Wind loading is a critical issue for large telescopes and will be even more problematic for proposed future giant telescopes. As the current-generation telescopes were being designed in the 1980s and 1990s, numerous studies were made to understand airflow through the enclosures and wind loading of the telescopes. Now that these telescopes are in operation, it is important to consider what can be learned from them to: (1) verify the assumptions and predictions of previous studies; (2) establish procedures to optimize telescope operation; and (3) guide the design of future extremely large telescopes. With these goals in mind, Gemini Observatory conducted a campaign during the integration of the southern Gemini telescope to simultaneously measure wind velocities inside and outside the enclosure and pressure variations on the (dummy) primary mirror. The data collected in this campaign have been analyzed and results are presented that address these three goals. This paper points out several results that are different from the assumptions of previous studies. It presents a rule of thumb for allowable wind speed around the Gemini primary mirror. Results are shown indicating that the average pressure pattern on the Gemini mirror is primarily produced by airflow around the telescope structure, but that much of the dynamic pressure variation at the mirror comes from turbulence generated by the enclosure. Also described is a strategy for developing realistic wind loading input for simulating the performance of an extremely large telescope, including the spatial and temporal variation of pressure on the primary mirror.

Keywords: Large telescopes, wind loading, correlation length, segmented mirrors.

1. INTRODUCTION

Before 1980, most observatories were designed to protect their telescopes from windshake as much as possible by embedding the telescopes inside large domes with minimal openings. However, a number of studies conducted in the early 1980s found that significant improvements in seeing were possible if local temperature differences could be reduced. Experience with more open enclosure designs such as the box-like enclosure employed by the MMT showed that they performed better than traditional, fully enclosed designs. In spite of the relatively larger opening and greater exposure to wind, experience at the MMT indicated that the best image sizes were obtained under a 10-20 mph wind.

These realizations led to a revolution in enclosure design, in which ventilation of the dome was recognized as being as important as wind protection. During the 1980s and 1990s, the design teams working on the current generation of large telescopes did a number of studies to understand these wind effects, as summarized in Section 2. Predicting the effect of the wind on a particular mountaintop for a given enclosure design is difficult, and often a number of simplifying assumptions were made to make the analysis possible.

Now that most of the 6-10-meter telescopes of this generation are in operation, it is possible to make direct measurements to: (1) verify the assumptions and predictions of previous studies; (2) establish procedures to optimize telescope operation; and (3) guide the design of future extremely large telescopes (ELTs).

With these goals in mind, Gemini Observatory conducted a campaign during the integration of the southern Gemini telescope to simultaneously measure wind velocities inside and outside the enclosure and pressure variations on the (dummy) primary mirror. This test program is described in Section 3. The extensive data collected in this campaign have been analyzed in a number of ways. The results are presented in Sections 4, 5 and 6. We have put the greatest emphasis on understanding how to model wind loading of extremely large telescopes, as described in Section 6.
2. PREVIOUS WIND STUDIES

Each of the current-generation large telescope projects has had to consider local seeing and wind-buffeting effects, and a number of papers and reports have been written on ventilation and wind loading of astronomical telescopes. These studies can be classified in three broad areas: investigating the effect of site topography on wind flow; evaluating the effect of enclosures to mitigate wind buffeting; and analyzing the effects of wind loading on the telescope structure and mirrors. Several different analytical techniques have been used, as summarized in the following sections.

2.1 Water tunnel tests
Several projects have tested scale models in water tunnels to evaluate airflow through proposed enclosure designs. For example, tests were conducted on preliminary Gemini Observatory enclosure designs at the water tunnel facility at the University of Washington. In these tests, vents in the sides of the enclosures were shown to reduce flushing times by factors of two to eight, and these results led to the incorporation of large vents into the sides of the Gemini enclosures.

Water tunnel tests provide an inexpensive way to visualize airflow patterns through an enclosure, and relative ventilation efficiencies can be inferred by measuring the time required to flush out air injected into the enclosure models. Because of the large differences in Reynolds number, water tunnel studies do not provide accurate representations of the turbulence in an enclosure and generally can’t give accurate quantitative information about wind loading.

2.2 Wind tunnel tests
A number of projects have also conducted wind tunnel tests of proposed telescope and enclosure designs to help determine survival-condition loads on the enclosure or telescope and to calculate mean pressures on parts of the structure (e.g., the primary mirror) for a given wind speed and orientation.

Wind tunnel tests can be used to visualize flow patterns for different wind orientations and can provide information on the static component of pressure at various points on a telescope model. However, they are generally not well suited for investigating dynamic interactions between the structure and the flow, because the several orders of magnitude difference in Reynolds number makes the accurate simulation of turbulent effects difficult, even when model features have been made intentionally rough. In addition, the pressure taps are normally recorded individually, so the data can’t provide simultaneous maps of pressure patterns over the structure.

