Concept study and validation of Antarctic telescope tower

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ABSTRACT

Studies by Mark Swain and a colleague at the Max Planck Institut für Astronomie, coupled with results from past and ongoing projects at Harvey Mudd College, strongly suggest that it may be possible to achieve imaging performance comparable to the Hubble Space Telescope at relatively low cost using available, commercial products. This is achievable by placing a 2.4 m telescope, with readily available adaptive optics, on a 30 m tower located at a high-elevation geological "dome" in Antarctica. An initial project surveyed relevant tower design approaches, then generated and evaluated six concept designs for telescope towers. Using data for typical and extreme wind at Dome C to generate wind loads, finite element analysis yielded lateral deflections at the top of 0.3 mm for typical winds and 12.1 mm for extreme gusts, with the lowest resonant frequency at 0.7 Hz; some tower concepts are innovative and allow for easy shipment, setup, and relocation. A subsequent project analyzed a tower designed by Hammerschlag and found fundamental resonance frequencies at 4.3 Hz for bending and 5.9 Hz for torsion; this project also designed and simulated an active telescope control system that maintained 17 milliarcsecond pointing error for the telescope atop the tower during typical wind conditions.

Keywords: tower, telescope, Antarctica, Dome C, pointing, controls, finite element, FEA, FEM, adaptive optics

1. INTRODUCTION

Three projects with the aim of researching and demonstrating the feasibility of next-generation infrared or optical telescopes in Antarctica have been carried out by Harvey Mudd College (HMC) in Claremont, CA, USA. The first project, conducted during the 2004-2005 academic year as a study on the transportability of a completed large-scale interferometer to central Antarctica[1], is documented in a companion paper[2]. The present report documents the second project, which occurred during the summer of 2005 and will be referred to as "initial." This project consisted of a concept study and design for a tower to elevate a telescope 30 meters above the Antarctic ice. A brief account of the third project, referred to as "subsequent," has also been included because its findings have immediate implications for earth-based, space-like interferometery. This project was carried out during the academic year of 2005-2006 in conjunction with the Max Planck Institut für Astronomie and the Sterrekundig Instituut; it used a more advanced tower design to test whether conventional controls could be used to maintain 25 milliarcsecond pointing atop the 30 meter tower. Complete documentation for the first two projects is available at http://www.eng.hmc.edu/clinic/nasajpl .

2. BACKGROUND

2.1 Motivation

Effort is underway to construct a large telescope at Dome C[1]. Research indicates that this or another dome in Antarctica offers superlative seeing conditions[2]. Weather models have suggested that elevating a telescope above the roughly 30 m (98 ft) turbulent boundary layer will further improve seeing[4]. Assuming a 2.4 m (94 in) telescope, Swain will shortly be publishing results which show that even with less than state-of-the-art adaptive optics (AO), i.e., a 37-element system, a telescope on a 30 meter tower at Dome C or Dome F should achieve a Sthrel number of 0.6 or higher in the visible wavelengths. With better AO that are still less powerful than state-of-the-art (~100-element systems), his simulations suggest that the interpretation of the Sthrel numbers in the visible range (0.8) begin to be limited by factors outside the

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model, such as the optical quality of back-end instruments, rather than seeing conditions. In this respect, the proposed concept is comparable to placing an instrument in space. Hence investigation is required to identify some structure that can elevate a heavy (10,000 to 15,000 kg or 22,000 to 33,000 lbs) telescope to 30 m and provide adequate stability to take advantage of seeing conditions. Pointing stability within 25 milliarcseconds is used as a target.

2.2 Conditions at Dome C

About 1100 km (680 miles) from the Antarctic coast, Dome C is currently accessible only by tractor-pulled sledge caravans and small aircraft[5]. The annual average temperature is roughly -45°C (-49°F) with extreme winter temperatures around -80°C (-112°F). The site is attractive to astronomers for a number of reasons including the high elevation (3200 m or 10,500 ft) and extremely dry, still air[1]. Low atmospheric turbulence makes for excellent seeing with small-wavelength telescopes. Weather models suggesting still better seeing above a 30 meter boundary layer are the motivation for this study. Other positive attributes of Dome C include very low annual snow accumulation and differential drift, as well as exceptional seismic stability[2].

Of most relevance to tower design are the wind conditions at Dome C. Most Antarctic wind is an effect of Katabatic flow, which causes wind velocity to increase moving downslope. Because Dome C is the third highest location on the continent of Antarctica, Katabatic flow is virtually nonexistent and the average ground wind velocity is a mere 2.7 m/s (6 mph)[6]. Figure 1 shows, on the left, weather simulation results for wind velocity-altitude profiles on two typical days and, on the right, an estimate with lower and upper bounds of gust velocities calculated every 6 minutes over 42 days. Another factor affecting tower design and requiring further investigation is the foundation's construction in the packed ice-snow combination, which is called firn.

