Appendix I
Temperature Impact on Cable Tensions

1.0 Introduction

The telescope structure is exposed to the elements and experiences daily fluctuations in air temperature and solar radiation levels. Temperature changes in the steel and concrete cause these materials to expand or contract, affecting the forces in the structure. The steel cables naturally tighten at night as they cool down and slacken during the day as they warm up. In the upgraded structure, the tiedown cable tensions are also actively controlled with jacks to keep the suspended structure at a constant elevation while the temperature varies. This appendix presents our analysis of the effect of the daily temperature cycles on the cable tensions.

2.0 Data

Our analysis relies on three sets of data recorded at the Arecibo Observatory (AO): air temperature, cable socket temperature, and tiedown tensions.

2.1 Air Temperature Data

The air temperature was measured continuously by a weather station located on the suspended structure (Figure 1), and we were provided with the minimum and maximum temperature recorded every day since January 2000. Although we only considered data between January 2005 and December 2015 due to gaps in the data outside that range, we consider those 11 years of data sufficient since the daily temperature cycles are not expected to vary significantly from year to year.

In this appendix, the *daily temperature range* is the difference between the high and low temperatures over a 24-hour period. The distribution of the daily temperature range between 2005 and 2015 is shown in Figure 2. The average range is 12.3°F, with a standard deviation of 3.0°F. Figure 3 shows the average daily low and high temperatures for each month of the year. While the temperatures are approximately 5°F higher in the summer months than in the winter months, the temperature range does not change significantly month to month. Additional air temperature statistics for each month are provided in Table 1.

Figure 1: Location of weather station on suspended structure
(photo: Mario Roberto Duran Ortiz, Wikipedia - CC BY-SA 4.0).

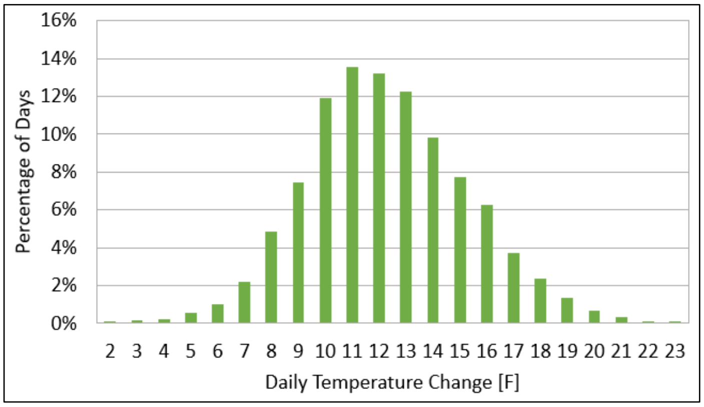

Figure 2: Distribution of daily air temperature ranges (January 1, 2005 to December 31, 2015).

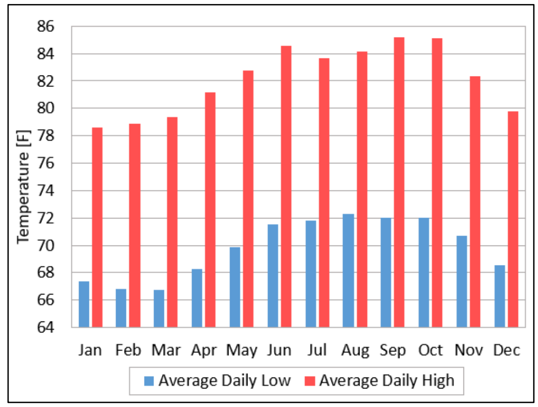

Figure 3: Monthly average of daily low and high air temperatures (January 1, 2005 to December 31, 2015).

Table 1: Daily air temperature range statistics by month (January 1, 2005 to December 31, 2015).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average Daily Low [°F]	67.4	66.8	66.7	68.3	69.9	71.6	71.8	72.3	72.0	72.0	70.7	68.6	69.8
Average Daily High [°F]	78.6	78.9	79.4	81.2	82.7	84.5	83.7	84.1	85.2	85.1	82.3	79.8	82.1
Average Daily Range [°F]	11.2	12.1	12.6	12.9	12.8	13.0	11.9	11.9	13.2	13.0	11.6	11.2	12.3
Daily Range Std. Dev. [°F]	3.3	3.2	3.1	2.9	3.0	2.8	2.6	2.9	3.1	2.7	2.9	2.8	3.0
Daily Range Coef. of Variation	0.29	0.26	0.24	0.22	0.24	0.22	0.22	0.24	0.23	0.20	0.25	0.25	0.24

2.2 Steel Temperature Data

After the first cable socket failure in August 2020, some of the remaining sockets were instrumented by Wiss, Janney, Elstner Associates, Inc. (WJE). For six of the sockets, the instrumentation included a thermocouple that measured the steel temperature on the surface of the socket. A month of data for one of the sockets is shown in Figure 4 as an example.