2.3 Site Wind Characterization
Several studies have been made to characterize the wind velocity at proposed and existing observatory sites. Wind power spectra have been published for several sites and vary somewhat in their behavior. While some results track the classical Davenport spectrum, others appear to have more energy in higher frequencies, in line with the Antoniou spectrum. The published results of such tests have frequently been limited to a single sensor at a single location, and often do not include enough time in the sample to allow for long averaging to smooth out the curve.

Measurements of spectra made during site testing normally do not take into account the effects of the enclosure and telescope in increasing wind turbulence, but several studies have reported increased wind energy at higher frequencies inside telescope enclosures.

2.4 Computational Fluid Dynamics
It has become increasingly common to employ computational fluid dynamics (CFD) analyses to predict the behavior of wind flow within the environment of the enclosure and in the area around the site. This technique was employed extensively, for example, to investigate the effects of local topography at both Mauna Kea and at Cerro Pachon. The approach has the advantage of allowing visualization and evaluation of the local conditions (velocities, pressures, etc.) at a large number of points, and it allows changing flow conditions, such as wind speed and direction.

Although a number of CFD studies of telescopes have been described in the literature, these studies have been limited in the level of detail they can model, and have typically been used to predict only average pressure patterns.
2.5 Wind-Buffeting studies

Many of the studies mentioned above have shed some light on issues of ventilation air flow through enclosures, but these studies did not produce data that was very useful for predicting the dynamic wind loading on the telescope, particularly on the primary mirror. This is a difficult problem, because both the spatial distribution and temporal frequency of the wind loading on the telescope are crucial to determining the structural response. For example, most large telescope mirror support systems can handle uniform wind pressure on the primary mirror, because it is only a small fraction of the mirror weight. Similarly, telescopes with active optics systems, either large-mirror bending systems or segmented-mirror position control systems, can compensate for a non-uniform wind pressure pattern, provided that the rate of change of the pattern is slow compared to the update cycle of the active system (slower than 0.1 Hz, for example). The problem comes from non-uniform pressure patterns that change at rates faster than about 0.1 Hz.

Several studies have attempted to measure wind pressure simultaneously at several points on a telescope primary mirror. Forbes and Gabor measured patterns of pressure at the MMT and at the United Kingdom Infrared Telescope (UKIRT) using differential pressure sensors recording pressure differences between the front and back of the mirror covers. However, they only used four sensors, so the spatial information they obtained was limited. Similarly, Itoh et al made measurements at the Canada France Hawai’i Telescope (CFHT) using differential pressure sensors to record pressure differences between the front and back of the CFHT mirror cover. Again, only five sensors were used, so the spatial information was limited.

Some of the most valuable measurements of wind loading prior to the recent tests at Gemini South were those taken by Noethe et al at La Silla. In these tests, 13 pressure taps were arranged in two concentric circles on a 3.5-m plywood dummy mirror, which was tested in two locations: (1) in a prototype inflatable dome, and (2) in the New Technology Telescope (NTT) enclosure. In these tests, the 13 measurements were fit with eight Zernike polynomials in order to gain insight into the frequency response and pressure distribution on the mirror. In all cases, the data were normalized according to the measured mean wind velocity for the time record. Some power spectral density (PSD) data were published from this data set, but only limited information is provided on the instantaneous pressure distribution across the mirror or the correlation of the pressure between points. Further, the dummy mirror was not installed in a telescope structure and was not located in the true position it would occupy in the center of the dome. Even so, this was the best information available at the time of construction of the Gemini telescopes, and these data were used as part of the basis for the Gemini design.

Recent measurements relevant to the design of extremely large telescopes have come from a series of tests performed at the Nobeyama 45-m mm-wave radio telescope. These tests were primarily intended to investigate the pointing performance of the structure in wind, and combined on-sky pointing measurements with direct measurement of structural motion via a large number of accelerometers. Because the size of the structure (and thus its natural frequency) is comparable to many ELT concepts, the data provide useful information on the frequency and amplitude of structural response due to wind. For example, for a parked telescope in calm wind, the typical motions of an accelerometer near the edge of the primary reflector were on the order of one micron RMS. When the wind was blowing at about 6-8 m/s, vibration of the structure increased by nearly a factor of ten. Typical motions of the M2 support were tens of microns.

Although this response information is very useful to anyone building an ELT of similar-size, it doesn’t provide direct information on the wind loading itself.

3. SUMMARY OF GEMINI SOUTH WIND MEASUREMENTS

During the integration of the Gemini South telescope on Cerro Pachon in May 2000, there was an opportunity to make direct measurements of telescope wind loading. A series of measurements was taken by Gemini staff working in collaboration with faculty and students of the University of Massachusetts at Lowell and the University of Arizona, in a program designed to provide information on the spatial distribution and temporal frequency of the wind loading on the primary mirror, correlated with wind velocity measurements around the mirror. This type of data is not available from any of the previous wind studies cited above.
The Gemini design makes an excellent test bed for this type of wind study, since the enclosure has large vent gates that allow controlled variation of wind-loading conditions from nearly fully protected to nearly fully exposed.

