroek of Starfire Optical Range has simulated the performance of active optics wavefront sensors in measuring the types of optical surface errors identified in the tolerance studies. His studies show that in the presence of atmospheric seeing, polynomial fitting errors, and detector radiometry effects the wavefront sensor can perform adequately, with a 99% chance of finding a bright enough star even at the North Galactic Pole.

Our preparations for the PDR have been aided by a Science Working Group chaired by Project Scientist Matt Mountain. The Group held two meetings, in September and November. By challenging our assumptions and helping to define suitable input for our design simulations, they provided a very healthy critical input to the process of preparing for the review. Their assessment of the performance of the Gemini primary mirror assembly is described in the Project Scientist's report in this newsletter.

Production of ULE™ glass at Corning continues. All the glass for the first mirror blank has been produced, and the option to purchase a second meniscus has been exercised. Corning has begun fusing boules into stacks to reach the necessary thickness for our mirror, and as expected the *fusion seams are of excellent quality, hardly visible to the* naked eye.

We have completed our evaluation of proposals for polishing the primary mirror. We anticipate signing a contract and announcing the successful bidder by the end of January.

GEMINI GROUP UPDATES

The design of the secondary mirror assembly has continued as time was available between preparations for the primary mirror PDR. We expect work on the secondary mirror to shift into high gear after the first of the year.

— ***Larry Stepp***
Optics Manager

Controls

Gemini Software Design

Hardware Architecture

The Gemini system will have the hardware architecture shown in the figure on the following page. The system can be broken down into the following components:

- workstations providing user interface and higher level control;
- VME crates providing real time control for individual mechanisms;
- a number of local area networks providing control, status, and data linkages between the workstations and the VME crates;
- a time bus for providing time distribution; and
- a TBR bus for providing deterministic transfer of digital information and analog synchronization signals between real-time systems.

The baseline choices for this hardware as approved by the System Design Review Committee are :

- Sun Sparcstations;
- Heurikon VME crates running Motorola 68040 CPU's;
- FDDI for LANs;
- GPS for time synchronization and NTS for time distribution; and
- VMIC reflective memory for deterministic transfer of digital information and coaxial cables for analog synchronization.

Software Architecture

The Gemini system will have the software architecture shown in the figure on page 20. The system can be broken down into the following major components:

- Queue Observing - handles preprogrammed observing, queue scheduling, and flexible scheduling;
- Observatory Control - handles command processing and sequencing;
- Telescope Control - controls mount, primary, secondary, instrument rotator, and enclosure;
- Instrument Control - scientific instrument;
- Data Handling - disk, tape, and archiving; and
- Data Processing - preprocessing and on-line data reduction.

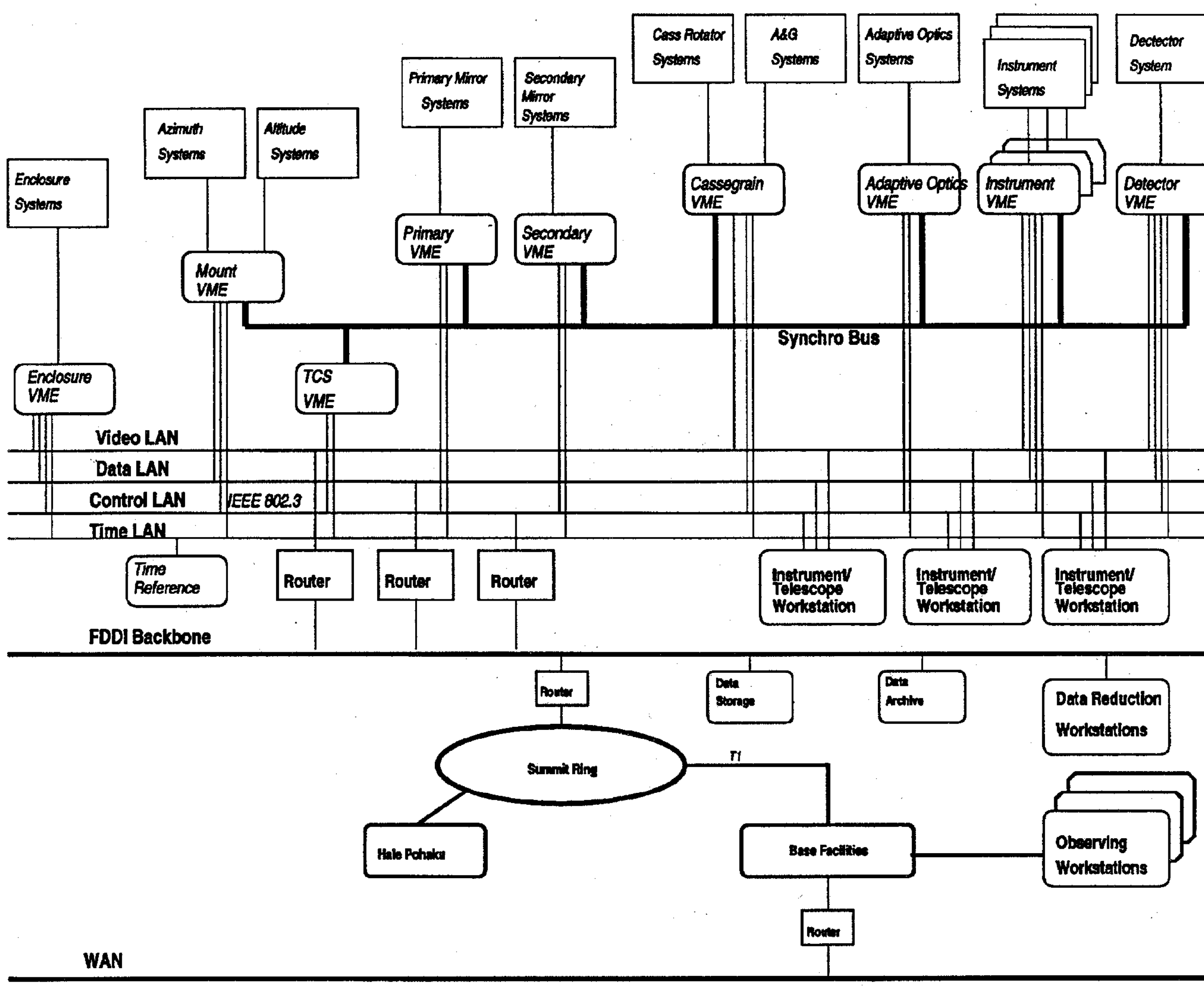
The baseline choices for this software as approved by the System Design Review Committee are:

