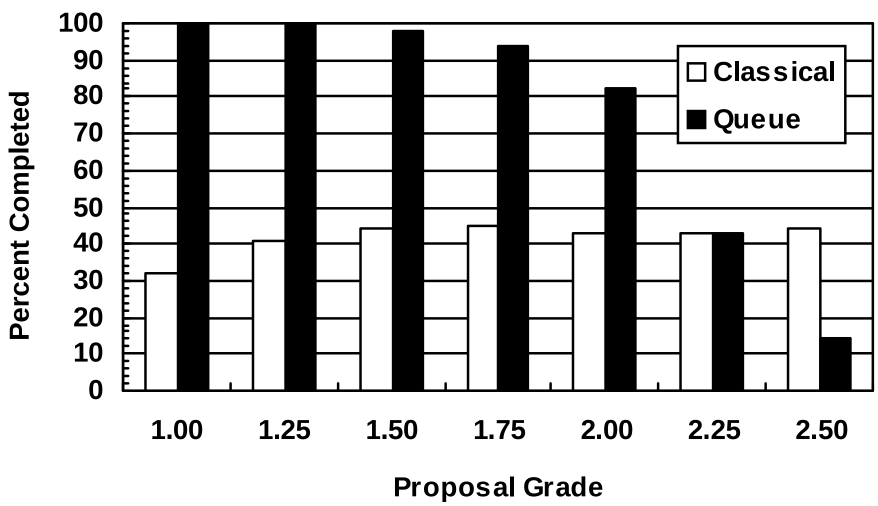
Assessment of Optimal Observing Modes with Gemini



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1.0 Introduction

The performance of the Gemini telescopes will be unique in that the sensitivity of most observations will be limited only by the physics of the atmosphere. The most important factors include atmospheric turbulence and emissivity. For example, in conditions of good seeing these telescopes will deliver images with resolutions of 0.1 - 0.2 arcseconds. In conditions of median seeing, the delivered images will have resolutions of ~ 0.4 - 0.6 arcseconds. At those thermal infrared wavelengths where the dominant source of background will be the telescope, low telescope emissivities of 2 - 4% will further increase this gain by factors of 2 - 3. The "dynamic range" of delivered image quality and infrared backgrounds will therefore be far greater than we have previously experienced with conventional ground based telescopes. As a consequence the resolution and speed with which we will be able to observe a given object will be intimately linked to the changing properties of the atmosphere.

Traditional methods of allocating time and operating ground based Optical/IR telescopes will only realize the full scientific potential of Gemini for those observers that happen to be at the telescope when atmospheric conditions suit their particular experiment. Unless we find ways of quickly adapting observations to exploit the best atmospheric conditions, the tremendous scientific potential of these telescopes will rely heavily on blind luck and the scientific benefits to the Gemini Partnership as a whole will be diminished. Consider the following simple argument. If allocations are randomly distributed throughout a given semester, the probability of any one experiment being able to exploit the best tenth percentile conditions for n consecutive nights is ~ 0.1^n assuming conditions fluctuate on a nightly basis and the entire semester is clear. The probability that an observer will get n consecutive nights where conditions are median or better is 0.5^n. The most probable outcome is of course that an observer will get a mixture of conditions, which means if seeing limited spectroscopy is being pursued, the integration times for a specific observation may vary by factors of 10 throughout a run.

In the following discussion we attempt to assess the impact that naturally varying conditions will have on the scientific output of the Gemini telescopes. Whenever possible site conditions measured at Mauna Kea by existing facilities are used to determine sensitivity variations for Gemini. Alternate observing modes are then explored to maximize the scientific productivity of the telescopes, given these varying conditions.

2.0 Atmospheric and Telescope Emissivity

The important aspect of water vapor measurements for Gemini is of course that such measurements directly map into emissivity measurements, hence the statistics of τ (the molecular optical depth) variations can be directly mapped into Mauna Kea emissivity variations. The atmospheric emissivity, ε, can be approximated by:

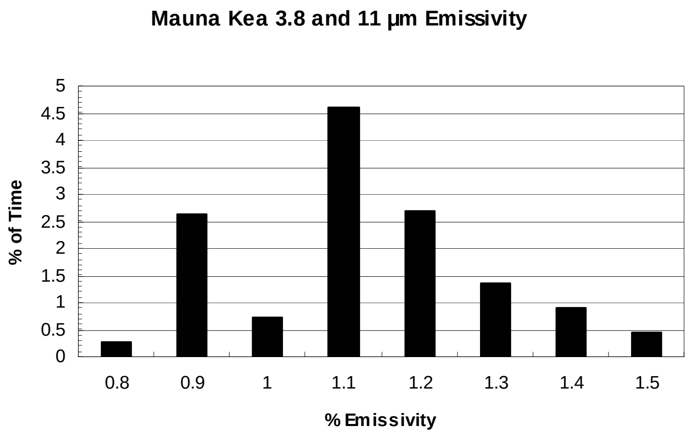

Figure 2.1 - Histograms of $\varepsilon_{3.8}$ and ε_{11} for Mauna Kea are plotted, based upon CSO τ measurements and formulae described here. Note that the ε values are identical.

$$\varepsilon \approx 1 - e^{-\tau \sec(Z)}$$

where Z is the zenith angle. Away from saturated H_2O lines, this can be approximated by:

$$\varepsilon \approx 1 - e^{-(\sigma + X_\lambda)\sec(Z)}$$

where σ is the water vapor column depth and X_λ is the contributor to the atmospheric optical depth from other molecular species. For the purposes of this analysis X_λ has been derived from Mauna Kea data and is assumed constant across the infrared windows in question. Combining the CSO measurements (discussed in §2.2) with the above formulae leads to Figure 2.1, which shows the distribution of emissivities over a 100 night period at Mauna Kea for the 3.8 and 11 µm windows. Note that due to the breakdown of the emissivity formula for large σ, only the emissivity for relatively low water vapor conditions is plotted.

Of course telescope emissivity also plays an important role in the total thermal background flux at the telescope focal plane. Figure 2.2 shows a model of the flux contribution from the atmosphere and telescope assuming a telescope temperature of 273 °K, zenith pointing, and an overall telescope emissivity of 2%. Telescope emissivity is of particular importance in the 10 µm window where, as can be seen in Figure 2.2, the contribution from the telescope in fact dominates that of the atmosphere.

2.1 Impact of Emissivity Variations on Observations

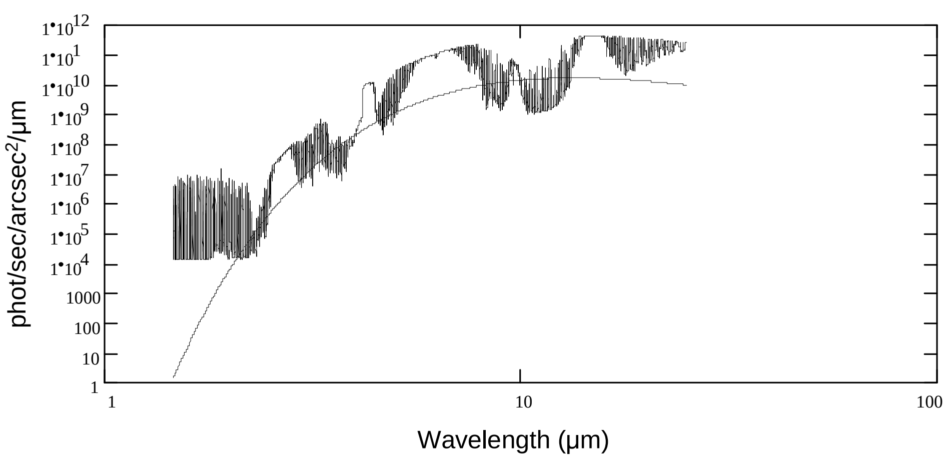

Figure 2.2 - Plots of F_λ vs. λ for the atmosphere and telescope are plotted in units of photons/sec/arcsec^2 at the Gemini focal plane.