3.1 Test setup
The top surface of the dummy primary mirror was instrumented with 24, and later, 32 differential pressure sensors, arranged as shown in Figure 1. Their readings were recorded simultaneously with the readings of five 3-axis ultrasonic anemometers located on the telescope and on top of the dome, at a rate of ten measurements per second for 300 seconds. For some of the tests, accelerometers were mounted on the telescope to measure the telescope structural response to the wind. Reference 26 gives a detailed description of the test setup and procedures.

![Figure 1. Locations of pressure sensors on the dummy mirror. Sensors 1 through 24 were used for the first set of tests; sensors 25 through 32 were added for the second set of tests.](image)

3.2 Test plan
We anticipated that, in addition to the wind speed, a number of parameters would affect the pressure loading on the primary mirror, including:

- Wind azimuth angle of attack (AoA)
- Telescope elevation angle (El)
- Upwind vent gate position (i.e., open, half open, closed) (UVG)
- Downwind vent gate position (DVG)

To cover the possible permutations of this parameter space with even a coarse resolution would take more test runs than time allowed. We elected instead to take a statistical approach to the test using standard design of experiments (DOE) approaches. In this way, we obtained better resolution for each of the parameters with fewer tests. The main tests falling into this category were an L16 array and two L9 arrays.

There were a total of 116 test runs of five minutes each, with 3000 time steps per test. Operating data were taken for a variety of telescope and enclosure configurations using the wind as the structural disturbance. Along with the wind test, modal tests were performed using 74 accelerometers and an instrumented impact hammer. A modal characterization report was produced by the University of Massachusetts at Lowell Modal Analysis and Controls Laboratory.

3.3 Data products
The tests produced a large volume of data. This wealth of data is both a great asset and a sizeable challenge. Much effort has already been invested in data reduction, as described in Section 5.5 of the GSMT Book. The raw data and the products of the basic data reductions such as time histories, average pressure patterns, real-time animations of the pressure patterns, power spectral density (PSD) plots, etc., are available at:

http://www.aura-nio.noao.edu/studies/smith0208/data.html.
4. RESULTS: COMPARISON TO PREVIOUS STUDIES

By studying the test data we have gained insight into many of the issues that were faced by the authors mentioned in Section 2 who tried to predict wind loading for the current generation of telescopes. These lessons learned were described in a previous paper\textsuperscript{26} and are summarized below.

4.1 Qualitative nature of wind loading on primary mirror

Several papers have modeled telescope wind loading as having a static component caused by the average wind velocity, and a dynamic component caused by the velocity fluctuation. The RMS of the dynamic component is stated to be smaller than the static component, based on the properties of the free air stream. Wind loading on the primary mirror is then found from the expression:

\[ P = \frac{1}{2} \rho CV^2 \]  

where:

- \( P \) = the pressure on the mirror
- \( \rho \) = air density
- \( C \) = a coefficient based on the mirror shape and the Reynolds number of the flow
- \( V \) = wind velocity

Because the dynamic pressure fluctuations were assumed to be smaller than the average pressure, the wind force on the mirror was assumed to continually press the mirror against its supports.

The Gemini South measurements show the true situation to be significantly different. Over any period of time longer than a few seconds, the average total wind force on the primary mirror is always close to zero, seldom more than 100 Newtons of total force on the 50 square meters of mirror surface. Wind pressures are negative (i.e., lifting off the supports) about as often as they are positive. The fluctuating portion of the wind pressure is consistently larger in amplitude than the average pressure pattern. It is clear that the turbulence induced by the enclosure and the telescope structure causes the flow patterns to be more complex than has often been assumed.

4.2 Effect of telescope structure around primary mirror

DeYoung\textsuperscript{20} modeled the wind pressure pattern on the Gemini primary mirror using CFD. Because CFD analyses are computationally intensive, the mirror and cell were modeled as a simple cylindrical disk. The resulting average pressure pattern, for a case in which the mirror is facing into the wind with the telescope pointing 30\degree from the zenith, are shown in Figure 2 (a), taken from DeYoung’s Figure 19a. An arrow has been added to show the direction of the wind.

Two of the Gemini test runs were done with the mirror in the same orientation relative to the wind. The average pressure patterns are shown in Figure 2 (b), with arrows indicating the average wind direction measured by anemometers on either side of the mirror. Note that the measured average pressure patterns are similar in shape to the CFD results (essentially a linear gradient) but they are opposite in sign. This fundamental difference is apparently caused by the telescope structure around the mirror (which can be seen in Figure 6).

To investigate this effect, Oleg Likhatchev of the University of Arizona performed a similar CFD analysis, but this time the disk representing the mirror has a raised ring around the edge to simulate the surrounding Gemini telescope structure. This analysis shows a low pressure at the leading edge of the mirror and a high pressure at the trailing edge. This pattern is very similar to the average pressure patterns measured at Gemini.