- Tk for the graphical user interface;
- UNIX and C for workstation programming;
- TCL as command language user interface - majority of workstation programming will be done in TCL;
- VxWorks and EPICS for real time programming;
- PV-WAVE for quick look pixel arithmetic;
- TCL interface to ADAM/IRAF for on-line and near-line pixel arithmetic; and
- pixel display and mechanism visualization using PV-Wave.

TCL/Tk

TCL is an extensible, embeddable programming language that provides a great deal of functionality useful for high-end control software. It provides a common com-

GEMINI GROUP UPDATES



Gemini Hardware Architecture

mand language across all processes and is fully featured, structured, and distributable. The TCL language supports rapid prototyping and eliminates much of the complexity associated with programming in lower-level languages such as C, while retaining convenient access to C when performance is an issue.

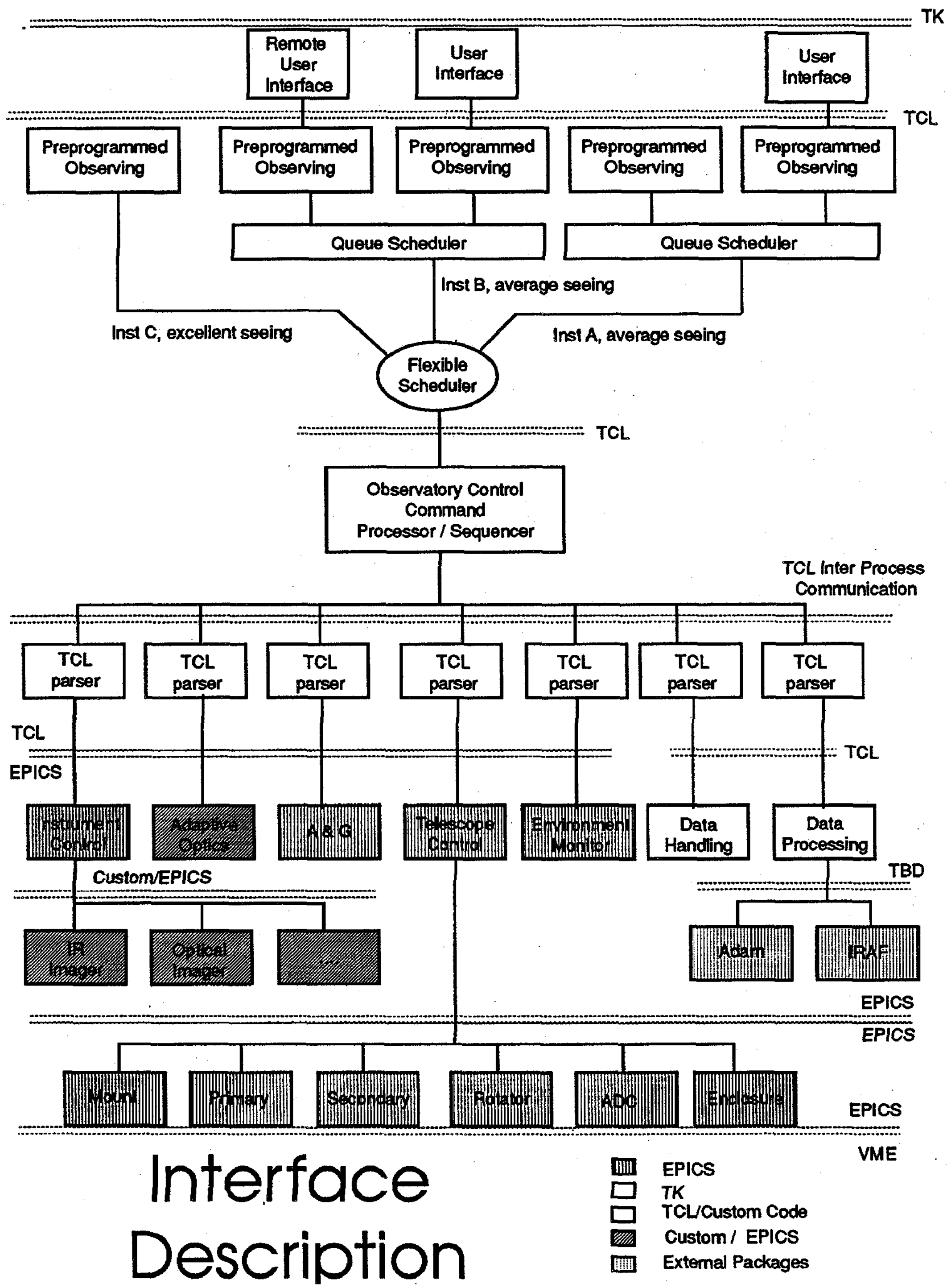
Tk is an extension to TCL providing access to an X-windows environment. Tk can be used when developing new software or as a means to (quickly) developing Graphical User Interfaces to existing programs. Tk's interface to X is considerably simpler than that presented to a C programmer, making GUI development less painful.