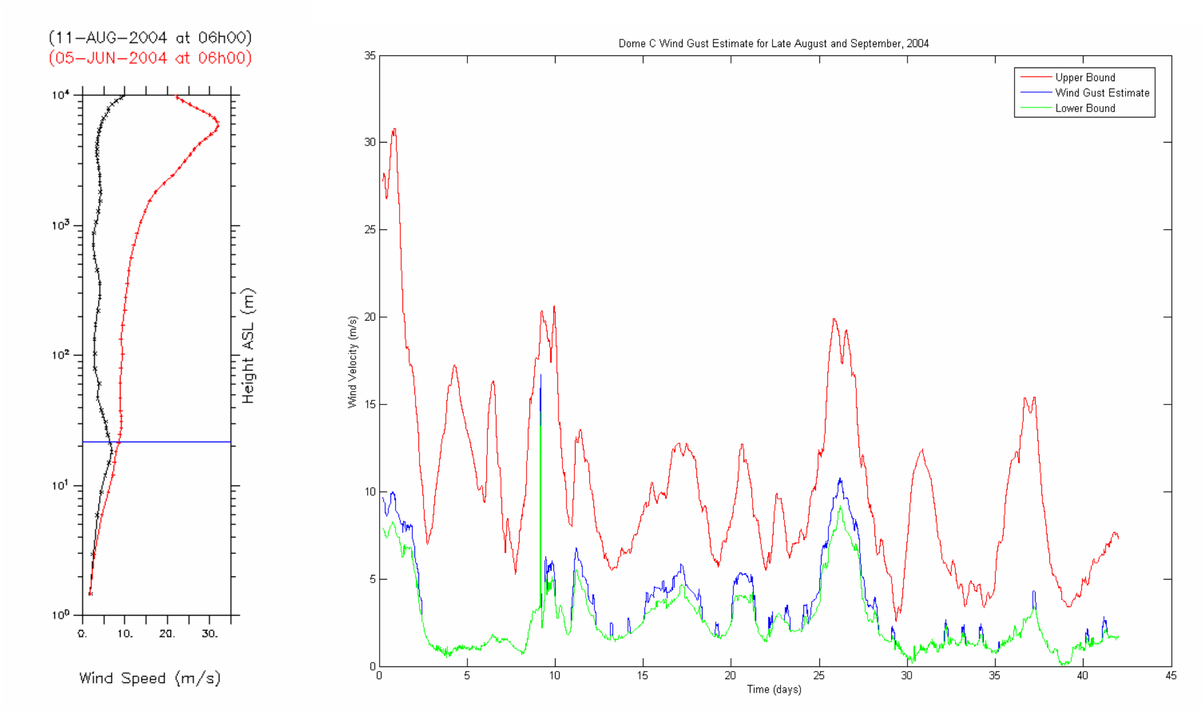

Figure 1. *Left:* Dome C wind altitude profile[4]. *Right:* Dome C wind gust estimate[7].

2.3 Description of Initial Project

The summer 2005 project began with a broad-based investigation into diverse tower types. A variety of sources were reviewed for a general understanding of tower design issues and ideas for specific designs. Research was also conducted on the evaluation and analysis of tower designs, with an emphasis on finite element techniques and the application of relevant wind loads. Design concepts were generated and built in SAP2000, a finite element modeling and analysis program. Loads were calculated from the Antarctic wind data shown in Figure 1 to simulate a range of wind conditions. Tower component dimensions were refined using an optimization technique included in the software. Then the wind loads were applied and analysis conducted; weight, deflection, modal frequency, buckling, and qualitative results were evaluated in order to compare the concept designs.

2.4 Description of Subsequent Project

In the 2005-2006 academic year, an HMC Clinic team continued the previous summer's investigation into the feasibility of stabilizing a telescope on top of a 30m tower at Dome C. The team began by re-examining the principles used to design stable towers that minimize the effects of Antarctic wind loading. The principles of stiffness, low weight, and parallel motion, as developed extensively by Dr. Robert Hammerschlag, were identified as essential. To test the performance of these concepts, the 15 m Dutch Open Telescope (DOT) tower, designed by Hammerschlag, was modeled and analyzed in ANSYS, a finite element program, using Antarctic wind loads. Results matched physical tests, thus validating the approach and enabling similar analysis of Hammerschlag's 30 m tower design. A pointing control system for a 12,000 kg telescope atop the 30 m tower was developed and simulated. Results suggested that the desired level of stability can be achieved.

3. INITIAL TOWER DESIGN

3.1 Approach

The first step was to research existing designs and possibilities. This allowed an understanding of typical towers, how they are designed, and what considerations demanded attention. The next step was to brainstorm concept designs. These were radically different from each other and in some cases very unlike typical towers. In order to analyze the concepts, the next step was detailing them to a level sufficient for simulation. This meant selecting dimensions, the number and configuration of components, and any special features such as pinned joints. Climbing devices were also added to the towers at this point. It should be noted that steel was selected for all material because of its strength and relatively low cost. Aluminum should also be explored, though care must be taken to avoid differential thermal expansion and shrinkage in multi-material structures.

In order to calculate the optimal cross-sectional shapes and sizes of structural components, SAP2000's "Steel Frame Design" feature was employed. This feature allowed the user to specify a well-known building standard, analyze the model, and use the analysis results in conjunction with the building standard to optimize the model's components. The model was then re-analyzed to find new results and subsequently re-optimized in an iterative process until improvement stopped. The building code used was *ASCE 10-97: Design of Latticed Steel Transmission Structures*[8].