The conclusion to be drawn is that CFD analyses will only yield accurate results if they model the shape of structures in the airflow with adequate detail.

4.3 Statistical evaluation of significant parameters

The statistical design of experiments (DOE) approach mentioned in Section 3.2 provides an estimate of the random variability in the experiment, which makes it possible to identify the parameters that are significant. A group of sixteen
tests has been analyzed as an L16 experimental group. Reference 29 describes this analysis and shows graphs of average pressure PSDs with curves plotted to show the variation caused by each of the test parameters (AoA, El, UVG, and DVG) along with calculated error bars per channel for each.

This analysis yields interesting results. The most significant parameter is the position of the upwind vent gate. The amplitude of the PSD is an order of magnitude higher when the UVG is open than when it is closed. The azimuth angle of attack has a modest effect, as does the position of the downwind vent gate. However, the telescope elevation angle has no statistically significant effect on the average PSD. This is perhaps surprising, but it is worth noting that this result is consistent with a result from the La Silla testing program, in which the average pressure was found to depend on the elevation angle, but the pressure variations did not.

Analysis of an additional L9 group indicated that there is essentially no change in the average pressure PSD when the upwind vent gate is changed from half to fully open.

5. RESULTS: GUIDANCE FOR OPERATING PROCEDURES

As described in reference 26, interpolated pressure maps have been created for each time step of each test run and the resulting deformations of the Gemini primary mirror have been calculated by finite-element analysis (FEA). The pressure pattern on the primary mirror varies in a complex way with relatively high spatial frequency content, but the deformation of the primary mirror itself is simpler. The mass and stiffness of the primary makes it act as a 'filter' to the incoming force. As a result, most of the deflections due to the complicated incident forcing distribution are manifest as piston, tip, tilt, focus and astigmatism. The Gemini telescopes have fast tip-tilt-focus secondary mirrors that can remove the effects of the small rigid body motions of the primary mirror. The remaining deflection pattern is essentially astigmatism (see middle plot of Figure 8, for example, which has tip, tilt and focus removed).

Based on analysis of the 116 test runs under a variety of conditions, it was concluded that to meet the Gemini error budget the allowable velocity at the primary mirror (M1) is approximately:

\[ V_{M1} = 3.2 - 0.8 \cos(\theta) \]  \hspace{1cm} (2)

in meters per second, where:

- \( V_{M1} \) = average wind velocity at primary mirror
- \( \theta \) = the AoA of the incoming wind (\( \theta = 0 \) for M1 facing into the wind).

This is similar to the target values used by Subaru and the ESO VLT.

6. RESULTS: INSIGHTS FOR DESIGN OF FUTURE GIANT TELESCOPES

Wind buffeting is a key concern in the design of a future giant optical/IR telescope. Wind-induced vibrate can cause image motion, misalignment of the optics, and global distortion of the primary mirror. Dynamic wind loading of the primary mirror segments can also cause position errors between segments. Minimizing wind effects is a systems engineering problem that involves telescope and enclosure design, as well as active and adaptive compensating systems. Before an adequate design strategy can be developed, three key questions about the wind loading must be answered:

(1) What is the source of the wind turbulence hitting the telescope? Measurements have shown that the wind hitting large telescopes is highly turbulent, creating spatial and temporal pressure variations. The deleterious effects of wind buffeting are primarily caused by the dynamic portion of the wind loading. This could come from: (1) turbulence in the incoming wind arriving at the enclosure; (2) turbulence induced by passing through openings in the enclosure; or (3) turbulence generated by interaction of the wind with surfaces on the telescope structure itself. To improve the design, we must understand the source of the turbulence.

(2) How can we accurately simulate wind loading of a future giant telescope? A key part of this question is, how can wind loading of a giant telescope be scaled or otherwise predicted based on measurements from smaller telescopes?
How is a segmented mirror telescope affected by wind? Current telescopes have mirrors large enough that they can no longer be considered rigid in the face of wind loading. Future giant segmented mirror telescopes will not only have mirrors that have to be treated as flexible, but their mirrors could become discontinuous if the wind causes significant position errors from one segment to the next. This would complicate correction of the wavefront by adaptive optics systems. It is important to understand how the wind loading interacts with the segment size.

Our analyses of the Gemini South data have been aimed at answering these three questions and we have made significant progress in several areas, as described in the following sections.

6.1. Source of pressure variations at the telescope

As the wind flows around the telescope, areas of high and low average pressure are created. In addition, turbulence is generated that causes dynamic fluctuations in pressure. This turbulence could be caused by the topography upstream from the observatory, by the air passing through openings in the enclosure, or by the airflow around parts of the telescope structure. It is important to understand the source of the pressure variations, both spatial and temporal, and by studying the Gemini South wind data, it is possible to gain some insights.

More than a dozen test runs have strong wind flows that are essentially parallel to the surface of the primary mirror. These are cases with both vent gates open at least halfway where either the telescope was zenith pointing, or the azimuth angle of attack was 690 degrees. Under these conditions the airflow pattern is relatively simple with the direction of air flow approximately the same over the entire surface.