The Software and Controls Group intends to use TCL and Tk as appropriate to simplify the task of developing high-level control software. TCL and Tk are free products with extensive use outside of the astronomical world and are now being used more frequently in astronomy.

System Design Review

From Sept.28 through Oct.1, 1993 the work of the Controls Group was reviewed by an external committee. This was not a Preliminary Design Review, but rather a review to assure that the design is reasonable and feasible and that a clear development path is firmly established. The

GEMINI GROUP UPDATES



Gemini Software Architecture

GEMINI GROUP UPDATES

SDR can be thought of as a precursor to the initiation of the work as Work Packages.

It was of particular importance to establish the hardware and software design as well as the baseline choices for hardware and software before any design work proceeds on the individual work packages.

Committee

The committee was made up of R.Murowinski (chair, DAO) and D.Crabtree (CADC) from Canada; M.Johnson (RGO), R.Laing (RGO), R.Meyers (Durham), M.Stewart (ROE), and P.Wallace (RAL) from the United Kingdom; and C.Christian (EUVE), J.Kerr (CFHT), B.Marshall (NOAO), J.Percival (Wisconsin), and R.Wolff (NOAO) from the United States.

Reviewed Materials

The committee was asked to review the following materials:

- Software & Controls Management Plan;
- software and hardware architecture;
- underlying hardware and software baseline choices selected;
- breakdown of the work into work packages;
- outline of a work package description; and
- individual work package overviews.

For each of these areas the committee was asked to make a recommendation as one of:

- recommended without conditions or reservations;
- recommended with conditions - conditions would be action items; once action items were completed satisfactorily project would continue;
- recommended with reservations - reservations would be potential problem areas that committee felt required additional work; and
- not recommended - reasons listed.

Of all the materials reviewed, the only document not recommended was the Observatory Control System Overview; this is discussed below. The Controls Group has a list of action items with which it is proceeding.

Actions

The major actions which the Controls Group is taking as a result of the review are described below.

Changes to Documentation

One result of the System Design Review is a decision to streamline the documentation being produced by the group. For example, the Software Concept Specification contains information that can be merged into three other existing documents: the Operational Concept Definition, the Software Requirements Specification, and the Software Design Description. This task is underway and will result in the SCS being removed from the supporting documentation set.

Break Down of Work Packages

The committee made some specific recommendations which we will adopt. The basic change will be to move the queue scheduling tasks from the Remote Operations work package and the TCL-EPICS tasks from the Instrument Control work package and put these into the Observatory Control work package.

Initial Work Packages Underway

The Instrument Control Infrastructure work package has started with the joint development of the Work Package Description and Scope of Work between the Project and the United Kingdom. This work package will provide a standard control system that will be used for the mount, mirrors, enclosure, etc., and can also be used for the control systems for the scientific instruments.

Once the Instrument work package is underway, the project will start the primary mirror support control system work package. This work package will provide the computer control for the major subsystems used to support the primary mirror.

Observatory Control System

The overview document for this subsystem was not recommended by the committee, which made the following statement:

"The OCS is very much the heart of the system, and needs to be treated differently from the other work packages. We would like Gemini to arrange

GEMINI GROUP UPDATES

for a considerably more detailed design to be presented in this document. One of the results of this design could be the dividing of this work package differently to retain better control of the product by the project office."

Steve Wampler has already started producing this more detailed design, and it will be available within the next four to six weeks. This design effort is focused on three steps:

1. Creation of a System Design Document - this document describes the overall design of the complete system in terms of a decomposition description, dependency description, interface description, and detailed design. These descriptions will be done using the Ward & Mellor methodology as implemented by the TSEE CASE design tool.

2. Revising the Observatory Control System Overview Document - at this point all the points made by the committee will be addressed.

3. Flow-down of these two documents into the overviews for remaining work packages - this will provide a consistent set of overviews appropriate for initiating the work package descriptions.

In parallel with this design effort, the Project will be looking at means of retaining better control of this work package.

Scientific Oversight

In order to provide scientific oversight of the Controls Group's efforts it is necessary to separate the reviews into verification and validation. The validation reviews will be scientific and will address whether the current design and its work products accurately reflect the Scientific Requirements. In a sense the validation reviews will answer the question: *"Are we building the correct software and controls ?"*. The verification reviews will be technical and will answer the question: *"Are we building the software and controls correctly?"*. Only the validation reviews will provide scientific oversight.

The validation reviews will be:

- Operational Concept Scientific Review,
- Operational Concept Scientific Walkthrough,
- Observatory Simulator Scientific Review,
- Observatory Control System Scientific Review,
- Mauna Kea Acceptance Test Review, and
- Cerro Pachon Acceptance Test Review.