SAP2000 was then used to improve the concepts' configurations. Ten variations on the most basic concept design were each optimized for strength and weight using the SAP2000 feature discussed in the previous paragraph. The variations were compared, and transferable characteristics of the variant with the best performance per weight were passed on to the other concepts. A more thorough approach would optimize each concept individually rather than applying the best characteristics of a single basic design. Next each concept was analyzed using telescope and wind loads, and the results were ready for the final comparison.

3.2 Concept Designs

The following figures and captions respectively show and describe each concept design in the optimized configuration that was used in analysis. Larger, color images are available online.

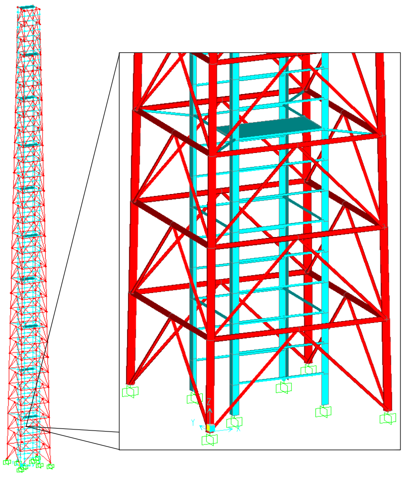

Figure 2. This tower is based on typical steel lattice towers that might be used for telecommunications antennae; it closely follows the guidelines set forth in ASCE's *Guide for Design of Steel Transmission Towers*[6] and TIA's *Structural Standards for Steel Antenna Towers and Antenna Supporting Structures*[9]. At the bottom it is a square measuring 2 m on each side, and it tapers to a 1 m x1 m square at the top. Each face has 30 equally spaced horizontal braces, and each of the gaps between braces contains two diagonal braces. Small horizontal members connect the structural and climbing lattices at the corners at every height where there is a landing. Nine other variations on this design were compared.

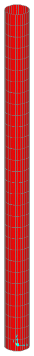

Figure 3. This design is an experiment to test if a tower can use a high mass to offer extremely high stability. Much of the answer to this question lies in a more thorough analysis of the foundation in firn. The tower is a simple circular pillar of concrete 2 m in diameter. Running its height are 8 concentrically positioned pieces of #18 (57.3 mm diameter) rebar, laterally supported by steel spirals. This tower is heavy, expensive, and difficult to construct.

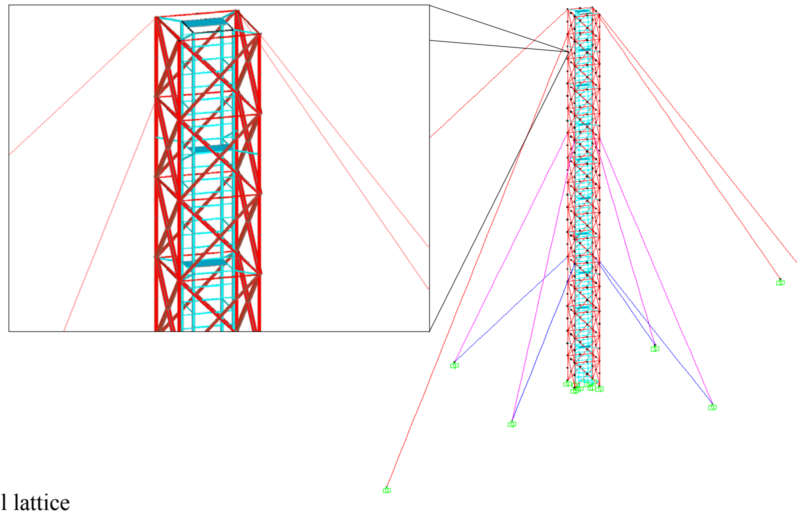

Figure 4. This tower is also a standard design. Its distinctive feature is the steel cable guys used for increased horizontal support and stability. There are three levels of guys; one comes off of each corner of the 2 m x 2 m square mast at 10, 20, and 30 m heights. The mast itself consists of 4 legs, horizontal braces spaced at each meter, and diagonal "X" braces between each horizontal. A climbing lattice identical to that in the Basic tower is located within the structural lattice. Analysis difficulties arose from an oversimplified approach to modeling the guys.

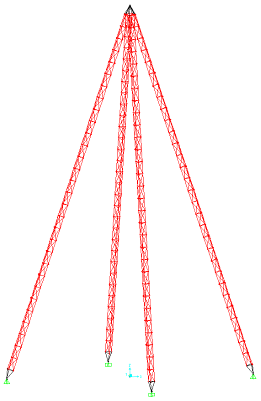

Figure 5. This design resembles the frame of a tepee. It consists of four equivalent legs. Each one is a steel truss that is strong, stiff, lightweight, and easily assembled or disassembled. This process consists of assembling the legs on the ground and hoisting them up together from the center. Provision must be made for mounting the telescope and maintenance access. Despite these issues, this is one of the easiest designs to assemble and relocate of those considered.