At thermal infrared wavelengths the predominant noise source is the combined shot noise from telescope emission, any contribution from the instrument, and atmospheric emission. Consequently the S/N ratio achieved for observing a fixed brightness source scales with $(\varepsilon_{tel} + \varepsilon_{inst} + \varepsilon_{atm})^{-1/2}$, ignoring changes in absorption due to water vapor. Alternatively, the integration time required to achieve a particular S/N on any given object scales with $(\varepsilon_{tel} + \varepsilon_{inst} + \varepsilon_{atm})$.

In Figure 2.3 the relative integration times required to do a specific observation in the 3.8 and 11 μm windows as a function of water vapor column are shown. The integration times are normalized to 1 mm PWV. The two curves represent the variations expected for a telescope + instrument emissivity of 10% and 3%, the latter being the value expected for Gemini. For a constant emissivity contribution from the telescope and instrument of ~10% (comparable to values currently measured on Mauna Kea telescopes) observations are relatively unaffected by the variations in the atmosphere as integration times vary by ±5%. However, if the telescope and instrument emissivity is reduced to 3%, the sensitivity variations in the same observation can be as great as ±20% depending on the water column density during a given night. This effect is even greater when the atmospheric emissivities are even larger. Figure 2.4 shows the equivalent curve to Figure 2.3 for the 20 μm case. The actual integration time required is less dependent on the value of ε, and is in fact dominated by the variations in the atmospheric emissivity. For example at 20 μm, the integration times can be halved if the water vapor column density changes from 1.0 to 0.3 mm precipitable H_2O. Given this perspective, it appears that variations in atmospheric emissivities directly effect the integration times even on current 4 m telescopes at these wavelengths. In other words, it is not clear the standard operating modes used currently on infrared 4 m telescopes in the most appropriate way for thermal infrared observations.

2.2 Water Vapor Variations

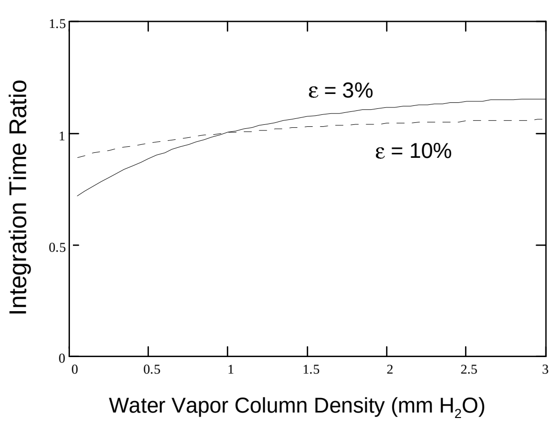

Figure 2.3 - Relative integration times for observations in the 3.8 and 11 μm windows for telescope emissivities of 3 and 10% are shown. Integration time ratios are normalized to the value at 1 mm H_2O.

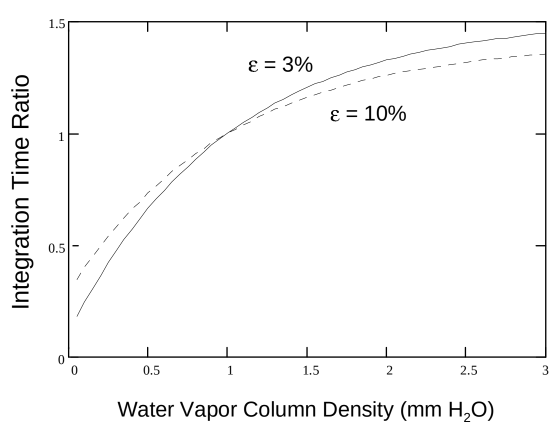

Figure 2.4 - Same as Figure 2.3 except the 20 μm case is shown. Note how large the variations in integration times are to reach a desired S/N ratio when the telescope emissivity approaches Gemini's goal of 2%.

The variations of the atmospheric emissivity at thermal IR wavelengths are predominantly due to water vapor variations in the atmosphere. The fact that the water column density can vary with time is shown quite graphically in the time sequence of satellite images of the water vapor column shown in Figure 2.5(a, b). These images are made of the earth on a regular basis by geostationary weather satellites and are made through a filter in one of the mid infrared water vapor lines. Unlike conventional weather satellite imagery, which only show condensed water (clouds), these images show both wet and dry streams of air passing over the earth's surface. These images are presented to demonstrate that the dry regions of the atmosphere move on similar time scales as any other large atmospheric structure.

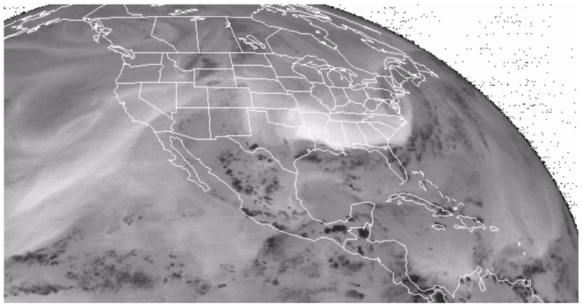

Figure 2.5(a) - Water vapor satellite imagery of the earth on August 22, 1994 is shown. Dark areas correspond to increasing water vapor absorption. Note the swath of relatively dry air across the southern U.S. behind a cold front. Also dry air is streaming from the Pacific over California and the Rockies.

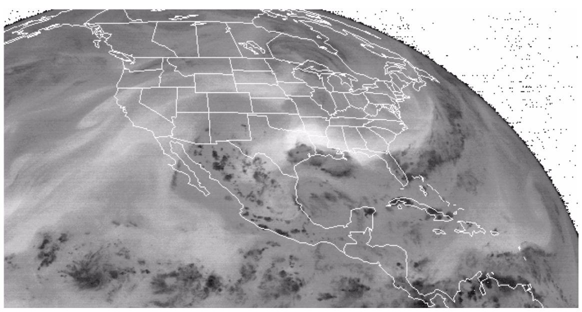

Figure 2.5(b) - Same as Figure 2.5(a) but 24 hours later. This time series illustrates the rate at which typical dry patches of the atmosphere move, i.e., generally time scales of days are required to change τ significantly for a fixed site on the earth.

Both short and long term variations in water vapor content of the atmosphere above Mauna Kea is provide by the CSO "τ meter", which measures on a continual basis the water optical depth at 225 GHz. Figure 2.6 illustrates measurements made by this monitor over the course of 100 nights in the spring and summer of 1994. Figure 2.7 illustrates about one month of night-time CSO τ measurements and confirms that the basic time scales of change implied by satellite imagery apply to ground based measurements, i.e., water vapor does not change rapidly from one hour to the next, rather it takes at least a half night to see significant changes. In the future we will attempt to correlate NOAA water vapor imagery of the central Pacific with CSO τ measurements. If these two techniques prove to be well correlated, it may be possible to *predict* nights of good or poor atmospheric emissivity, something of use in designing observing queues before each night with Gemini

The key to developing a successful operating strategy designed to exploit the infrared atmospheric emissivities is therefore to understand the time scales of water vapor variations. All of the information available points to water vapor densities being independent of the time of day and that the most significant changes occur over time scales of days rather than hours. Consequently a near optimum strategy for Gemini would be to select low emissivity nights or half nights, rather than trying to adapt to hourly changes.

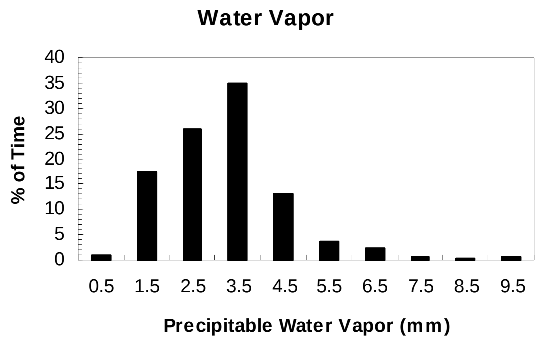

Figure 2.6 - A histogram of water vapor measurements made with the CSO τ meter is shown for 100 nights. The conversion between 225 GHz opacity and precipitable water vapor was provided by Colin Masson (1992, Proceedings of IAU Colloquium No. 140, "Astronomy with Millimeter and Submillimeter Wave Interferometry").