The committee pointed out that both the Operational Concept Description and the Software Requirements Specification should have Scientific Oversight. The recommended means of reviewing these documents is to use rapid prototyping in order to provide a user interface that simulates the system being reviewed. The project is currently assessing the implications of providing this.

Telescope Simulation

The baseline nonlinear control simulation for the telescope was improved to include nonlinear bearing friction as specified by Kaman Aerospace. This model is currently being used to evaluate the effects of encoder quantization, friction, structural modeling, and tracking rate. We will add the effects of controller sampling, torque quantization, and torque disturbances at a later date.

The model as currently constructed uses the output of Finite Element Analysis to construct the state space representations of the mechanical structures in the telescope — pier/soil, mount, tube, instrument support structure, primary mirror, and secondary mirror. These structures are linked together with nonlinear models of the bearings and actuators separating them. Models for the sensors available are used as error signals for the control systems driving the actuators.

ADAM Workshop in La Palma

Steve Wampler and Peregrine McGehee both gave presentations at the ADAM workshop held during September in La Palma. The purpose of the trip was twofold: to learn more about the UK astronomical community and their approach to software and controls development, and to provide that same community with an overview of the plans for software and control within the Gemini Project.

Steve gave a presentation on the results of the Software and Controls Workshop held in Tucson in July, followed by an informal presentation of the Gemini error budget philosophy. Peregrine presented the EPICS system and dis-

GEMINI GROUP UPDATES

cussed how it would be used in the Gemini Project as well as how it might be incorporated into ADAM and DRAMA.

ADASS '93

Steve and Peregrine also attended the October ADASS conference in Victoria, Canada. Peregrine provided a poster session on the use of EPICS for real-time control in telescopes while Steve's poster session discussed the use of off-the-shelf software for integrating data reduction packages.

Electronic Access to Documents

The Gemini ftp area is located on:

gemini.tuc.noao.edu:~ftp/gemini

and is accessible via anonymous ftp from any machine on the internet. This area has electronic copies of documents (mainly from the Controls Group) which are generally in encapsulated postscript format.

Gemini also supports a World Wide Web server on:

icarus.tuc.noao.edu

Gemini has also added a gopher server on:

gemini.tuc.noao.edu

which, among other documents, has the Gemini Controls Group documents. A large number of these documents are duplicates of those in the anonymous ftp area, but an increasing number are the actual source files kept on the Gemini optical disk document archive.

A problem with the anonymous ftp area, in addition to the large amounts of disk space required, is that there is considerable overhead associated with the creation of the postscript files and keeping them up to date. Internal to Gemini we keep most documents in AmiPro format and these documents, once released, are stored on the optical disk in AmiPro format. We would like to move away from anonymous ftp in postscript format to gopher access in AmiPro format for Gemini documents. This would lower Gemini's investment in document duplication and maintenance. We would, of course, be able to service specific requests for documents in alternative formats. We have tested this arrangement using a PC gopher client which accesses the optical disk via gopher and displays the file using an AmiPro viewer in the PC. A similar method of retrieving drawings works using an AutoCad viewer on the PC. We welcome the communities' comments (sysrick@noao.edu).

— ***Rick McGonegal***
Controls Manager

GEMINI GROUP UPDATES

Instrumentation

Progress with the Instrument Working Groups

All of the groups have now submitted their reports to the project containing their recommendations on instrument requirements for Gemini (a synopsis of these reports appeared in the September Newsletter). These reports form an extensive reference from which the Instrument Group will prepare the Instrument Plan that is to be presented to the Gemini Board for approval in May. We would like to thank all the working group members for their enthusiastic participation in this definition process, and in particular we would like to thank the Chairs for their time in preparing these reports.

CRDA with Starfire

The CRDA with the Phillips Laboratory, Starfire Optical Range has been extended until September of 1994. The efforts from this collaborative agreement, undertaken mainly by Dr. Brent Ellerbroek, have continued to be of immense value to the project. A summary of the near-term tasks that Starfire will be working on with us is given below.

- Natural Guide Star Active Optics - Radiometry, Error estimation due to noise and fitting errors.
- Tip/Tilt and Focus Control - Investigation into the following: Encircled energy vs. Jitter, Star image shape with Adaptive Optics, Wind Shake tip/tilt analysis, Anisoplanitism effects, servo model.
- Natural Guide Star and Laser Beacon Adaptive Optics - Analysis using Mauna Kea C_n^2 Profile, Multi-Conjugate System, Laser Beacon power requirements.
- Natural Guide Star Curvature Sensing - Optimal Estimator Analysis, Wave Optics Simulation.

— D. J. Robertson

Temperature Predictions on Mauna Kea and Cerro Pachon

The Instrumentation Group has been analyzing meteorological data from existing observatories on Mauna Kea in order to establish baseline conditions under which the telescopes must operate. We have established such basic data as mean annual temperature, mean nightly temperature profiles for each month, and a classification scheme for variations in the temperature behavior.

We are currently investigating the effect of winds on the temperature behavior, and are writing algorithms to predict the temperature at the beginning of each night's observing. Our approach so far has been to use the statistical behavior of the temperature itself to predict the expected temperature, and this has met with some success. Assuming that each night will begin at the same temperature as the last one leads to an RMS error over a year of 1.6 degrees C. Our single channel predictor has reduced this to 1.3 degrees C RMS.