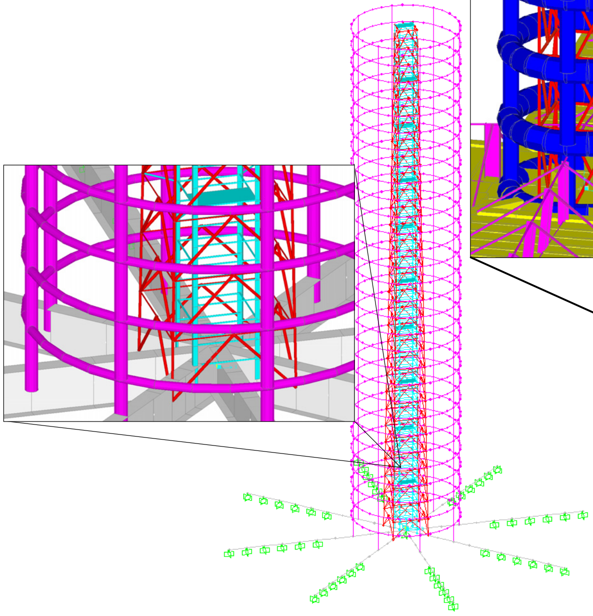

Figure 6. This design employs a wind shield to damp the effects of the wind on the tower. An internal steel lattice provides support for the telescope. It includes a climbing device. An external frame supports a thin metal or plastic shield that blocks wind. The shield is a circle 6 m in diameter that extends the full 30 m height of the tower. Its frame is a cylindrical grid that consists of 8 legs and 30 levels of horizontal supports. Similar designs in other telescopes have never succeeded in preventing all vibration transmission through the ground, but separate tower and shield foundations isolated mechanically or by distance could negate the effects of wind[10]. This model provides some isolation by fixing both the tower and shield to 8 steel 0.75 m x 0.26 m I-beams that are intended to simulate firn. A better method for simulating the foundation should be employed.

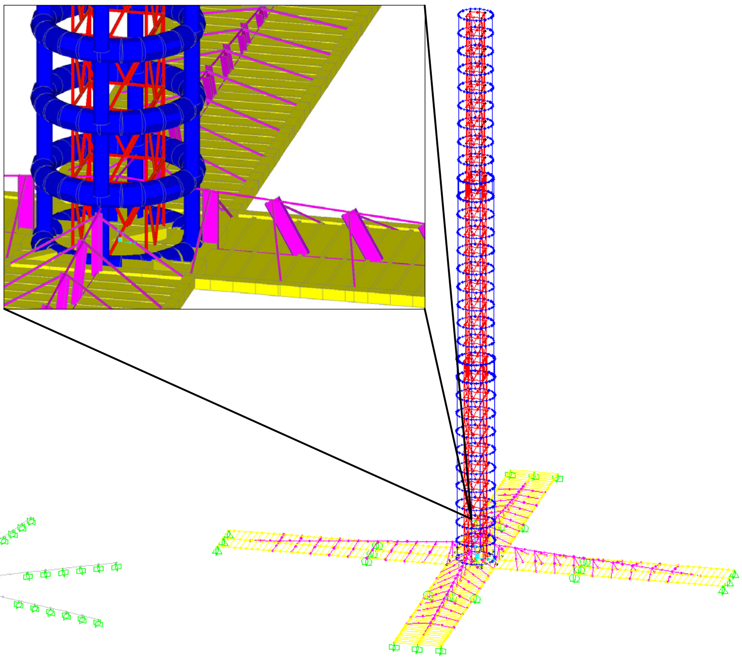

Figure 7. This concept attempts to streamline the process of shipping, setup, and subsequent relocation while maximizing performance. This is done by utilizing the tower's shipping container as a structural component. Before shipment from the construction site, both the support lattice and a protective wind shield collapse to fit within one 12.2 m x 2.6 m x 2.4 m shipping container. At Dome C, the site is prepared by compacting snow for a simple foundation. Then the container is raised on end by a crane, potentially the one already in use there. The sides of the container fold down and rest on the compacted snow, and load-distributing struts are unfolded and locked into place to complete the foundation. Then the support lattice and shield are extended to their full height, and the tower is ready to function. This process is easily reversed to allow for relocation.

4. INITIAL TOWER EVALUATION

SAP2000 used a set of user-defined parameters termed "load cases" to dictate the spatial distribution of load forces and moments on the tower. These forces were calculated by using the wind velocity data displayed in Figure 1 and techniques published in engineering standards[8,9,11,12,13,14,15]. The load values are shown in Table 1. Next, "analysis cases" were defined. These were SAP2000 parameters defined in much the same fashion as load cases. Analysis cases determined when the load cases would be applied and which mathematical analyses would be employed. Thus each analysis case yielded a specific type of information about the tower's performance. There were analysis cases to examine types of loading that varied from simple self-weight to the most extreme combination of deflected weight and gust wind loads; there were also modal and buckling analysis cases. The analysis cases are listed and described in Table 2. The results for the optimized designs show each concept's performance in terms of deflection, resonant frequencies, buckling safety factors, and weight. A detailed description of the evaluation process is included in the project's final report, which is available online at the web address cited in the Introduction.

Table 1. Load cases for each concept design.