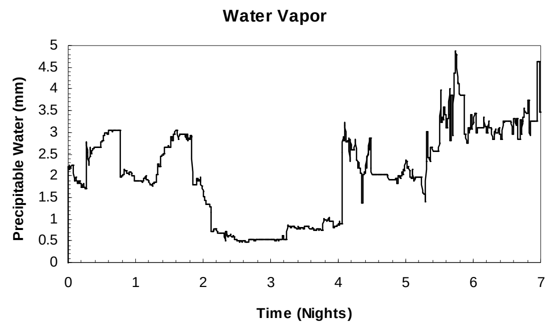

Figure 2.7 - Approximately one week of water vapor measurements made at CSO are shown to illustrate the typical rate of change in atmospheric water vapor as measured on Mauna Kea.

3.0 Image Quality - Overview

The physical processes that contribute to seeing have been well described. Variations in seeing are controlled by complex phenomena, but in general are described as the combination of telescope/dome and natural (external to the dome) seeing conditions. More specifically, to first order the delivered image quality at the telescope focal plane can approximated by:

$$\theta_{50}(delivered) \approx \{\theta_{50}(atm)^n + \theta_{50}(tel)^n\}^{1/n}$$

where n ~ 5/3 to 2. In the next section we characterize Mauna Kea atmospheric seeing conditions before assessing total seeing variations in terms of telescope sensitivity.

3.1 Image Quality - Natural Seeing Variations

Characterizing the natural seeing on Mauna Kea based upon image quality data measurements made at observatories is complicated because it is difficult to isolate telescope/dome seeing from natural seeing. Racine et al. (1991, *P.A.S.P.*, **103**,1020) attempted to do this and found that at visual wavelengths natural seeing on Mauna Kea is typically ~0.3 to 0.4 arcseconds, in agreement with other studies.

In an effort to characterize natural seeing independent of dome/telescope effects we have examined seeing data gathered by the CfA seeing monitor. This monitor measures the phase difference across a 100 m baseline from a satellite transmitting at 12 GHz. These phase differences are scaled to optical seeing by assuming Komolgorov statistics (see Mason, 1993, "Seeing", IAU Symp. 158). When compared on a night-by-night basis, seeing measured by the CfA monitor appears to be at least weakly correlated with CFHT image quality measurements. This is the most that would be expected given the myriad of complicating factors associated with the CFHT measurements. Comparing 100 nights of CfA data with Racine et al.'s measurements of natural seeing leads to Figure 3.1. In Figure 3.1 natural seeing statistics made by Racine et al. at optical wavelengths are overlaid with radio seeing measured at CfA but

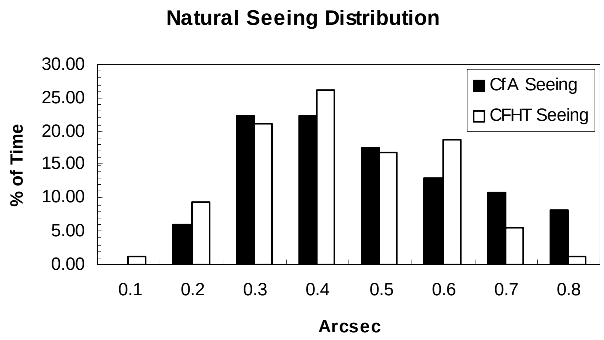

Figure 3.1 - A histogram distribution of seeing at the CfA and the CFHT is shown. Note that though the CfA monitor runs continuously, only night-time measurements are included in this histogram and the CfA data beyond 0.8" have been clipped to mimic the selection effect evident in the CFHT data (i.e., seeing measurements are not made during cloudy conditions).

scaled to optical wavelength. The fact that these seeing distributions appear so similar suggests a relationship between the physics dictating CFHT measurements and CfA measurements, i.e., water vapor may play important roles in both measurements. This relationship was predicted by Masson 1993 based upon the observation that phase variations measured across a 10 m baseline (where optical and radio data overlap) have a ratio of ~20:1 between radio and optical wavelengths, which is close to the change in refractive index of water across this wavelength range. Detailed side-by-side seeing measurement comparisons between the CfA monitor and CFHT are scheduled during 1995 to further study these phenomena. For the purposes of this report, we only wish to point out here that, given the similarity of the CfA and CFHT natural seeing measurements, we take the CfA data to be representative of natural seeing for Gemini. Hence, though this is not definitive proof of a causal connection between radio and optical seeing, the CfA database does provide a good approximation for a seeing "behavioral model" for Mauna Kea and is used as a basis for the following illustrative examples of the effects of seeing variations on Gemini observations.

3.2 Image Quality - Telescope Seeing Variations

Including the contribution from the telescope to the total seeing is also rather complicated. At 2.2 μm the Gemini image quality requirement represents a 15% increase in the tip/tilt corrected 50% and 85% encircled energy diameters (θ_{50} and θ_{85}). This is equivalent to a quadratic contribution to the θ_{50} of 0.075 arcseconds. Since the Gemini telescopes use stars to provide feedback to the active control system to maintain the telescope alignment and remove tip/tilt effects, as the seeing degrades so does the accuracy of these corrections.

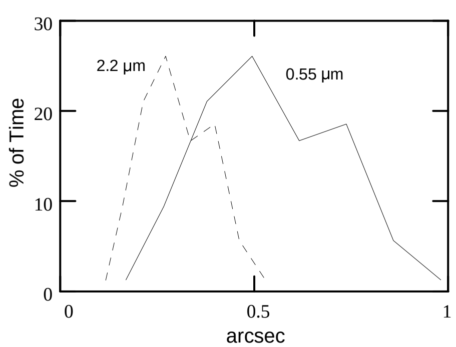

Figure 3.2 - Predicted delivered imaged quality distributions for Gemini at 2.2 and 0.55 μm are shown. Gemini will clearly be much more susceptible to optical than infrared variations.

Figure 3.2 shows the expected distribution of delivered image quality at 0.55 μm and 2.2 μm for the Gemini telescopes, assuming the histogram from Racine et al. (1991), tip/tilt removed, and r_0 scaling as $\lambda^{6/5}$.

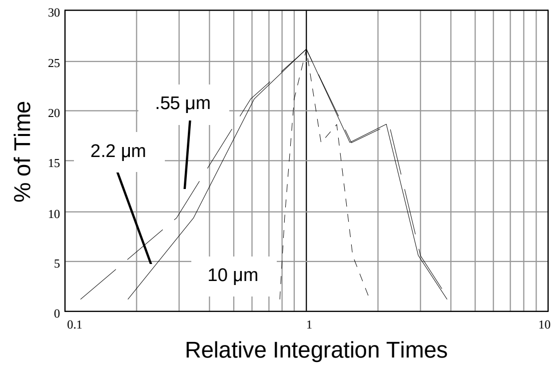

Figure 3.3 - Relative integration times at 3 wavelengths given Mauna Kea seeing distributions are plotted. Diffraction effects make 10 μm imaging least susceptible to variations in seeing.