These cases exhibit common characteristics for both the average pressure patterns and the areas of highest RMS pressure variation, regardless of whether the wind is approaching the telescope from the observing slit, from the side vents, or halfway in between. The incoming side of the mirror always exhibits low average pressure, and the outgoing side always exhibits high pressure. The maximum pressure variability tends to be on the left and right sides of the mirror relative to the wind flow direction.

Because the effective openings in the dome are quite different for different AoA, the characteristic average pressure patterns on the mirror don’t appear to be caused by the dome. Rather, they seem to be caused by the interaction of the airflow with the telescope. Similarly, the fact that the areas of highest RMS pressure variation are associated with the sides of the mirror relative to the flow direction implies that most of this turbulence is generated at the telescope structure. If the main source of this turbulence were the air flowing past edges of the enclosure openings, the turbulence would not be as localized on the mirror, and would vary with AoA.

Angeli et al found that under high wind conditions, with the vent gates open, the wind pressure PSDs fit a theoretical von Karmann curve. Considering the bandwidth at which the lower frequency end of the von Karmann curve rolls off, a characteristic length was derived that corresponds to an outer scale of turbulence. Angeli showed that areas on the mirror that exhibited higher turbulence (for example, downwind of the central baffle tube) had shorter characteristic lengths. However, there was some indication that the characteristic length associated with the background turbulence over the majority of the mirror surface was affected by the AoA – the characteristic length was larger when the incoming air flow passed through the observing slit than when it passed through the side vents.

Xu et al reported on CFD studies of airflow past a 30-meter mirror facesheet similar to proposed designs for the Giant Segmented Mirror Telescope. In contrast to earlier CFD studies that were limited to steady-state conditions, this study models three-dimensional unsteady viscous flow. The results show significant vortices generated by the edge of the mirror. One interesting result is that a mirror model with a serrated edge formed by the edges of the hexagonal segments performed better than a simpler mirror model with a smooth, circular edge, because the large vortices evident in the circular-edge model were broken into smaller, less disruptive vortices by the serrated edge.

These studies indicate that the average pressure pattern on the primary mirror, and much of the dynamic pressure variations on the mirror, are caused by the interaction of the airflow with the telescope structure. This highlights the
need to consider aerodynamic design of the telescope structure. This is not necessarily streamlining – it may be necessary to incorporate intentionally rough surfaces to break up large vortices.

### 6.2 Scaling wind modeling to larger telescopes

Finite-element analysis can be used to evaluate the response of a proposed telescope structure to wind loading, but a fundamental question is what that loading would be on a future giant telescope. For example, the wind pressure data from the Gemini South measurements could be used to extrapolate the wind loading on the primary mirror of a giant telescope, but how should it be done? The pressure patterns could simply be scaled to a larger size, but that would imply an unrealistically large outer scale of turbulence. Alternatively, the larger mirror surface could be “tiled” with multiple copies of the Gemini pressure data, but as described in Section 6.1, it is becoming clear that in the Gemini data the average pressure pattern, and the areas of highest pressure variation, are correlated with telescope structural features around the periphery of the mirror that would not exist in the center of a larger mirror.

A key question related to this issue is whether a large proportion of the wind variation on the Gemini mirror can be represented as a time-varying amplitude of the average pressure pattern. This is based on the idea that the wind flow past the telescope creates a particular pressure pattern on the mirror, and as the outside wind velocity varies with time, the amplitude of the pressure pattern will also vary. We decided to see how well the dynamic pressure pattern could be fit with this time-varying pressure “mode”.

In the case of unsteady flow, the wind velocity at the mirror can be decomposed into the mean and a fluctuating part:

\[
\mathbf{u}(\mathbf{r}, t) = \mathbf{U}(\mathbf{r}) + \mathbf{u}'(\mathbf{r}, t)
\]

Here \( u \) is the instantaneous wind velocity, \( \mathbf{U} \) is the mean wind velocity, \( u' \) is the fluctuating (time varying) part of the wind velocity, and \( \mathbf{r} \) and \( t \) denote the position on the mirror and time, respectively.

Correspondingly, the pressure at a given point on the primary mirror can be expressed as the sum of the mean pressure and a time varying part:

\[
p(\mathbf{r}, t) = p(\mathbf{r}) + p'(\mathbf{r}, t)
\]

Here \( p \) is the instantaneous pressure, \( \bar{p} \) is the mean pressure, and \( p' \) is the time varying part of the pressure.