The average daily low and high surface temperatures for each of the six sockets are shown in Figure 5. The daily low temperature is consistently between 70.5°F and 72.5°F for every socket, while the daily high temperature varies more significantly between sockets, from 83°F to 90°F. The wider range of daily high temperatures may be due to shade, as each socket surface with a thermocouple is shielded from direct sunlight at a different time of the day. Additional statistics on the socket surface temperatures are provided in Table 2. On average over the six sockets, the daily temperature range is 14.8°F, which is 2.5°F higher than the average daily air temperature range, and can be attributed to solar radiation heating up the steel to a temperature higher than that of the air.

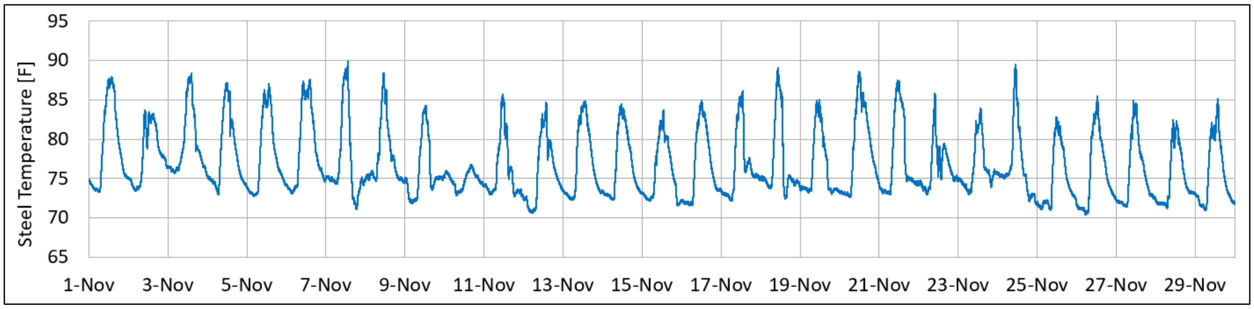

Figure 4: B4N socket surface temperatures recorded in November 2020.

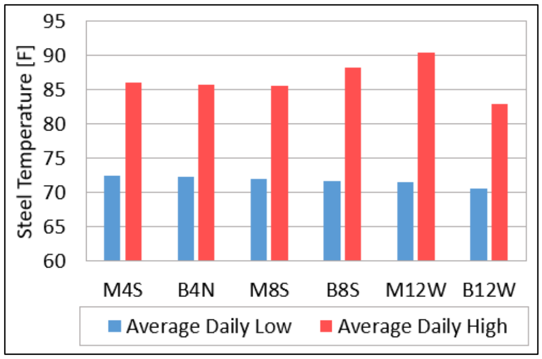

Figure 5: Average daily low and high socket surface temperatures in November 2020.

Table 2: Statistics on socket surface daily temperature range in November 2020.

	M4S	B4N	M8S	B8S	M12W	B12W	Overall
Average Daily Low [°F]	72.5	72.3	71.9	71.6	71.4	70.6	71.7
Average Daily High [°F]	86.1	85.7	85.6	88.2	90.4	83.0	86.5
Average Daily Range [°F]	13.6	13.4	13.7	16.6	18.9	12.4	14.8
Daily Range Std. Dev. [°F]	2.8	2.6	2.6	3.3	3.1	1.9	3.6
Daily Range Coef. of Variation	0.21	0.19	0.19	0.20	0.17	0.15	0.24

2.3 Tiedown Tension Data

The upgraded telescope structure has three vertical tiedowns connecting the platform to the ground below through the primary reflector (Figure 6). Each tiedown consists of two parallel cables tied to the ground with a single electro-mechanical jack (Figure 7). The jacks are used to adjust the tiedown tension so that the platform remains at a constant elevation while the structure undergoes temperature changes. The three jacks are displacement-controlled and share the same displacement at any point in time. The jack displacement adjusted automatically based on the average elevation of the platform, which is measured from the rim road with laser rangers.