Model	**Drag Coefficient**	**Load Case (forces in N)**							
		meansteady			**maxsteady**			**meangust**	**maxgust**
		bottom	**middle**	**top**	**bottom**	**middle**	**top**		
basic	2	202.900	447.100	684.300	811.400	1144.600	1396.500	1052.1	50946.000
basic10	1.7	265.200	650.800	1107.200	1060.800	1666.000	2259.500	1531.300	74150.000
pillar	1.16	127.900	355.300	696.300	511.600	909.400	1421.000	835.9	40477.000
guyed	2	220.500	612.500	1200.500	882.000	1568.000	2450.000	1441.3	69789.000
guy3	0.5	negligible						3.6	174.471
guy2	0.5							2.400	116.314
guy1	0.5							1.200	58.157
tepee into	varies	0.740	2.056	4.030	2.961	5.264	8.225	1.513	73.275
tepee across	varies	0.772	2.144	4.202	3.087	5.488	8.575	1.6814	81.417
shield	1.1	181.900	505.300	990.400	727.700	1293.600	2021.300	1189.000	57576.000
blossom	1.1	121.30	336.90	660.30	485.10	862.40	1347.50	792.692	38384

Table 2. Analysis cases.

Analysis Case	**Type**	**Load Case**	**Stiffness from…**	**Purpose**
DEAD	static	dead		deflection and stress from self-weight (and telescope for all), reality check
MODAL	modal	dead		undisturbed modes, reality check
BUCKLE	buckling	dead		undisturbed buckling modes and factors, reality check
WEIGHT	nonlinear static	dead		non-linear self-weight deflection and stress, generate stiffness for PD analyses
PDMODAL	modal eigen	dead	WEIGHT	modes considering nonlinearity
PDBUCKLE	buckling	dead	WEIGHT	buckling modes and factors considering nonlinearity, reality check
MEANSTEADY	nonlinear static	dead, meansteady		response to typical steady wind, precursor for MEANGUST
MEANMODAL	modal eigen	dead, meansteady	MEANSTEADY	modes considering nonlinear deflection from typical steady wind
MEANGUST	nonlinear static	meangust	follows MEANSTEADY	response to typical transient wind
MAXSTEADY	nonlinear static	dead, maxsteady		response to extreme steady wind, precursor for MAXGUST
MAXMODAL	modal eigen	dead, maxsteady	MAXSTEADY	modes considering nonlinear deflection from extreme steady wind
MAXBUCKLE	buckling	dead, maxsteady	MAXSTEADY	buckling due to extreme steady wind
MAXGUST	nonlinear static	maxgust	follows MAXSTEADY	response to extreme transient wind

5. INITIAL STUDY'S FINDINGS

Table 3 summarizes the analysis results, which are available in detail online. All simulations accounted for a 10,000 kg telescope mounted at the top. “Buckling factor” indicates the factor by which the applied load could be multiplied before buckling occurred. Some additional, qualitative metrics were used in the comparison: estimated shipping size (measured in standard 40 ft [12.2 m] shipping containers and assuming a reasonable amount of preassembly), relative ease of setup, and transportability.

Table 3. Analysis results summary.

Design	Max Vertical Deflection at Top (mm)		Max Lateral Deflection at top (mm)		First Mode (Hz)	Lowest Buckling Factor	Weight (kg) [lb]	Shipping Size (Containers)	Setup Rank	Mobility
	typical	max	typical	max	typical	max				
Basic	-3.1	4.9	11.5	101	1.75	7.63	4214 [9290]	3	3	low
Guyed	*	-316	*	780	0.84	? (>1.5)	7053 [15549]	3	5	low
Pillar	-1.3	-1.3	0.5	7.9	0.98	33.1	226456 [499250]	4+	6	low
Tepee	-4.1	-4.1	0.08	0.4	1.06	2.04	2084 [4594]	1	2	medium
Shield	-3.8	-3.9	0.3	5.1	1.09	6.1	18058 [39811]	3+	4	low
Blossom	-6.3	-7	0.3	12.1	0.7	2.03	12371 [27273]	1	1	high
* indicates that unknown computational problems caused the analysis to fail										

The optimized Basic design had deflections of one or two orders of magnitude greater than most other designs. Its weight was second lowest, and its ease of shipping and assembly made this design mediocre.

The Guyed design was relatively poorly designed and analyzed, as reflected by the results. A more informed attempt should be made before this design, or some modification to another design incorporating guys, is discarded.

The Pillar design showed acceptable deflection performance and the highest resistance to buckling, but its weight and difficulty of assembly were excessive. A hollow version might have been better, but it is unlikely that the Pillar will ever be competitive. The idea behind the Pillar design was to use extreme mass and size to impart earth-like stability to the telescope; similar possibilities including a pyramid or hill should be explored.

In lateral deflection, which is likely to be more dynamic and therefore detrimental to the telescope, the Tepee design was best. It also had the lowest weight, and easy shipping and setup. Its low buckling safety factor indicated that it was somewhat flimsy, but this may be corrected by improving the trusses that constituted its legs. However, this design provided no means for mounting the telescope or allowing maintenance access. If these issues can be successfully addressed without compromising the design's benefits, it is likely the best.

The remaining designs, Shield and Blossom, had similarly high weights. The Shield deflected much less, but would require the most additional analysis. It used I-beams with guessed dimensions to simulate the icy firn terrain, and inaccuracy likely contributed large error in one direction or the other. Despite its larger deflections, the Blossom was much stronger and would be far more convenient. It was also one of the most accurately simulated models.