By neglecting the higher order terms, the mean and fluctuating parts of the pressure can be approximated as functions of the fluid density \( \rho \), the mean and fluctuating wind velocity components \( \mathbf{U} \) and \( \mathbf{u}' \), and the pressure coefficient \( C_p \), as follows:

\[
\bar{p}(\mathbf{r}) = \frac{1}{2} \rho \mathbf{U}^2(\mathbf{r}) C_p(\mathbf{r})
\]

\[
p'(\mathbf{r}, t) = \rho \mathbf{U}(\mathbf{r}) \mathbf{u}'(\mathbf{r}, t) C_p(\mathbf{r})
\]

This yields:

\[
p(\mathbf{r}, t) = \bar{p}(\mathbf{r}) \left[ 1 + \frac{2}{\mathbf{U}(\mathbf{r})} \mathbf{u}'(\mathbf{r}, t) \right] = c(\mathbf{r}, t) \bar{p}(\mathbf{r})
\]

where \( c \) is a fitting coefficient. However, we know that by definition the time average of the fluctuating velocity component is zero. It follows then that the coefficient \( c \) can be perceived as independent of position \( \mathbf{r} \), while its time average is 1.

Consequently, the pressure on the primary mirror can be expressed as the sum of a time-varying pressure pattern and a residual error term accounting for the approximations:
The fit coefficient was evaluated using a least squares fit to the data measured at the pressure sensors. Corresponding to the finite spatial sampling of the pressure measurement on the mirror, Equation 9 is modified as follows:

\[ p_i(t) = c(t) \bar{p}_i + p_{r,i}(t), \]  

where: \( p_i(t) \) is the measured pressure data at time \( t \) at the \( i^{th} \) sensor, \( c(t) \) is the coefficient of fit at time \( t \), \( \bar{p}_i(t) \) is the temporal average pressure at the \( i^{th} \) sensor, and \( p_{r,i}(t) \) is the least squares fit residual at time \( t \) at the \( i^{th} \) sensor.

To compare the magnitudes of the terms in Equation (10), the average of the pressure squared terms is computed:

\[ \bar{p}_i^2(t) = c^2(t) \bar{p}_i^2 + p_{r,i}^2(t) + 2c(t) \bar{p}_i p_{r,i}(t) \]  

Figure 3 (a) shows the average pressure pattern for a typical wind case with vent gates open. For this case, the value of the coefficient was calculated for each of the 3000 time steps using a least squares fit. The time variation of this coefficient is plotted in Figure 3 (b). Note that the average value of the coefficient is indeed 1. To evaluate how well the time-varying pressure pattern fit the data, the amplitudes of each term in Equation (9) are plotted in Figure 3 (c). As can be seen, the fitted pressure pattern contains most of the energy and the residuals are relatively small. The last term in the equation represents the cross product and its values are very small. This implies insignificant correlation between the coefficient and the residual, which in turn validates the approximation of neglecting the higher order terms in Equation (5). In Figure 3 (d) the amplitude of the residual errors is plotted for each sensor location, showing that there is only one region where localized turbulence has caused appreciable residual errors. The somewhat increased residual error indicates that very strong local effects can limit our assumption of a position independent coefficient.

These results imply that the wind loading variation can be represented accurately as a pressure pattern with time-varying amplitude, plus a relatively small amount of random variation.

Figure 4 (a) compares the PSD of the coefficient to the PSDs of the three anemometers that were close to the mirror surface. It can be seen that they have similar properties and approximately the same slope. The slope of the PSD was evaluated using a least squares fit, as shown in Figure 4 (b). The slope is –1.384, while we would expect a slope of –1.67 for velocity PSD, according to Kolmogorov theory. However, when the number of test cases is increased, the average slope falls much closer to the Kolmogorov value. For 14 cases evaluated to date, the average slope is –1.70. It shows that the fitting coefficient can indeed be treated as a linear function of the fluctuating velocity.

These results are significant because they point to a strategy for modeling the wind loading of extremely large telescopes. To model the dynamic pressure variations on the primary mirror of a future telescope:

1. Create a CFD model of the telescope in its enclosure, that has a suitable level of geometric fidelity;
2. Run a steady-state analysis of this model for a given wind orientation and speed, and determine the average pressure pattern on the mirror;
3. Create an FEA model of the telescope;
4. Apply the pressure pattern to the FEA model dynamically, with a Kolmogorov PSD, plus a small amount of random pressure variation superimposed as noise.

This approach should be feasible for integrated modeling of giant telescopes, because only steady-state CFD modeling is required, which is significantly less computationally intensive than modeling unsteady flow.
6.3 Effect of wind buffeting on a segmented mirror telescope

A segmented mirror telescope has increased susceptibility to wind buffeting because the segments are individually supported. To assess the required stiffness of these supports and the required bandwidth of segment position control, we need to understand the spatial and temporal variation of the wind pressure related to the size of proposed segments.

Angeli et al.\textsuperscript{30} evaluated the spatial characteristics of the pressure variations in the Gemini data using a structure function. For this analysis, the average pressure pattern of each data set was subtracted from the data, so the structure function represents the dynamic portion of the pressures. A correlation length was derived for each structure function. Interestingly, the correlation lengths did not depend on telescope elevation angle, but did depend on azimuth angle of attack. This suggests the dynamic portion of the pressure variability is largely caused by the turbulence generated as the air passes through the openings in the enclosure. An example of one of these structure functions is shown in Figure 5.