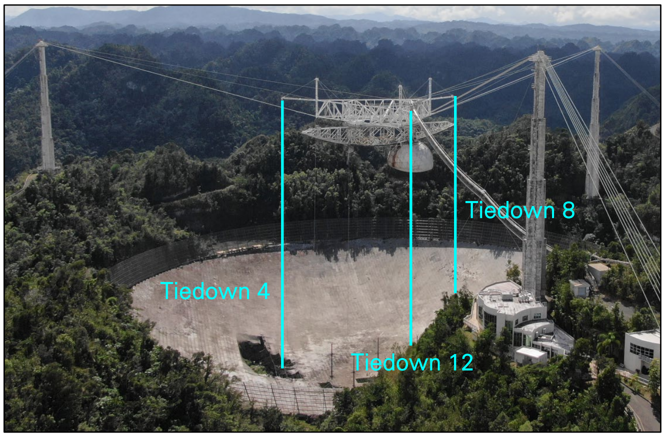

Figure 6: Upgraded structure tiedowns *(photo: NSF).*

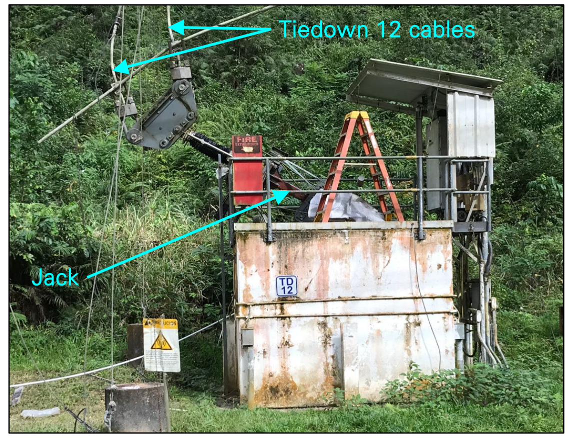

Figure 7: Base of tiedown 12, after telescope collapse.

Each tiedown cable is also equipped with a load cell that measures the cable tension. Cable tensions recorded since 2004 were provided by AO, together with records of the azimuth arm, Gregorian and line feed positions. This data is shown in Figure 8 and Figure 9 for two weeks near the start and end of the data set: the first week of August 2020 (last week of telescope operation, before the first cable failure), and the same week in 2004 (the first year for which tiedown tension data is available). For both weeks, the total tiedown tension (sum of the six tiedown cable tensions) experiences relatively smooth daily cycles compared to the more rapid changes of the azimuth arm, Gregorian and line feed positions, which is consistent with the tiedown jacks being adjusted to compensate only for temperature effects over the course of a day. The total tiedown tension varies between 60 kilopound (kip) and 120 kip in 2004, and between 30 kip and 90 kip in 2020. The overall decrease of 30 kip between 2004 and 2020 may be due to further loads added to the suspended structure or to some relaxation in the cable system supporting the structure. However, in both 2004 and 2020, the total tiedown tension varies by approximately 60 kip each day.