Our efforts now are aimed at forming appropriate statistics from other meteorological variables and combining them into a multi-channel predictor. It is too early to quantify the results, but we expect further improvement from this approach.

In addition to using statistical techniques to predict the temperature on a given night, the Instrumentation Group is also investigating a neural network predictor approach to the problem. This is still in the early stages of development.

— W. Weller

Progress on the Cassegrain Instrument Cluster

Interface between the Instrument Rotator and the Primary Mirror Cell

The instrument cluster for the Gemini telescopes is bigger and heavier than any existing telescope instrumentation assembly. This, coupled with the demands for excellent image quality, requires careful design of the mirror cell/instrument rotator/instrument support structure interfaces. The design of the instrument rotator is central to this

GEMINI GROUP UPDATES

area. The interface between the instrument support structure and the primary mirror cell must support 13 tonnes with a center of gravity one meter distant and control the rotation of this assembly to a few thousandths of a degree.

A main component of the instrument rotator is a large-diameter crossed roller bearing (1.5 meters). This type of bearing is capable of supporting loads 15 to 20 times that imposed by the instrument cluster. As the telescope tube rotates from horizon to zenith, the proportions of moment, radial and axial loads change on the bearing. These loads are resolved within the bearing into compression loads on the individual rollers. As the rollers compress, the instrument cluster will sag, piston and tilt systematically with altitude angle. The magnitude of these deformations is an important parameter of the active optics system. They indicate the magnitude of translation, piston and tilt required for the primary and secondary, if telescope collimation and instrument focus are to be maintained. The changing loads on the bearing also affect the bearing friction. In addition to the effects of changing loads are the effects of lack of flatness or roundness in the bearing mounts. Geometric errors such as these will distort the bearing during assembly increasing bearing friction. Because the mounting structures are very stiff, this friction will vary as the bearing is rotated. In addition to these 'initial flatness errors' the bearing interfaces will deform. It is important that the deformations are small and smoothly varying along the bearing circumference. Discontinuities will increase the bearing friction and could potentially damage the bearing. The combination of these effects will result in a systematic variation of rotator friction with position, speed and telescope tube altitude. This is an important consideration for the instrument rotator drive system and servo control system.

A preliminary Finite Element Model has been constructed for the bearing and adjacent structures to look at the expected flexures. ***Figure 7*** shows the deformations (in mm) around half the circumference of the instrument support structure interface when the telescope is pointing at horizon. A best fit straight line shows a sag of 0.0003 degrees, and smoothly varying deformations from flatness of two microns. The interface plate is 63.5 mm thick. Such a model can be used to optimize the local stiffness of the mirror cell against cost or mass.— ***D. Montgomery***

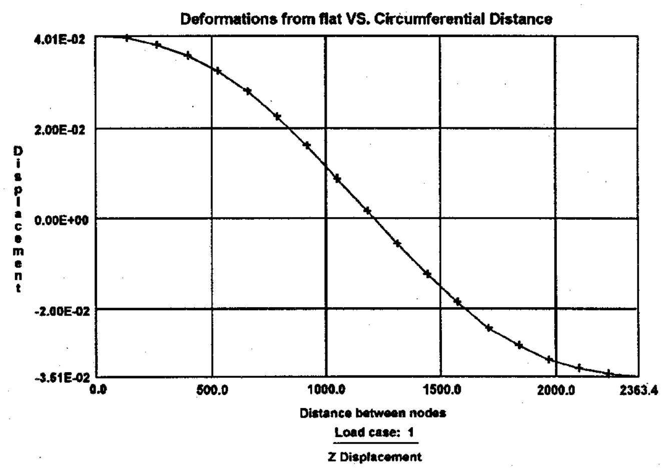


Figure 7. Deformations (mm) around half the circumference of the ISS with the telescope horizon pointing.

Cassegrain Rotator - Preliminary Servo Analysis

Initial investigation of the Instrument Rotator Servo Control System is underway. The investigation is based on the results of a report prepared by Dr. Malur K. Sundareshan[1], "Preliminary studies on development of a robust controller for Cassegrain Rotator for the Gemini 8-M Telescopes, 1993". The Control Systems Toolbox with Matlab and Simulink are being used to conduct the simulations and analyses.

The preliminary goals are to develop a stable, top-level linear model of the instrument rotator system and to become familiar with the Matlab software. The top level system includes basic linear models of the following components: motor, gear, and the damping effect of the rotator. It treats the two opposing pairs of motors as one entity, neglects friction, stiction, and other nonlinear effects of the bearing and dead zones/backlash in the gear drives.

The next goal will be to validate a preliminary model for the rotator system, so that parametric studies including the bearings and encoders can be conducted. Three principle areas will be investigated:

- modeling of the rotator drive motors;

[1] Professor, Department of Electrical and Computer Engineering, University of Arizona.

GEMINI GROUP UPDATES

- developing an accurate model of gear indexing errors; and
- determination of where the feedback loop needs to be closed for the system.

The second phase of this preliminary servo modeling will be to include nonlinear effects, and to conduct parametric studies of the bearing and desired controller.

The main parameters of the bearing which will be considered are the rotator "spring constant" and the viscous damping coefficient. The positional and tracking accuracy for the desired tracking motions will also be considered. The effects of the cable wrap can be approximated as providing additional drag which modifies the damping coefficient. The primary tool that will be used to determine the performance tradeoffs is a root locus plot which can be generated for a linearized system in Matlab. The emphasis will be on placing the closed-loop poles, since their locations determine the rise time, overshoot, and settling times. Since a root locus is based on a linear model, the results will be verified by simulating the system with the nonlinear effects.