![Figure 5](image-url) Pressure structure function on the mirror surface facing into the wind with a zenith angle of 30 degrees.

The correlation lengths range from about 0.8 meter to 2 meters. This is significant because this is the size range of segments for most of the proposed ELT designs. Because the wind pressures are not significantly correlated over scales larger than this, the segments will tend to move independently, creating discontinuities at their edges.

To evaluate the effect of the measured wind input on a segmented mirror telescope, we have modeled a segmented mirror consisting of 36 segments, each of which is 1.33 meters across corners. Figure 6 illustrates this concept; Figure 6 (a) shows the Gemini South telescope, and Figure 6 (b) shows an imaginary segmented Gemini telescope of the type modeled. This model is appropriate for several reasons: (1) the Gemini data can be applied directly without introducing any uncertainties in scaling or extrapolation; (2) this model is sufficient to answer questions about the required stiffness of supports and the required bandwidth of the control; (3) this model provides an opportunity to further develop our integrated modeling tools for segmented mirrors; and (4) evaluating the response of a 36-segment system requires much less computational power than evaluating the response of a proposed ELT concept, such as the GSMT point design.\textsuperscript{33}

A finite-element model of the 36-segment mirror was created. The mirror support points and actuator locations are derived from the segment support for the GSMT point design. The material properties of the segment are those of Zerodur. The initial actuator stiffness was assumed to be $10^7$ N/m.

The segment finite-element model has been fully analyzed and the results have been verified with a closed-form solution. For the assumed actuator stiffness, the self-weight-induced deflection of the segment on its actuators was calculated to be 50 microns P-V along the optical axis, and the fundamental frequency of the segment on its support is 47 Hz (tilt mode).

An influence matrix was established to calculate the segment motions of piston, tip, and tilt caused by the applied wind pressures. In order to simulate the wind buffeting effects, wind pressures on each segment at each time instant were
converted to a force set \((F_z, M_x, M_y)\) evaluated at the center of the hexagonal segment. This set of forces was applied to the FE model and segment deflections were calculated for each time step.

To validate this approach, the response of the segmented mirror to a typical wind case was evaluated. Segment deformations were calculated for a test case where the telescope was zenith pointing, with an AoA of 0\(^\circ\) and both vent gates open. Figure 7 shows the response at one time step in that simulation. Figure 7 (a) shows the wind pressure pattern and Figure 7 (b) shows the segment position response. The correlation between the input and the response confirms that the model is set up correctly. The influence of the wind pressure on the segments is apparent.

Once the segment motions have been calculated, it is possible to calculate a spot diagram to simulate the combined image formed by the mirror. As a first-order approximation we have implemented a geometric ray calculation. For visible wavelengths, the diffraction-limited spot size of a single segment is approximately 0.1 arcsec. Figure 7 (c) shows a simulated spot diagram for the same time step represented in 7 (a) and 7 (b). Each small circle is 0.1 arcsec diameter and represents the position of the image from a single segment. The larger circle represents a nominal seeing-limited angular resolution of 0.5 arcsec, for comparison. We have also calculated the integrated encircled energy distributions for the entire 5-minute test run. For this case, 90\% of the energy is contained in a 0.346 arcsec diameter circle. Note that this result is for a passive mirror support, i.e., with the segment position control system turned off. The performance of the 36-segment mirror model with an active position control system is described in reference 34.

The response of the segmented mirror is quite different than the response of the real, monolithic Gemini primary mirror. The short correlation length of the pressure variations is not an issue for a relatively stiff, monolithic mirror – the Gemini mirror exhibits mostly low order aberrations as described in Section 5. However, the deformation of the segmented mirror contains high spatial frequencies. Figure 8 provides a comparison. Figure 8 (a) shows a wind pressure pattern at a particular time instant in a test case with the telescope pointed 30 degrees from the zenith, an AoA of 0\(^\circ\) and both vent gates open. This pattern was used as an example in a previous paper\(^{26}\). Figure 8 (b) is the resulting deformation (after piston, tilt, and focus were removed) of the Gemini primary mirror from this pressure pattern, determined by FEA. Figure 8 (c) is the deformation of the segmented mirror model for the same pressure pattern.

7. SUMMARY AND CONCLUSIONS

This paper has presented results, calculated from wind loading data measured at the Gemini South telescope, aimed at addressing the goals of: (1) verifying the assumptions and predictions of previous wind studies; (2) establishing procedures to optimize operation of the Gemini telescopes; and (3) guiding the design of future giant telescopes.

These data exhibit clear differences from previous assumptions about wind loading conditions in observatories. The average total wind force on the Gemini primary mirror is always close to zero, because wind pressures are negative about as often as they are positive. The fluctuating portion of the wind pressure is consistently larger in amplitude than the average pressure pattern.