Based on these results, the Tepee design appeared best but may be useless because it does not provide for installation of the telescope or maintenance access. If these issues cannot be resolved, the Blossom design is the most desirable.

6. SUBSEQUENT TOWER EVALUATION

A team of students in the Clinic program at Harvey Mudd College continued the study of stable towers by re-evaluating the most important characteristics of such a tower. They were assisted by Robert Hammerschlag of the Sterrekundig Instituut Utrecht in the Netherlands, whose designs[16] they simulated. Ultimately, wind loads corresponding to conditions at Dome C, Antarctica were applied to the models for analysis.

6.1 Towers with Stiffness, Low Weight, and Parallel Motion

Stiff, lightweight towers have proven effective in providing stable support for telescopes because their behavior is characterized by high frequency, low amplitude vibration modes. These vibrations may be compensated for by a telescope's internal fast tip/tilt mirrors. The stiffness can be increased in a number of ways. The first is by designing stiff joints in which the centerlines of the joined members meet at a common point. Utilizing triangle geometry in the design also increases the stiffness without adding significant weight. Finally, use of slender, hollow tubes and open framework designs can further reduce the weight without sacrificing stiffness. The use of an open framework design also increases the tower's transparency to wind. In addition, a tower that is designed such that its geometry is symmetric with respect to both horizontal axes will deflect symmetrically about these axes when loaded laterally. This deflection will result in movement that is parallel to the ground. For the purposes of astronomical observations, parallel deflections do not affect the pointing of the telescope.

6.2 DOT Tower

The Dutch Open Telescope (DOT) Tower is a 15m tower located on La Palma, in the Canary Islands. The tower, designed by Hammerschlag, supports a solar telescope[17]. The tower utilizes the principles of stiffness, low weight, and parallel motion; in addition the triangular legs of the telescope tower are slender, with a length to diameter ratio of 61.4:1. The legs minimize the weight of the structure and increase its wind transparency; they are symmetric with respect to the horizontal axes and deflect with parallel motion. The stiffness of the joints was increased by using fixed joints, rather than joints that were pinned or free in some degree(s) of freedom, in the telescope platform and the tower legs. Interferometric measurements recorded a maximum tilt in the east-west direction of only 0.010 arcseconds under conditions of wind gust up to 10 m/s[18].

The DOT tower was modeled to validate the team's technique prior to modeling the 30m tower. This also provided general tower response characteristics for the controls aspect of the project. Finally, the DOT analysis provided a test case that determined an appropriate level of model detail for adequate characterization of the 30m tower. Because no detailed construction documents of the DOT tower were available, the model was constructed in SolidWorks, a 3D CAD program, based on simple diagrams and pictures of the existing tower provided by Hammerschlag. The model differed from the actual tower in two ways. First, the top platform of the tower was replaced by a simple rectangular platform with a small dome approximating the substantial mass of the Dutch Open Telescope. A load approximating that due to wind resistance of the larger real platform was determined and applied to the model. Second, simplifications were made to the base of the tower in order to reduce computation time. These simplifications were compensated for by parameters introduced in the ANSYS simulation.

The 3D model was imported into the ANSYS Workbench interface using the CAD Associativity feature. A finite element mesh was generated by stipulating appropriate sizing, method, and relevance constraints to various parts of the model. Contact regions between parts in the solid model were defined as pure bonded contacts in order to constrain degrees of freedom relative to the contact surfaces and approximate contacts using bonded epoxy. This linear contact type was chosen over alternate nonlinear contacts (frictional and rough) on the basis that relative motion between contact pairs in the real tower was negligible. To compensate for the removal of the stiffening structure at the base of the tower, the bottoms of the columns were designated as fixed points. The eigenfrequency stiffening mechanism, a minor component used to adjust the tower's frequency, was simulated by a beam with one end attached where the mechanism would be and the other end fixed in space. Structural damping in the tower was approximated by introducing a β-damping factor for proportional damping, and the damping mechanism between members was approximated by introducing a constant damping term. The loading was determined using the following wind velocity-to-force relation $F_{wind}=Aav^2X$, in which A was the projected area of the cross section in ft^2, a was a proportionality constant of 0.004 $\mathrm{psf \cdot mph^{-2}}$, v was wind velocity in mph, and X was a dimensionless constant dependent on the cross-sectional shape (0.67 for a cylinder). The wind velocities used were taken from data measured by Travouillon[2]. The forces were applied as distributed loads across the surfaces of the members and platform.

Results of the simulation included frequency response estimates for the platform. These results closely matched information obtained from physical tests of the tower, thus validating the analysis technique sufficiently to warrant its use on the 30 m tower design.

6.3 30 Meter Tower

Hammerschlag has also worked on the design for a stiff, lightweight 30 m tower that can be used to support a telescope of 12,000 kg. This tower is to be built with coupled c-beams and tubes of varying diameter. The base of the tower will be 12m by 12m square. In Figure 8, the four outer posts comprise the parallel motion framework for the tower.