After the root loci plots have been generated for various cases, a decision will be made as to which parameters are most desirable and/or feasible. These parameters will be used in the development of a feed-forward controller. Development of the feed-forward will begin with the selection of a range of proportional gains (P) and developing the root loci for the parametric cases of interest. Then the root-loci plots will be generated for a range of proportional + integral (I) values. Finally, this will be done for a PID (derivative) controller. A determination of the optimum situation will then be made.

Results of these activities are expected to be available before the Instrument Rotator Preliminary Design Review (PDR); they will be discussed in detail at that time.

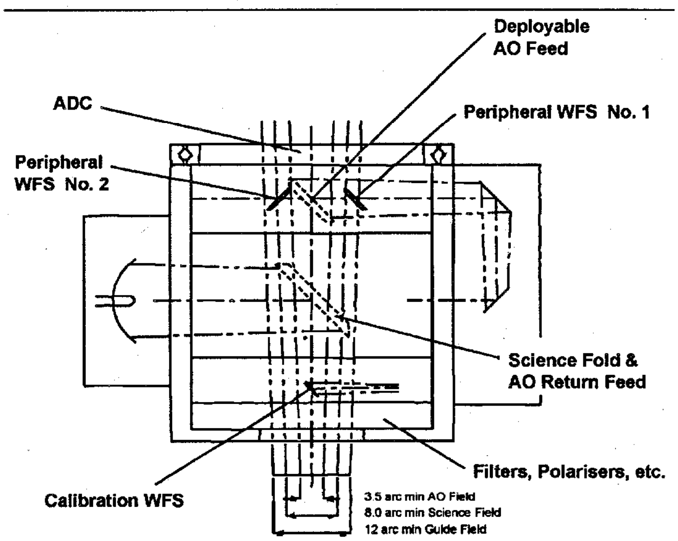
— S. M. Wieland

Integration of A&G and Adaptive Optics with the Instrument Support Structure

Our earlier scheme for integrating the A&G and Adaptive Optics systems with the instrument support structure was giving us some problems. The areas of concern were primarily the limited unvignetted field available to the guide probes and the amount of space available for the AO system.

David Gellatly (RGO) and David Montgomery have been working together to produce a scheme which is altogether more satisfactory. The guide probes have moved above the instrument fold mirror which allays the vignetting problems, and the AO system now occupies a port on the side of the ISS in the same way as an instrument would. The AO system has a deployable mirror which intercepts the beam at the top of the ISS, and the feed to the instruments is provided by the common instrument feed mirror. The common instrument feed mirror is now sized to accommodate a 7' science field which can be used for both IR and Optical modes. This does away with the requirement for two mirror deployment mechanisms. ***Figure 8*** shows a schematic of our present design.

—David J. Robertson
Instrumentation Manager



ELEVATION SHOWING VARIOUS OPTIONS

Figure 8. Schematic of the Instrument Support Structure showing positions of critical components. AO and Calibration units are shown for illustration only.

Reports from the National Project Offices

From the UK Project Manager

Late in the Summer of 1992 I took on the job of UK Gemini Project Manager. Working in an international project adds extra complexities because of cultural differences. Not only are we nations divided by a common language but, it seems, astronomers separated by a common science. Thus though I didn't expect that I would be well known in the US astronomy community, I did expect a more faithful picture of UK astronomy to be perceived by US astronomers. Canadian astronomers do know us a little better; we share a submillimeter telescope and have 4m facilities on the same mountain. In this newsletter I would like to introduce myself and say a little about present status and future trends in UK ground-based optical and infrared facilities.

First a few words about myself. My experience with large telescopes started in the mid-1970's. From 1979 to 1985 I was Astronomer-in-Charge in Hawaii, directing the operation of the UK Infrared Telescope in its infancy and also making arrangements for the siting of the JCMT. Those were formative years for Mauna Kea, and I like to think that I helped show the potential of the site for the kind of astronomy targeted by Gemini. From the beginning of 1985 I was Head of Technology at the Royal Observatory, Edinburgh. In that role I developed the instrument building activity here into one of constructing and delivering complete instrument systems. My time in Hawaii taught me that what front-line facilities need is not just the basic hardware but an astronomy-ready system including hardware, the software both to run it and to reduce data complete with calibration facilities. Moreover it must be integrated, tested and documented before delivery. During that time we built UKT14, IRCAM and CGS4, all of which have been requested and scheduled for the majority of nights during the years in which they were pre-eminent. Currently, big projects are a submillimeter camera and a mid-IR spectrometer.

The past few months have seen the merger of our two Royal Observatories in the UK into one operating on two island sites and two UK sites. My "day job" is Head of Development. This is effectively overall programme manager of the enhancements to and instruments for our telescopes on La Palma and Mauna Kea. Current strong themes of this work include the improvement of image quality, increasing the number of detector elements in the focal plane and making observing easier and improving quality control through semi-automatic pre-programming, data reduction and remote working.