What is the effect on a given observation due to these changing images? The spatial resolution is of course affected, and if we assume spatial information is proportional to number of resolved pixels across an image, the information content in a given image would scale as θ^{-2}. Alternatively, if the observations are background noise limited, which will be the case with most imaging and median resolution spectroscopy on Gemini, the S/N on compact sources will scale as θ^{-1}, or integration time to reach a given signal to noise becomes proportional to θ^2. Therefore for most observations on Gemini, a good relative figure of merit is

$$information\ content \approx \frac{1}{image\ diameter^2} \approx \frac{1}{integration\ time}$$

Figures 3.3 shows the effects on integration time calculated for 0.55, 2.2, and 10 μm (without chopping). At 10 μm diffraction is a dominant contributor to the delivered image quality, so the integration times are less sensitive to atmospheric seeing variations. What is apparent is that if the goal is to observe small compact objects, at wavelengths where telescope diffraction is not a significant contributor, either with small pixels or small slits, the speed that an observer can complete a given observation will vary by factors of 4 - 10 depending on atmospheric conditions.

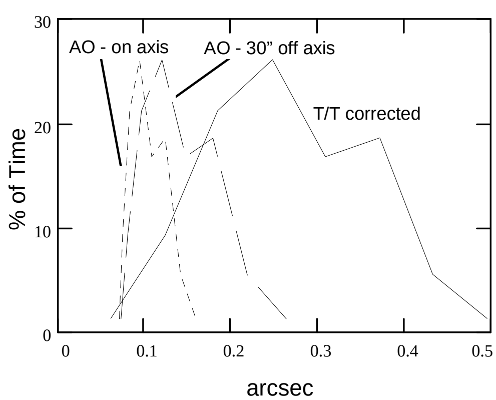

Figure 4.1 - A plot of the distribution of AO corrected image quality at 2.2 μm is shown for stars on axis (short-dash) and 30" off axis (long dash). The solid line corresponds to tip/tilt corrected.

4.0 The Role of Adaptive Optics

At near infrared wavelengths adaptive optics can significantly improve the Strehl ratios of delivered images to the Gemini focal plane. However the extent to which an AO system can correct atmospheric turbulence is directly related to the strength and speed of that turbulence, which manifests itself as "seeing", through phase errors in the correction servo both from bandwidth limitations and from measurement errors of the chosen reference star. This latter effect is simply illustrated by the measurement error expected from a simple quad cell:

$$tilt\ error \approx \frac{\lambda}{r_0} \frac{\sqrt{4 \times background + 4 \times read\ noise^2}}{flux\ across\ quadcell}$$

For a given brightness star, the measurement error is proportional to the seeing.

For a low order AO system on Gemini (n = 7) the spread in 50% encircled energy diameters at 2.2 μm has been simply modeled (using the extrapolation formulae from Racine and Roddier) in Figure 4.1 assuming the Racine seeing distribution for Mauna Kea. The short-dashed line is for an on axis point coincident with the reference star. From this plot it is clear that the spread in delivered 50% encircled energy diameters is relatively small. The long-dashed curve is for a point 30" off axis, which shows that the range in energy diameters is more pronounced. A comparison of relative integration times to reach a constant S/N normalized to the median seeing value at the center of the field is shown in Figure 4.2. In this case there is relatively small spread for on axis points, the relative integration times varying from 0.7 for the 10% best seeing to 2.0 for the 10% worst seeing value. However 30 arcseconds off axis the relative integration times can vary by 0.8 to 5 for the same seeing values. Therefore even with an AO system the integration times required across a 1 arcminute FOV, for a MOS spectrograph for example, will depend significantly on the intrinsic atmospheric seeing. This is independent of changes in the velocities <v> of high altitude winds which directly affect the Greenwood frequency through $f_G = 0.426\langle v\rangle/r_0$ and hence change the required sampling rate and servo bandwidth to produce the same degree of correction. The degradation in delivered Strehl as targets move off axis is also dependent on the effective height of the turbulent layer <h>, the isoplanatic angle being proportional to ~ 1/<h>. Hence for adaptive optics experiments both the information content in an image and the required integration times (in the case of a spectrograph) across a given FOV will depend on essentially three atmospheric parameters, r_0 (~1/θ), f_G, and <h>, all of which can vary independently through out any given run.

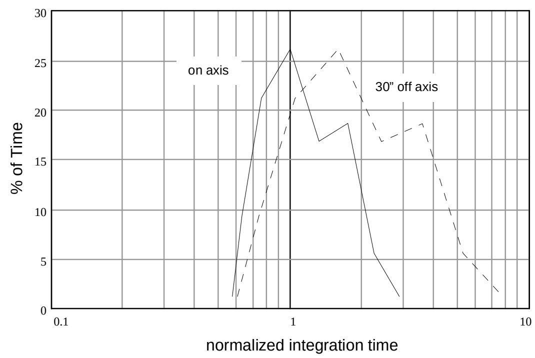

Figure 4.2 - The relative integration times at 2.2 μm for on and off axis AO corrected stars is shown.

5.0 Time scales of Seeing Variability and Seeing/Emissivity Correlations

Figure 5.1 is a plot of 4 consecutive nights of image quality measured at CFHT. Note that the image quality varies in a fairly chaotic manner, .i.e., no real cyclic behavior is found in seeing. Periods of good seeing or bad seeing can occur over hours or days.

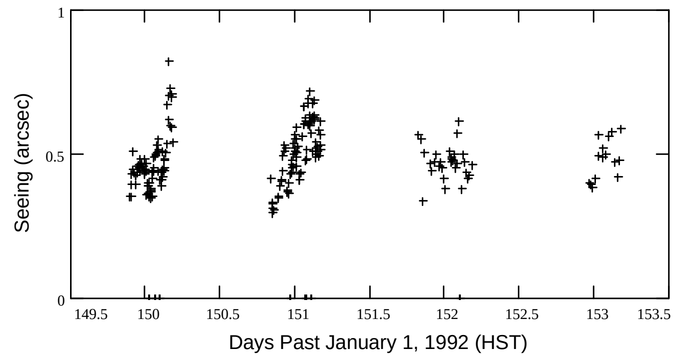

Figure 5.1 - Four consecutive nights of image quality data measured at CFHT with HRCam are shown.

As has been discussed before the processes contributing to atmospheric emissivity and atmospheric seeing are different, with the latter being a more complex interplay between several turbulent layers and high altitude winds. However, on Mauna Kea there are periods when the intrinsic seeing is dominated by a single layer, and if this layer coincides with that transporting the water vapor some correlation in conditions may exist. In fact for the CfA site survey, using the two data sets described above (CSO τ and CfA seeing), some correlation between very dry conditions and good seeing have been found. Figure 5.2 shows 3 consecutive nights of τ data and Figure 5.3 shows corresponding seeing measurements made at 12 GHz. Note that on July 12/13 the water vapor was fairly high (~4.5 mm) and stable, while the seeing was erratic and typically >2". The next night the water vapor was nearly 2X lower and the seeing was good and stable. Finally, on July 14/15 the water vapor is systematically lower from ~20 to 02 hours HST and during this time the seeing is systematically below ~1" - the only time that night seeing was subarcsecond. The trend implied by these and other comparisons is that, in the radio, seeing is correlated with water vapor density for values below ~3 mm, but above that seeing is both poor and highly variable.

All of this implies that there are conditions in the thermal IR when both the very best images can be obtained with the lowest IR backgrounds. As has been seen from the discussions in §2.1, water vapor variations effect most directly observations in the 5 and 20 µm windows, which happen to be at wavelengths where telescope diffraction is significant, and hence delivered image quality is less sensitive to atmospheric effects. At other wavelengths, 3 µm for

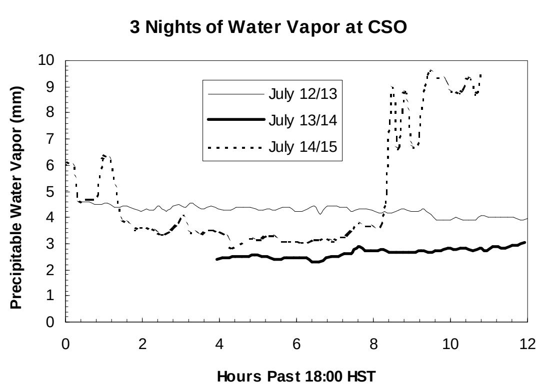

Figure 5.2 - Three consecutive nights of water vapor measurements are depicted.