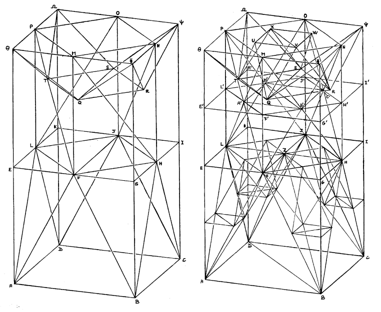

Figure 8. 30m Tower (simplified version on left)

The inner structure of the tower resists torsion and bending, keeping the tower stiff while still maintaining a minimalist construction. The stiffening structure imparts only lateral forces that do not interfere with the parallel motion frame. They force the structure into a higher buckling mode. The 30m tower was simultaneously evaluated with two separate methods. One method constructed a model of the tower in SolidWorks, then transferred it into ANSYS Workbench for analysis; the other method constructed and analyzed the tower using only ANSYS.

In the SolidWorks model, tube diameters were assigned as specified in the design by Hammerschlag. Joints between the tubes were designed to be stiff and lightweight with a single intersection point. To simplify the model, tubes with appropriately calculated inertial properties replaced all coupled c-beams. In the ANSYS-only model, material and structural properties were assigned to simulate a tower built of the appropriate tubes and coupled c-beams. This model was also analyzed with forces derived from Travouillon's data.

The frequencies and deformation shapes of the lowest 30 eigenmodes were determined for the SolidWorks model. The first bending mode was found at 4.3 Hz. Regarding the telescope's pointing, this result is of small consequence because motion parallel to the ground is maintained in bending. The greater potential threat comes from torsional motion, and the first torsional mode was found at 5.9 Hz. These results were considered trustworthy based on the analysis of the DOT tower, which showed strong agreement with physical tests.

7. CONTROL SYSTEM

A control system may be necessary to correct motion that is transmitted through the tower to the telescope as well as any vibrations caused by wind loading directly on the telescope. The control system proposed by the team contained two parts: a pointing model designed to move the entire telescope, and a model that controlled the tip-tilt mirror. The former model was required to change overall pointing on the sky by shifting the telescope about both the azimuth and elevation axes; the latter controlled for small scale motion. The pointing servo was designed to control for low frequency, higher amplitude vibration while the fast tip-tilt mirror attenuated higher-frequency, lower-amplitude vibration.

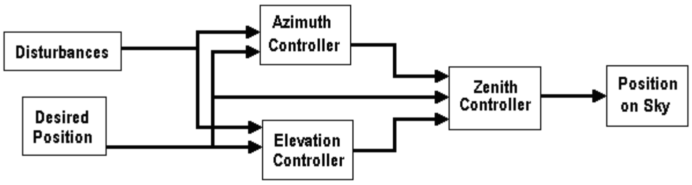

Figure 9. Block Diagram of Pointing Model.

Figure 9 shows a block diagram of the pointing model. EOS Technologies supplied a general pointing model, used for their 1.8 meter telescope, which utilized a PID control system. Control was improved by adjusting the PID coefficients. Desired pointing angle and wind-induced disturbances, provided by Hammerschlag[16], were input to both the azimuth and elevation axis controllers. Each axis input ran through a closed-loop control system and was then combined in the zenith controller to produce the final telescope position on the sky.

The large-scale pointing servo controlled pointing accuracy within fractions of an arcsecond, but not within the given goal of 25 milliarcseconds RMS needed for interferometery. To fine tune the pointing, the signal was sent through the fast tip-tilt mirror servo controller. To approximate a tip-tilt pointing servo, the EOS Technologies model was used as a template. The main parameters changed were the PID coefficients and the constants for the moments of inertia. Another modification took into consideration the tip-tilt mirror's limited range of angular motion compared to that of the telescope. With both control systems in place, the error due to the previously mentioned input was reduced to approximately 30 milliarcseconds.

To correct for some remaining error at a frequency too low even for the pointing controller, a parametric oscillator was added as shown in Figure 10.

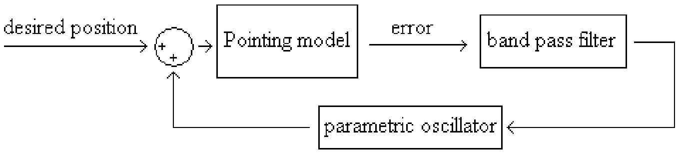

Figure 10. Model with added parametric oscillator.

This was implemented by applying a band-pass filter to the error from the pointing model, thus selecting the amplitude and frequency to be corrected. From this low-frequency disturbance, an identical signal was generated with a relative phase displacement of $\pi/2$; Figure 11 shows the low-frequency disturbance as the choppy signal and the parametric oscillator wave as the smooth signal. The parametric oscillator signal was added to the *rate of change* of the disturbance, thus greatly reducing the disturbance as time progressed. Another small phase adjustment was made to account for the propagation time of the pointing error signal through the band-pass filter.

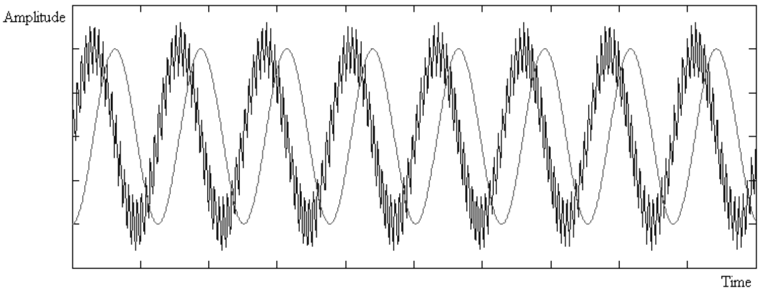

Figure 11. Pointing model (choppy) and parametric oscillator (smooth) signals.