Moving on to the UK astronomy community, what is the flavour of UK astronomy, how is it changing? When I graduated in the UK radio astronomy was outstanding, indeed as a physics student I was aware of little else. In working with Gemini I find that most US astronomers see the UK prominent in visible and UV astronomy. (Perhaps, understandably because of our involvement in IUE and HST, as well as the success of the AAT and instruments such as the IPCS in the last decade, together with our setting up of the La Palma Observatory.) But maybe it is simply because most US astronomers are optical astronomers themselves! The great desire of the US community for an 8m infrared capable telescope reflects a trend in wavelength awareness newer in the US than in the UK. I have looked back at the time schedules for the 4m telescopes in which the UK has a share. These are the AAT, the UKIRT, and the WHT. I found that almost exactly 50% of the total UK nights have been scheduled for infrared observing! UKIRT is a dedicated 4m telescope, wholly British; the AAT has always had a very good infrared instrument, and the larger WHT (4.2m) has attracted visitor infrared instruments. An analysis of refereed publications shows a similar breakdown. Thus the data show the UK to have a very strong element of ground-based infrared astronomy, indeed perhaps, as a fraction of national programme, the biggest among the Gemini partners.

Our telescope time is over-subscribed by a factor of about four. Thus there is pressure both to provide high throughput instruments and time efficiency tools at the telescope. Instruments are automated and there is intelligence in the observing system to offer the most efficient configuration and prompt data quality control actions. At UKIRT observers have become accustomed to having a spectrometer for which the observing session can be prepared ahead of time using a text editor; this covers not only

Reports from the National Project Offices

the observations themselves but the initial spectral extraction. This ability to pre-programme observing at home or office will be extended when the upgraded 256-square infrared imager is installed early in 1994.

Today we have all the tools in place for observatory control, including flexible scheduling and remote observing. The remaining constraint is one of bandwidth, thus for submillimeter broad-band photometry where low data rates obtain observers have been able to participate from their home in the UK. When Gemini comes on-line for scheduled astronomy, the bandwidth for communications, especially to major centres for astronomy research will have increased.

However important operational and instrument efficiencies are, more fundamental gains are now sought by improving the information fed to instruments. Our science committee in the UK has prepared a proposal for installing adaptive optics systems on our 4m telescopes complete with compatible instruments within the next five years. This is not a technically driven proposal; the whole scheme is based on clear astronomy goals. Sample observing programmes are set out and the AO systems to make them possible are specified. We anticipate funding at the $1M per year level and have begun arrangement to start monitoring r_o and t_o at Mauna Kea and La Palma. As a precursor to the AO projects, the image hygiene of our facilities is being improved through thermal management and active optics.

From this outline I hope readers gain a better picture of the UK astronomy community. It has become science-goal oriented; infrared observing is an everyday part of the programme to the extent that it uses half the available 4m time and has a substantial presence in publications. Pre-programmed observing with data reduction at the telescope is becoming routine. Our large telescope facilities are being upgraded. Therefore UK astronomers will not only be ready to use the Gemini telescopes effectively, but they will expect the highest standards of efficiency and performance from them at all wavelengths. It is my job to work with the other Gemini Project managers to enable the Gemini team in its wider international sense to deliver the project's performance. Though the cash resources of Gemini are limited, there is a great deal of contemporaneous activity by the UK which can be exploited by Gemini. Using experience is a very valuable way of containing total cost, and proving solutions on existing facilities reduces risk.

Gemini is a very high priority in the UK astronomy programme, a project to which we are wholly committed. For me with my background in high mountain astronomy and in innovation, Gemini is the culmination of much of my experience.

— ***Terry Lee***
UK Project Manager

Reports from the National Project Offices

The Number of Faint Objects in the Near-Infrared

— *T.J. Davidge (UBC)*
— *S.J. Lilly (U. Toronto)*
— *P. Roche (Oxford)*

One of the issues considered by the Gemini Infrared Spectrograph Working Group was observing efficiency. Two ways of increasing the efficiency of spectroscopic observations are (1) cross-dispersion, to increase wavelength coverage, and (2) multi-object capabilities, to increase the number of sources observed. The latter option will undoubtedly prove to be challenging to implement; nevertheless, a cooled multi-object spectrograph would provide a unique capability for Gemini. A potential criticism against multi-object capabilities longward of 1 m is that the density of suitably bright objects may be too low to justify the construction of such an instrument. This is almost certainly the case in the thermal regime, where the high sky background severly limits the faint limit (although certain classes of objects, such as embedded star clusters may provide fields which are sufficiently rich to justify multi-object capabilities longward of 2.5 μm). Nevertheless, a significant multiplex gain may be realised in the near-infrared, which we define here to span the wavelength interval 1 -2.5 μm. In order to investigate the scientific usefulness for a near-infrared multi-object spectrograph, we examined the surface densities of two classes of objects: faint galaxies and sub-stellar objects, and the results of this study are briefly summarized here. A more thorough discussion of these results can be found in the final report of the Infrared Spectrograph Working Group.

Before computing the surface density of objects in the near-infrared, it was necessary to make assumptions about the capabilities of the Gemini spectrograph. These were that:

(1) The overall throughput of the spectrograph will be identical to that of the UKIRT device CGS4, based on the performance figures published by Mountain (1991, JCMT-UKIRT Newsletter, No. 1, 2).

(2) The observations will be recorded with a spectral resolution of 500. This is sufficient to detect both molecular and atomic absorption features in stellar spectra. The airglow lines which dominate the sky background in the 1-2μm regime are unresolved in this case, so that the sky background appears continuous on the wavelength axis.

(3) The observations would be recorded with an image scale of 0.15 arcsec/pixel, producing a 6.6 square arcmin field-of-view with a 1024 x 1024 detector.