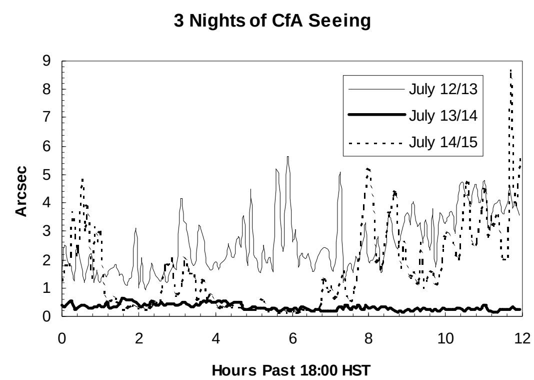

Figure 5.3 - Radio seeing measurements are presented. They are derived from the same 3 nights shown in Figure 5.1. Note that two of the nights exhibit no changes from dusk to dawn, while the third shows changes on time scales of ~8 hours.

example, the θ^2 dependency on integration time (producing factors of 2-3) is a more dominant factor in a given observation than the ±20% variations in atmospheric emissivity. Hence for this discussion we will assume that the scientific goals of Gemini can be fully exploited by considering atmospheric variations independently of emissivity variations. That is, successful observations can be planned across the Gemini wavelength range for conditions of median to high atmospheric emissivity and good seeing (0.5 - 4.0 µm) and conversely for conditions of low atmospheric emissivity in conditions of median to poor seeing (5 - 30 µm).

6.0 Photometric verses Non-photometric Nights.

A more familiar variable to traditional Optical/IR observing is whether the sky is cloud free or to what extent it is cloud covered. Adapting to cloud conditions is already a familiar problem for ground based observers, both in the infrared and optical. For example on UKIRT, which can simultaneously have up to 4 instruments mounted at the Cassegrain focus, the appearance of high altitude cirrus will make 10 µm observing nearly useless and observers will switch to 1-2 µm imaging or spectroscopy in preference to abandoning their observing run. When good photometric conditions degrade in the optical, photometrists will switch to spectroscopy, assuming a spectrograph is available, where absolute fluxes are less important. In conditions of patchy clouds all observers will adapt their observing program by switching between objects to avoid clouds.

As will be discussed in the next section, for Gemini we will need a more general extension of this "adaptable behavior", where obtaining optimum conditions will require balancing not only clear vs. cloudy conditions but also taking into consideration atmospheric emissivity, intrinsic seeing conditions, wind speed and direction and even the speed of high altitude wind for adaptive optics.

7.0 Choosing the Appropriate Observing Modes for Gemini

In an attempt to quantify the gains and losses of different observing approaches on Gemini we constructed a model that simulates the choices made among possible observations based on a distribution of environmental conditions. We have performed two experiments with this model, one simulating the WIYN 3.5-meter telescope on Kitt Peak and one simulating the northern Gemini telescope.

The reasons for starting with the WIYN telescope are a) the telescope has only two instruments, an imager and a multi-fiber spectrograph, both of which have well understood capabilities, and b) the telescope has sufficiently good optical and thermal quality that the delivered image quality distribution encompasses a large range, much as will be the case with image quality and emissivity on the Gemini telescopes.

The simulation of WIYN is laid out as follows. Each semester on the WIYN telescope consists of 75 nights (NOAO's share of the time is 40% of the total). Within the model, there are 25 programs, each program consisting of 24 observations. Each night is considered to be eight hours long, and each observation requires one hour under nominal conditions. Thus, each program can be executed in three clear nights. The proposals are assigned scientific grades, modeled on the KPNO grading system - a scale of 1.0 to 5.0, 1.0 being best. The expected distribution is approximated by the top one-third of a Gaussian with mean = 3.0 and $\sigma = 1$. This might be interpreted as a factor of three over-subscription for the telescope.

The WIYN telescope has two instruments, and the beam can be switched from one to the other in a few minutes. These instruments are an optical imager with small pixels to sample the good quality images expected from this telescope, and a multi-fiber spectrograph, which has 100 fibers positioned by a robot. The fibers project to 2 arcsecond diameter circles in the focal plane of the telescope. The expectation is that user interest will center on high resolution imaging and both low and high spectral resolution multi-object spectroscopy with the fiber spectrograph. In the model, 25% of the programs are assigned to imaging, and half of these are presumed to require seeing of 0.5 arcseconds or better. The other half of the imaging programs require 1.0 arcsecond images or better (Science programs which do not require seeing better than 1.0 arcseconds can be more effectively done on other telescopes). The remaining 75% of the observing time is assigned to the fiber spectrograph. Because the fibers have 2 arcsecond diameters, the time to reach a given S/N is not sensitive to seeing unless the seeing is worse than 1.0 arcseconds. Above that threshold, the efficiency of the system gradually degrades. Thus, we adopt an exposure time to reach a given S/N which depends linearly on the seeing when the seeing is worse than 1.0 arcsecond.

The environmental conditions for the telescope are very simply approximated. It is assumed that the skies are clear 67% of the time and cloudy 33% of the time. Each night is either entirely clear or entirely cloudy. The seeing distribution is approximated from a small amount of experience with the WIYN telescope and a larger amount with the MDM 2.4-meter Hiltner telescope. This distribution is shown in Figure 7.1. As in the case of the transparency, each night is assigned a single value for the seeing.

The simulation runs through each semester in two ways, one which approximates the classical mode of observing and one which uses a queue scheduling approach. In the classical mode, programs are chosen at random and assigned three nights on the telescope. For the transparency and seeing assigned to each night, the number of observations finished for that program are calculated. At the end of the semester, the total exposures obtained for each program are tallied. Statistics of success are kept in terms of programs of different scientific grades, programs doing spectroscopy, high

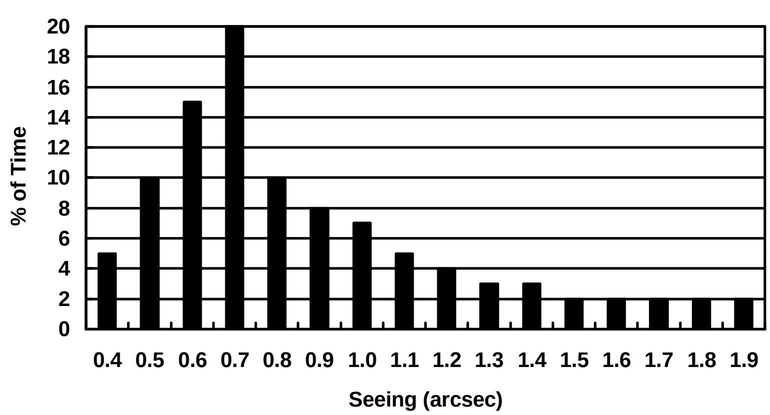

Figure 7.1 - The WIYN seeing distribution used in the model is depicted.

resolution imaging, low resolution imaging, and all programs.

In the queue mode, the programs are divided into three queues, one for the high resolution imaging observations, requiring 0.5 arcsecond seeing, one for the low resolution imaging observations, requiring 1.0 arcsecond seeing, and one for the fiber spectroscopy. On clear nights when the seeing is worse than 1.0 arcsecond, the spectroscopy observations are executed in order of their scientific rank. On clear nights when the seeing is better than 0.5 arcseconds, the high resolution observations are executed first, followed by the highest ranking proposals from the other two queues. On clear nights with intermediate seeing, the highest ranked proposals from the low resolution imaging or spectroscopy queues are executed.