The data also differ significantly from previous CFD analysis of wind pressure patterns on the Gemini mirror. Further CFD models have shown that qualitatively correct results can only be obtained if the CFD model has sufficient geometric detail to match the shape of the telescope structure.

Procedures have been developed to guide the deployment of the Gemini vent gates during telescope operation to provide adequate ventilation but keep mirror deformation within the error budget. The resulting criterion has a dependence on azimuth angle of attack, but not on elevation, because the telescope elevation angle has little effect on the dynamic portion of the wind loading.

Wind buffeting will be a significant challenge for future giant telescopes, and several key questions about wind loading must be answered: (1) What is the source of the pressure variation at the telescope? (2) How can the wind loading of a future giant telescope be simulated? and (3) How is a segmented mirror affected by wind? Through analysis of the Gemini South data, progress has been made at answering these questions.
The average pressure pattern on the Gemini mirror is primarily caused by the interaction of the airflow with the telescope structure, rather than by turbulence in the incoming wind or by turbulence generated at openings in the enclosure. This highlights the need to consider the aerodynamic design of any future telescope structure.

The characteristic length associated with the dynamic pressure variation over the majority of the Gemini mirror surface was affected by the azimuth angle of attack, which implies that this background turbulence is largely caused by the airflow through the enclosure openings. However, there are areas on the mirror with increased turbulence having a smaller characteristic length, that typically appear in the same orientations on the mirror relative to the wind direction, that appear to be caused primarily by the air flow around the telescope structure.

It has been demonstrated that, at least for the high wind (open vent) cases, the dynamic wind loading on the mirror can be represented as a fixed pressure pattern with time-varying amplitude following a Kolmogorov spectrum, plus a relatively small amount of random variation. This leads to a feasible methodology for modeling wind loading of future giant telescopes based on steady-state CFD modeling.

The correlation length of the Gemini wind pressure data is typically 1-2 meters, which will cause difficulty to mirror segments having similar dimensions, since the movements of the segments will tend to be uncorrelated. Gemini wind pressure data have been applied to a model segmented mirror, which does indeed show changing segment edge discontinuities if dynamic position control is not included in the model. FEA results show that the response of the model segmented mirror is quite different than the response of the real, monolithic Gemini primary mirror, which exhibits only low order aberrations when subjected to the same wind input.

The AURA New Initiatives Office is developing analytical and integrated modeling tools that can be used to simulate the performance of the proposed Giant Segmented Mirror Telescope. We welcome collaboration with any group interested in investigating wind loading of large telescope.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Gemini staff on Cerro Pachon in setting up and performing the wind tests, particularly John Roberts, Gabriel Perez, Pedro Gigoux, Manual Lazo, Mike Sheehan, and Pablo Prado. We would like to thank the following individuals at the University of Arizona: Oleg Likhatchev for his helpful comments and CFD analysis, Seongho Kim for animations of the wind data and FEA results, and Junpyo Lee for finite-element segment modeling. Dr. Guanpeng Xu of the Tennessee State University is also acknowledged for CFD wind flow analyses. Thanks are extended to Rick Robles for illustrations and Konstantinos Vogiatzis for helpful comments and review.

The New Initiatives Office is a partnership between two divisions of the Association of Universities for Research in Astronomy (AURA), Inc.: the National Optical Astronomy Observatory (NOAO) and the Gemini Observatory. NOAO is operated by AURA under cooperative agreement with the National Science Foundation (NSF). The Gemini Observatory is operated by AURA under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

REFERENCES

Figure 2. Predicted and measured average pressures on the mirror facing into the wind direction and tilted 30 degrees from the zenith. (a) shows the predicted pressure distribution on the surface of the 8-meter diameter Gemini mirror from a simple disk CFD model (DeYoung). (b) shows the average pressure patterns from two tests having the same relative wind angle – full scale is 65 Pascals. The black dots identify the locations of pressure sensors. (c) illustrates a CFD model with a raised edge (top) and its pressure pattern for the same wind angle (bottom). (CFD model by Likhatchev).

Figure 3. Representation of the pressure variation by a time-varying average pressure pattern. (a) The average pressure pattern on the mirror for a test with AoA = 90° and zenith angle = 60°. (b) Time history of the coefficient of fit, C(t). (c) The quality of fit for pressure-squared averages at each sensor location. (d) The average fit residuals.
Figure 4. PSD plots of $C(t)$ and wind velocity at the mirror. (a) PSD plots of $C(t)$ and the velocity at anemometers on +X, -X, and –Y axes. (b) Best fit of $C(t)$ to frequency for one test case, compared with the Kolmogarov expression.

Figure 6. The Gemini 8m telescope with the real M1 and an imaginary segmented primary replacing the real mirror.

Figure 7. Wind pressure distribution, segmented mirror response and resulting spot diagram at a single time instant.

Figure 8. Pressure and deformations for test case with AoA = 0°, zenith angle = 30°, and both vent gates open.