(4) Only 75 percent of the detector surface could be sampled at any given time, to avoid overlap of spectra and spectra which fall off the detector.

The brightnesses which would produce a 10 sigma detection per resolution element after a 3-hour exposure in the H and K bandpasses are listed below. These results indicate that with an 8-metre telescope which delivers consistently good image quality it will be possible to investigate objects which are, by infrared standards, extremely faint. Moreover, it is also apparent that there are clear benefits to using narrow slits.

Slit Width (arcsec)	FWHM (arcsec)	H	K
1.0	0.5	20.7	20.0
0.4	0.2	21.7	21.0

Two particular science programs, one pertaining to extended objects, the other to point sources, were considered. Details of these programs are descibed below:

Reports from the National Project Offices

(1) Studies of high-redshift galaxies. Near-infrared spectroscopic observations of distant galaxies are desireable since, for redshifts greater than 1, the 1-2μm region contains the restframe optical portion of the spectrum, knowledge of which is important for understanding the physical conditions and stellar contents of these systems. Given that galaxies are extended objects, we assume that they would be observed through a one-arcsec wide slit. Consequently, from the table, the faint limit which we consider is $K < 20$. Broadhurst et al. (1992; Nature, 355, 55) investigated number counts of faint galaxies in the K-band, and their data suggest that ~40,000 galaxies per square degree are present with $K < 20$. Consequently, the number of faint galaxies which could be observed with our assumed spectrograph configuration is:

$$40000 \text{ gal/deg} \times 1.8 \times 10^{-3} \text{ deg/field} \times 0.75 = 55 \text{ galaxies/field}$$

The models considered by Broadhurst et al. indicate that 20 - 40% of these objects will have redshifts ≥ 1, so the number of high redshift objects per field will be ~16 .

(2) Studies of sub-stellar objects in nearby star clusters. Young star clusters provide one of the most promising environments for brown dwarf searches. Indeed, during the initial phases of their contraction (i.e. within about 1 Gyr of their formation), sub-stellar objects have brightnesses comparable to that of main-sequence stars. Spectroscopy provides one of the most reliable ways to distinguish between true sub-stellar objects and heavily reddened background stars. The near-infrared spectral region is of particular importance in this regard as it contains numerous temperature and surface-gravity sensitive transitions, which can be used to distinguish between sub-stellar objects and foreground dwarfs (e.g. Davidge & Boeshaar 1993, ApJL, 403, L47). Moreover, the largest single source of opacity in the atmospheres of cool dwarfs is the H_2O bands which dominate their near-infrared spectral-energy distribution. Knowledge of these features is essential to compute accurate luminosities and effective temperatures. Simons & Becklin (1992, ApJ, 390, 431) surveyed the Pleiades for brown dwarf candidates and found ~1 K=15 candidate per 5 square arcmin. Because these objects are point sources, they could be observed with a narrow (~ 0.4 arcsec) slit, where the faint limit is $K = 21.0$. Therefore, Pleiades-like brown-dwarf candidates could be observed out to distances of ~2000 parsecs, where the number density would be ~ 50 per square arcmin. This implies that ~ 250 brown-dwarf candidates per field would be present.

The basic conclusion of this investigation is that the number density of science sources is sufficiently high that a large gain in observing efficiency could be realised if multi-object capabilities were implemented on the Gemini IR spectrograph. Clearly the next step is to investigate the practical considerations of implementing such a capability.

GEMINI

8-M Telescopes Project

950 N. Cherry Avenue
P.O. Box 26732
Tucson, Arizona 85726-6732
Fax: (602) 322-8590

The following technical reports have been published by the Gemini Project since the last edition of the Gemini Newsletter (September 1993). Copies of these publications are available on request by contacting the Gemini Project at the above address, Fax number or by E-mail (lfriedmn@noao.edu), attention: Linda Friedman, Documentation Coordinator. Specific report numbers are listed following the author(s) name in parenthesis.

Technical Reports

6/21/93 — Visual Scientific Development & Control Environments, S. Wampler (TN-C-G0009)

8/23/93 — *Restriction Imposed on Tip-Tilt for an Off-Axis Guide Star*, M. Burns (TN-C-G0011)

8/23/93 — SNR vs. Sample Rate for Tip-Tilt Using an Off-Axis Guide Star, M. Burns (TN-C-G0012)

8/19/93 — Windshake vs. Sample Rate and Centroid Error vs. Sample Rate for Tip-Tilt Using an Off-Axis Guide Star, M. Burns (TN-C-G0013)

9/13/93 — Summary of Gemini Control Simulations, M. Burns (TN-C-G0015)

8/16/93 — Thermal Emissivity Analysis of a Gemini 8-meter Telescopes Design, Ann St. Clair Dinger, Sterling Federal Systems, Inc.; NASA-Ames Research Center (RPT-SFS-G0020)

7/13/93 — Gemini Support Facility Roof Thermal Analysis, R. Ford (TN-TE-G0016)

10/15/93 — Gemini 8m Telescope Enclosure Design Requirements Document (Rev. 2), Telescope Structure, Building & Enclosure Group (SPE-TE-G0012)

10/27/93 — Gemini 8m Telescope Enclosure Base, Support Facility & Site Work Design Requirements Document, Telescope Structure, Building & Enclosure Group (SPE-TE-G0013)

4/20/92 — Line of Sight Sensitivity Equations, E. Huang (TN-O-G0017)