After 200 runs through the one semester simulation, the results can be summarized as follows:

1. About 20% more exposures are completed in queue mode than in classical mode (63% in queue vs 53% in classical).
2. 60% (15/25) of the proposals get completed in queue mode as opposed to about 10% (2.7/25) in classical mode.
3. 60% (15/25) of the proposals get at least some data in queue mode as opposed to 90% (22/25) in classical mode.
4. The gain in queue mode is almost entirely in the imaging queues - particularly in the high resolution queue (for which only 10% of the exposures are done in classical mode while 65% are done in queue mode). This is a result of the tuning of the algorithm and the fact that this kind of observation requires conditions which only occur occasionally.
5. Among the exposures which are obtained in classical mode, there is no discrimination with grade, while for queue, essentially all the proposals down to a grade of 2.25 get done with a tail down to a grade of 3.

These results are just as expected for this very simple model. The extra exposures obtained are accounted for by the fraction of time that the requirements of the program at the telescope in classical mode are incompatible with the environmental conditions. Many more programs get completed in queue mode because programs are worked on until they are completed, rather than being kicked off the telescope after three nights. The other side of this is that everyone who comes to the telescope for three nights in the classical mode has a pretty good chance of getting some data, whereas those at the bottom of the queue do not get any data. The biggest gain in queue mode is in the programs which require the most unusual environmental conditions. The 10% success ratio for the high resolution imaging programs in classical mode is just the product of the 15% of the time that the seeing is good enough to execute these observations and the 67% clear fraction. In the queue mode, this 10% of the total nights of the semester are enough to execute two-thirds of all the high resolution imaging exposures. Finally, since the order of each queue is determined by scientific rank, the highest ranked programs are executed at the expense of the lower ranked ones.

Program	% of time	Moon	Skies	Water Vapor	Seeing
10 µm Imaging	15	any	photometric	any	not sensitive
5 µm Spect.	10	any	spectroscopic	low	not sensitive
2 µm Imaging	25	dark or gray	spectroscopic	any	background limited
Fiber Feed	10	dark or gray	spectroscopic	any	not sensitive
MOS-high res.	20	dark	spectroscopic	any	requires 20% best
MOS-low res.	20	dark	spectroscopic	any	background limited

Table 7.1 - The basic assumptions used in the Gemini queue model are outlined.

As a more sophisticated application, we also looked at a simple approximation of queue-scheduled observations on the northern Gemini telescope. For this simulation we assumed six queues of ranked programs on five separate instruments. The environmental conditions required by each of the queues are listed in the Table 7.1. For each night, we randomly drew the environmental conditions (seeing, precipitable water vapor, sky clearness) for a given night from distributions for Mauna Kea. Each program consisted of 24 observations each of which would require one hour under median conditions. The simulation was normalized to 180 nights, and the lunar phase was determined by tracking it through a 29 day cycle.

This simulation used a particularly simple algorithm for selecting a program. It merely chose the highest ranked program which was feasible under the current conditions. There was no attempt to further optimize, e.g., by executing observations requiring dark time in the hours before moonrise or after moonset on bright nights, or biasing the selection toward the proposals that require the rarest conditions.

As in the case of the WIYN simulation there are gains in overall observations obtained, programs completed, and the fraction of observations for highly ranked programs which are made. Again, the programs which require the rarest conditions see the largest increase; the MOS high resolution queue which requires seeing in the top 20% shows a gain of almost a factor of 3. The fact that the overall gain is much larger than in the WIYN simulation is due to the larger number of environmental parameters used to optimize the simulation and the larger "dynamic range" in each parameter.

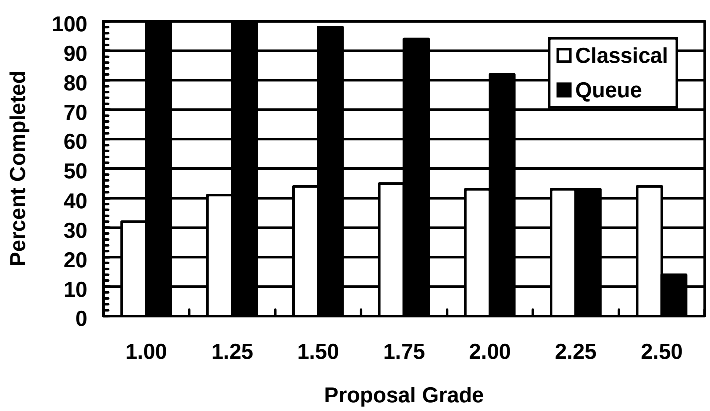

Figure 7.2 - The number of exposures completed as a function of proposal grade for classical and queue observing is plotted. Grades have been binned such that a score of 1 is the highest quality proposal. A greater fraction of highly graded programs are completed in queue than classical modes.

This simulation should be interpreted as evidence for a substantial scientific gain from queue scheduling. However, it should be noted that there are many simplifications and assumptions which make a quantitative interpretation of these results suspect. For instance, it has been assumed

	Classical	Queue
Observations Completed	43.0%	67.5%
Programs Completed	22.0%	65.8%
10 μm Imaging	47.3%	75.5%
5 μm Spectroscopy	51.0%	97.7%
2 μm Imaging	54.0%	76.8%
Fiber Feed	50.8%	73.9%
MOS-High Res.	10.2%	28.6%
MOS-Low Res.	51.2%	71.7%

Table 7.2 - The results of the Gemini queue model are summarized.

that the observer can change from any instrument to any other instrument instantly. No account has been taken of backup programs that an observer might bring for conditions less than optimum for the approved project. No account has been taken of the time required to obtain calibration data. It has been assumed that the conditions are constant throughout a night. Obviously, if the seeing timescale is short compared to a typical exposure time, the whole approach of optimizing the program for the current conditions will be very much less efficient.

8.0 Proposal for Allocating Time and Operating the Gemini Telescopes

It is clear from the discussions above that the best science will be done on Gemini when atmospheric conditions match the goals of a specific program. The best method to maximize the science done on Gemini is have access to several instruments or modes of observing and couple this versatility with an observing scheme that can adapt to changing conditions. This is at variance with the way most time is allocated on ground based Optical/IR telescopes today. The variations in integration times for high performance telescopes like Gemini are essentially statistical in nature, and during a fixed allocation of 2-3 consecutive nights, the probability of an observer being able to predict the required integration time needed to complete a program to within a factor of 2-10 is small.

One way to handle such uncertainties would be for Gemini to require observers to arrive at the telescope with a fully structured and responsive program. That is, if the best tenth percentile conditions occur observers will have backup lists of objects that can be observed if integration times are 4-5 times faster than anticipated. Alternatively if these conditions do not occur the time would be used differently but equally effectively. This raises several problems:

1. Is this backup program of the same scientific merit as the original program? If the observers require the best tenth percentile conditions for their principal program surely the TAC will require that the back-up program be of similar merit to allocate any time since the most probable outcome is that the observers will get average conditions. On both UKIRT and the JCMT, allocations of time to observe in the unpredictable 20 - 30 μm or 350 μm windows became rare as both Telescope Allocation Committees responded to the large over subscription rates by awarding time to "safe" proposals whose principal goals could return scientific results in average conditions.

2. To fully exploit the Gemini telescopes will require a great deal of preparation. For example, guide stars of adequate brightness and distance from the science object will have to be selected, the optimum elevations and azimuth tracks will have to be

selected to avoid problems with zenith blind spots, cable wrap limitations, wind bounce, lunar scattering, and airmass effects (image quality on Gemini will degrade as $\sec(Z)^{0.6}$) must all be considered. For fully structured and responsive programs observers may require up to 5 times as many objects prepared in this way, a considerable preparation overhead for conditions that may never occur.

3. If an observer or observing team develops and prepares a competitive and responsive program to seeing conditions, what happens when the seeing becomes average to mediocre but the thermal atmospheric emissivity drops to below 1% at 10 μm? It is unlikely that an observing team using the high resolution optical spectrograph (HROS) will have a fully competitive program that can use the 10-20 μm camera or visa versa - as the emissivity degrades the Optical/UV seeing allows the use of 0.3 arcsecond slits on HROS and it is unlikely that the 10 μm camera team can make optimum use of HROS which in these conditions will outperform HIRES on KECK. In both cases the most likely outcome is that the best conditions will be underutilized unless an HROS group and 10 μm camera group negotiate to determine which experiment will benefit the most from the current conditions

What becomes apparent is that if we want to fully exploit the Gemini telescopes' unique characteristics and push observational astronomy into the new regimes that has driven this project from its inception we may have to explore less traditional ways of allocating observing time. What an observer should be seeking is reliable data rather than just telescope time.