Figure 12 shows a block diagram of the combined system, or the global pointing model, with the parametric oscillator and its band-pass filter simplified to a feed-forward signal customized for this simulation. The error obtained by the whole system was approximately 17 milliarcseconds RMS, substantially better than the goal of 25 milliarcseconds.

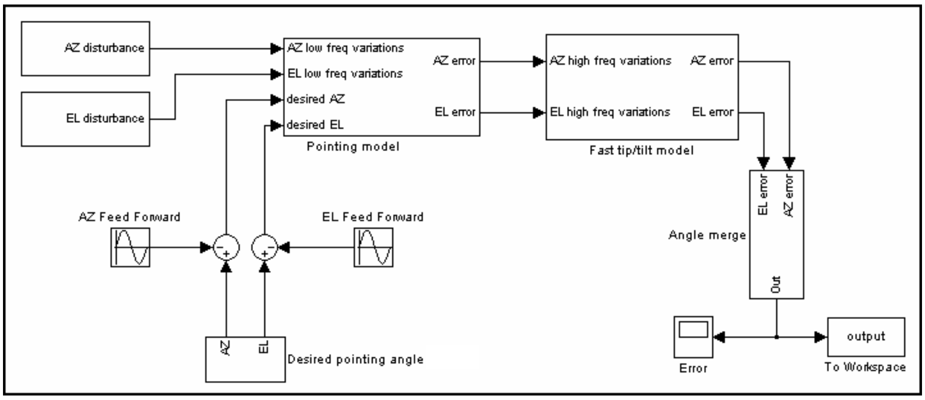

Figure 12. Global pointing model.

A series of simulations was run to determine the allowable time delay in, and overall effectiveness of, the feedback loop. A delay of 0.03 seconds caused some instability in the system; with more than 0.05 s of delay, the system fell into extreme instability. In tests of open loop versus closed loop, the closed loop data path with feed-forward gave errors on the order of 17 milliarcseconds RMS, while the open loop path resulted in errors around 3 arc*minutes*. Figure 13 shows the final result for the closed loop control system.

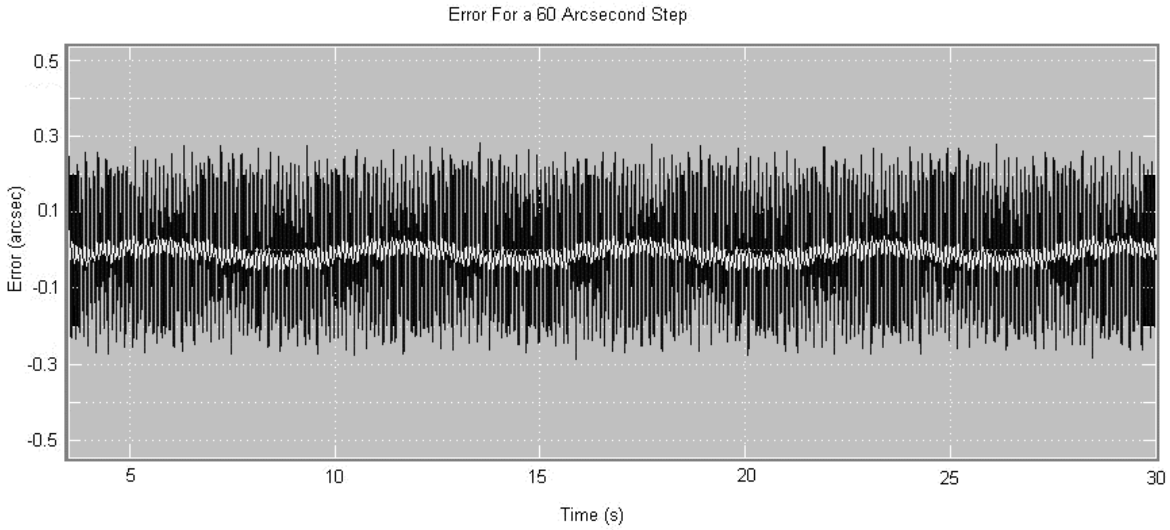

Figure 13. Wind-induced disturbance (black), and corrected pointing (white).

8. CONCLUSION

Two studies used finite element analysis and feedback control design to evaluate the stability of a telescope on a 30 m tower in Antarctica. The initial study provided innovative concept designs for telescope towers. When supporting a 10,000 kg telescope, lateral deflections at the top of the most desirable design were limited to 0.3 mm in typical winds and 12.1 mm in extreme gusts, with a first resonant mode at 0.7 Hz. The subsequent study showed that a more sophisticated tower design by Robert Hammerschlag had lowest resonant modes at 4.3 Hz for bending and 5.9 Hz for torsion. A control system for pointing and adaptive optics was designed to maintain a pointing error of 17 milliarcseconds for a 12,000 kg telescope on this tower, thus facilitating Hubble-like capabilities in an Antarctic telescope built with relatively inexpensive current technology.

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