Clearly, the only pragmatic way to respond to changing atmospheric conditions is to find a way of building responsive science programs. One approach is to use an observing queuing system. In such a system several experiments (hence several instruments) are on standby to be switched in as conditions and science objectives demand. As part of the scientific justification for each program, the range of seeing or water vapor conditions acceptable will have to be outlined in the original telescope proposal. A natural question is therefore what mix of responsive queued observations and fixed duration classical allocations should be adopted. Furthermore who should be responsible for executing these programs?

It is already becoming common to allocate 10% of a semester to service observing, where pre-planned observations are performed by support astronomers on behalf of proposing astronomers. In the case of UKIRT this can be quite a responsive program, accepting applications up to 2-3 weeks before the scheduled service run. However this time is allocated classically in that it is scheduled in advance into an observing semester. Consequently the probability of a service run getting either the best tenth percentile seeing or emissivity conditions is $(0.1 \times 0.1) + (0.1 \times 0.1) = 0.02$.

A more radical model is required. For example, an entire semester of proposals can be graded into A, B, and C scientific categories by National TACs and passed to the Gemini operations team and international TAC for scheduling and prioritization "fine tuning". Adopting the model used for the CFHT, the role of the International TAC is to review the Gemini Operations scheduling plan to ensure it reflects the individual national TAC's intent and to be the scientific arbitrator in cases of scheduling conflicts.

Under a classical/queue system astronomers would in essence designate proposals as classical or queue and justify that selection in the proposal. In other words the astronomer must decide if his/her proposal is best done as classical or queued, not the TAC. Note that in these baseline definitions remote observing is not included but certainly must be included in a future more refined plan.

The follow definitions describe the basic types of proposals available to astronomers.

Classical: Proposing astronomer(s) come to site and conduct observations in the same manner commonly performed at observatories today. It is assumed that classical proposals typically get allocated 2 to 3 nights or shifts (an average of 2.5 shifts per proposal). All visitor instrument allocations would have to be categorized as classical unless the instrument team was prepared to "stand by" on Mauna Kea or Cerro Pachon for superb conditions. This does raise the issue of what happens if conditions do not permit the efficient use of a "visiting" adaptive optics coronagraph or a "visiting" 30 micron camera?

Queue: Proposing astronomer(s) remain at their home location(s) and allow the Gemini operations staff to conduct observations. These proposals may demand the absolute best conditions in order to be successfully completed. The proposing astronomer(s) should recommend the conditions required to successfully complete their program. A key part of the overall queued approach is that PI's and Gemini support staff remain in contact to confirm the integrity of data.

Under this arrangement a schedule for a semester of Gemini time would be created by first filling time slots with high priority classical runs based first upon grade then upon secondary issues like target position, lunar phase, etc. Next, a lengthy queue would be created from queue-based proposals to essentially fill in the gaps created by the fixed-schedule classical runs. Queues would be setup according to proposal grade, target position, observing condition requirements, etc. Finally engineering time would be allocated based upon scheduling constraints set by the operations staff (e.g., time needed to commission new instruments before the next semester) and discretionary time would be dispersed throughout the schedule as needed.

The best science will be done on Gemini by groups that are prepared to be responsive to conditions. For example if one group is undertaking a large number of galaxy redshift determinations using the facility MOS, the faintest fields, probably requiring the narrowest slits, are reserved for good seeing conditions. If the group has a long enough allocation there will be a significant probability that they will get to use the 0.25 - 0.3 arcsecond slits. So one approach would be to allocate this group time in hours, and they would complete all the "average observations" until conditions improved. The consequence of not getting the good conditions required for the faintest observations before the “average observations” are completed is to have the MOS group waiting around “on call” for their conditions to materialize. Another option is to leave all the preparation material with a support astronomer and ask for these observations to be put into the observatory queue for "good seeing" experiments. A similar argument can be constructed for a combined 10 - 30 μm experiment using the facility camera, again waiting "on call" for 30 μm conditions or leaving all the observing details with the support staff to be used in the "low emissivity" observation queue if low water vapor conditions did not occur during this allocation. In both these cases the programs would have to be allocated as a combination of classical and queue programs.

It is important to realize that using Gemini's facility instruments will be, especially in the early days, a relatively complex undertaking. Even the "simple" 1-5 μm imager will need to be configured for:

- filters and plate scale
- optimal read modes
- tip/tilt feedback from either the fast array readout and/or on-board or peripheral wavefront sensors and this may require further real-time optimization if wind or seeing conditions change.
- if AO is required further optimization of the order of correction and bandwidths will be required
- on board and/or peripheral wavefront sensor guide stars will have to accommodate the telescope dither pattern
- data reduction recipe chosen

Consequently significant support staff help will be needed just to optimize any given observation mode on Gemini. Given the necessary complexity and lack of maturity of the Gemini system, local knowledge will be a crucial element in observing at or near state of the art performance. Therefore once an observation has been well defined and an observing sequence planned with the help of a Gemini support astronomer, this should engender sufficient confidence to allow the support astronomer to undertake observations on behalf of allocated observers who have "run out of hours" and do not want to remain on call. A key to this will be returning reduced data quickly to the observer for review and possible revision of the observing sequences.

While there are strong arguments that can be made favoring significant fractions of observing time being allocated as queue observing, it is important to recognize the ongoing need to support classical observing at the Gemini telescopes too. There are a number of scenarios that one can envision which will demand classical observing, including:

Visitor Instruments: Gemini must be prepared to accommodate visiting instrumentation on a regular basis since there will undoubtedly be instruments developed that permit unique observations that are not possible with Gemini facility instruments. Accordingly classical runs must be assigned to accommodate the scheduling demands of visiting instruments (e.g., transportation of people, hardware, etc. to the summit).

Complex Observations: While the local operations staffs should be able to acquire data for a large fraction of the observing proposals submitted, some programs will undoubtedly require novel techniques, experience with a particular object, or demand so much manpower to complete that the local staffs will not be able to acquire data to the satisfaction of astronomers. One such example might be with the multi-object spectrograph (MOS), in which a team of people may be needed to handle detailed target acquisition/selection, background data processing, and slit cutting in a large scale MOS survey program. The experience at CFHT with their MOS has been that for programs demanding maximum data throughput from MOS a team of nearly a half dozen is required to make efficient use of summit resources (acquiring raw data, reducing images for mask selection, cutting masks, etc.). Likewise time sensitive programs like occultation experiments often require considerable expertise to carry out and may be best handled by a combination of visiting astronomers familiar with the subtleties of occultations and the local operations staff to provide guidance in the optimal use of Gemini.

Startup of Long Term Programs: Some programs may require experimentation to perfect data acquisition techniques and on-site instruction from PI's of the local Gemini staff may be needed to "train" them in the subtle aspects of the observations in order to assure that science goals are met. Subsequent observations to support such long term programs could be made by the local staff through queue runs, but only after adequate instruction has been received from the PI through a classical run.

Graduate Student Training: There is no substitute for hands-on training at an observatory in the formal training of graduate students to modern telescope operations. Accordingly it will be important that Gemini remain available to graduate students and their supervisors through classical observing runs.

There are several approaches possible to juggling the balance between classical and queued programs. Some of the possibilities have been illustrated in Table 8.1. For example "Model 1" could allocate 50% to classical allocations and the remaining 50% to queued programs. Included in Table 8.1 is an estimate of the number of staff astronomers required to support this type of allocation assuming the following:

	Mauna Kea Distribution of Nights							Number Astro's Needed
Partner	US	UK	Canada	Chile	Argentina	Brazil	Hawaii	
% of Nights	45	22.5	13.5	4.5	2.25	2.25	10	
No. of Nights	67.9	35.9	21.6	7.2	3.6	3.6	15.6	
Queue=50%	33.93	17.94	10.76	3.59	1.79	1.79	7.76	5.6
Classical=50%	33.93	17.94	10.76	3.59	1.79	1.79	7.76	
Queue=70%	47.51	25.11	15.07	5.02	2.51	2.51	10.86	6.5
Classical=30%	20.36	10.76	6.46	2.15	1.08	1.08	4.65	
Queue=100%	67.87	35.87	21.52	7.17	3.59	3.59	15.51	7.5
Classical=0%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

Table 8.1 - The distribution of nights in a semester for the various partners in the Gemini telescopes for the Mauna Kea site is tabulated for 3 possible breakdowns in queue/classical observing. For each model the total number of astronomers needed to support the model is listed. It is assumed 15% of the nights are allocated as engineering/discretionary time.

1. Classical runs (average duration 2.5 nights) require a support astronomer on the first night only.

2. Queued and Engineering time observations require a staff astronomer on the telescope every night.

3. The staff astronomers are required to work 4 nights in every 30 on the telescope (on Mauna Kea this becomes essentially 5 nights in every 30 due to acclimatization)

4. No account is made of “additional” help from visiting astronomers “on call” or graduate students.

5. Engineering/discretionary time is allocated 15% of the time available.

The probability of getting the best tenth percentile conditions for a classical or queue program would be $0.1^{2.5} + 0.5 = 0.503$ since in the 50% classical model queue programs would be done if the right conditions occurred. This could be achieved with an average of 5.6 staff astronomers

“Model 2” allocates 30% of the time to classical and 70% to queued proposals. The probability of getting good conditions for classical and queue proposals rises to $0.1^{2.5} + 0.7 = 0.703$ and requires 6.5 staff astronomers. “Model 3” is the most extreme in that it eliminates all classical allocations and implies all observations are directly undertaken by support staff. This may exclude visitor instruments and large innovative programs unless observing teams (or their graduate students) are prepared to spend a significant time at the observatory or on-call over a remote link. However it has the merit of ensuring there is a probability approaching 1.0 that all grade A queue programs will be undertaken in optimum conditions and as the previously described models have shown would produce the greatest return in data compared to the other models. A total of 7.5 support astronomers would be required to support this observing mode.

The issue of course is which of these models would give the greatest scientific return from the Gemini Telescopes and can we afford to support any of these options?

9.0 Queued Observing and Adopting a Different Approach to Operations.

The cost of operating Gemini similarly to current telescopes can be easily estimated. We will need on average 5 - 6 staff astronomers, sufficient telescope operators to keep the telescope safely running 365 days/year and an operations crew divided into a sufficient number of shifts on each telescope to ensure an engineering team be continually on call to enable the Gemini telescopes to meet their 2% down time requirement called for in the SRD. If a problem occurs it has to be fixed, usually immediately or at least within a day crew shift, which can equal only 5-6 hours on Mauna Kea, to get the visiting astronomer "back on line" before the next night begins. This is what has been appropriately called the "frenetic support model" (Boksenberg, private communication).

Now imagine being on Mauna Kea or Cerro Pachon near the turn of this century where 70% - 80% of the observations are being run by queues scheduling up to three instruments that are simultaneously mounted on the telescope. If a fault develops in say the 1-5 micron array controller, the Astronomer and Telescope Operator can take it "off line" and start up the MOS queue or 10 micron camera queue. Once this alternative instrument is "on line", one of the two support staff can try and diagnose what is wrong and log a fault report. Apologies are sent to the remote observer, if connected, and assurances given that they will be called when the problem is fixed - after all this program was rated highly and has to be done this semester. Had a fault developed with the AO system or the surface heating controller, similarly the on-site TO and Astronomer would have the option to switch to an alternative program that did not need AO or was less susceptible to mirror seeing problems. Having the freedom to adapt to unpredictable atmospheric conditions means we will also have the freedom to adapt to unpredictable faults.

The following day the day crew can try (again) to diagnose the fault and determine if it can be properly repaired (a card needs replacing) or requires more specialist help (the observing sequence has unearthed a software bug). Since the telescope has multiple queues, nothing is lost scientifically if the problem takes two to three days to repair, hence the notorious "quick fix" which is never allowed to go away, is no longer a required response.

This should allow the development of a different support model for the Gemini Telescopes. So the real questions relevant to the costs of queued observing become:

1. If upward of 70% of the telescope time is queued could we afford to have a less responsive support team in return for guaranteeing that all high priority queued observations will be completed in a given semester?

2. Even if we lose the entire telescope for a few days, do we lose anything scientifically if the operations team's principal mission is to complete all the high priority science programs at the expense of the more speculative "look and see" or calibration programs that could be rescheduled the following semester?

3. If we have two telescopes which will share identical observing systems, admittedly separated by a continent, are there instances were high priority programs could be transferred to the other telescope (we will have two MOS's, and eventually two 1-5 μm cameras)?

Queued observations offer an escape from the usual frenetic support model, of which many of us are all too familiar, to a more planned and structured approach to getting the best science out of the Gemini telescopes. At the same time we do not preclude classical observing with this approach since we can now predict with some certainty which telescope time is going to require "frenetic support" and it will only represent 20%-30% of the semester. At the turn of this century, it is likely to become the norm for teams separated by continents to consult colleagues, discuss problems and diagnose faults via high bandwidth links. Much of the software on Mauna Kea is already supported and updated remotely. We could consider operating with smaller dedicated support teams and have our "experts" concentrated only at one site rather than requiring two such teams on call at all times. Consequently, adopting a large measure of queued observing on the Gemini telescopes may actually lead to a more cost effective operation than has been appreciated and actually return better science to the Gemini partnership.

10 Conclusions

Within the next 5 years we will begin to have access to 8 meter telescopes whose performance will be limited only by the physics of the atmosphere. The combination of an increased understanding of the effects of dome and mirror seeing and the use of sophisticated control techniques to maintain telescope alignment and reduce the effects of wind buffeting mean that the delivered image quality is a sensitive function of the atmospheric seeing. Achieving telescope emissivities of 2 - 4% will further reduce the background for thermal infrared observations by factors of 2 - 4 compared to conventional telescopes when the atmospheric emissivities drop below 1 - 2%.

By looking at the variations in seeing conditions and water vapor column densities on Mauna Kea it becomes apparent that for most observations on Gemini the resolution and speed with which we will be able to observe a given object will be intimately linked to the changing properties of the atmosphere. The "dynamic range" of delivered image quality and infrared backgrounds will therefore be far greater than we have previously experienced with conventional ground based telescopes. The variations in integration times for a given experiment on Gemini will be essentially statistical in nature, and during a fixed allocation of 2-3 consecutive nights, the probability of an observer being able to predict the required integration time needed to complete a program to within a factor of 2-10 is small. The probability of utilizing the best tenth percentile conditions with this traditional approach, during which periods Gemini will have unchangeable sensitivities, is diminishingly small. A more radical model to allocating telescope time is required.

The best science will be done on Gemini by groups that are prepared to be responsive to conditions. This is at variance with the way most time is allocated on ground based Optical/IR telescopes today. We have proposed that a substantial proportion of the Telescope time be allocated as Queued observations, with a substantial part of these observations undertaken by Staff Astronomers, Visiting Astronomers on call and by Remote Observers.

The opportunity queued observations offers is to escape from the usual frenetic support model, to a more planned and structured approach to getting the best science out of the Gemini telescopes. Large responsive support teams at each site may not be prerequisite and the notorious "quick fix" may no longer be the required response to any nighttime fault. Consequently, adopting a large measure of queued observing on the Gemini telescopes may actually lead to a more cost effective operation than has been appreciated and actually return better science to the Gemini partnership.

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