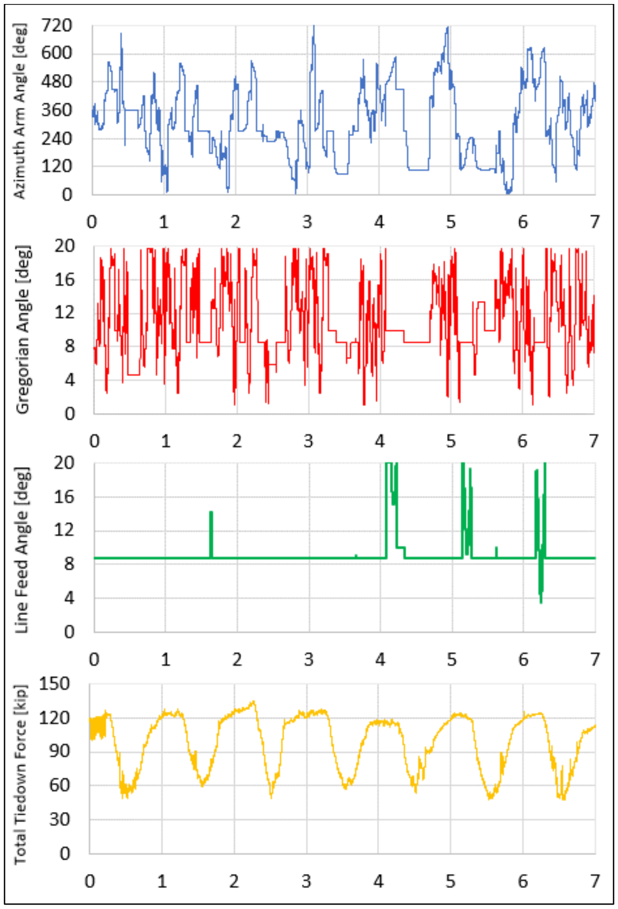

Figure 8: Telescope operation monitoring data for first week of August 2004.

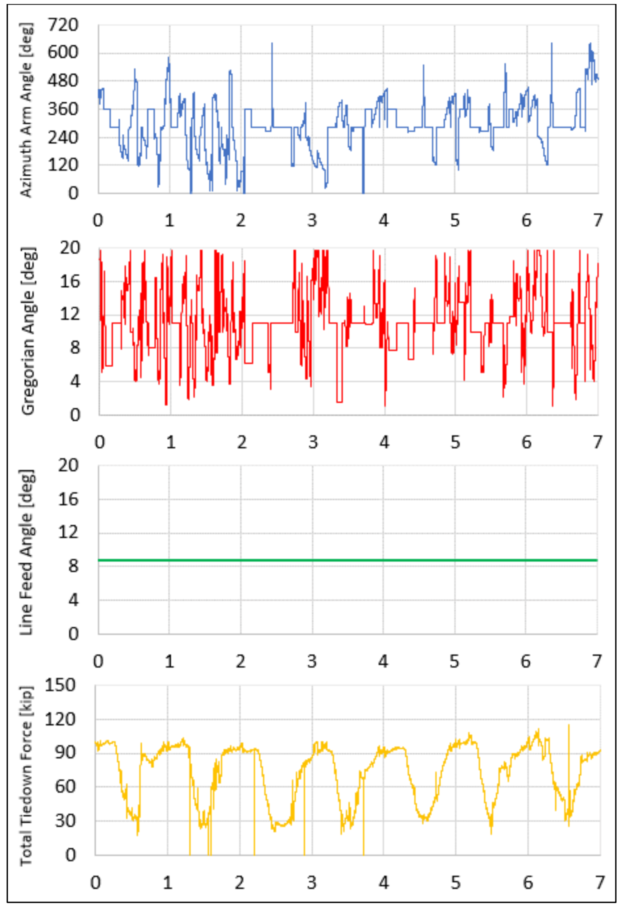

Figure 9: Telescope operation monitoring data for first week of August 2020.

3.0 Analysis

Based on the above data, we performed heat transfer and structural analysis to determine the effect of daily temperature cycles on the cable tensions.

3.1 Concrete Tower Temperature Analysis

No temperature measurements of the concrete towers are available, as far as we know. The towers are made of 6-foot-thick reinforced concrete walls. Since concrete has a relatively low thermal conductivity, most of the tower volume should remain at a constant temperature through the day-night cycle. To verify this, we performed a heat transfer analysis on two tower cross-sections: the top of Tower 4 (smallest tower cross-section) and the bottom of Tower 8 (largest tower cross-section).

The heat transfer analysis was performed in two dimensions, where each tower section is modeled as a single layer of solid elements. The concrete properties considered in the model are summarized in Table 3. To model the daily temperature cycles, we considered a time-dependent adiabatic surface temperature (AST) – the concrete surface temperature when it reaches thermal equilibrium with the environment, accounting for both convective and radiative heat transfers. The AST is assumed to be similar to the temperature measured on the surface of the steel sockets, which varies by 15°F each day on average (Table 2). For the analysis of the towers, we assumed that the AST varies linearly between 70°F at midnight and 85°F at noon. Convective and radiative heat transfer was modeled between the environment's AST and the concrete surface, and conductive heat transfer was modeled within the concrete. The analysis simulates the temperature cycle over a number of days until a steady state is reached, where the concrete undergoes the same temperature change every day.

The results of the heat transfer analysis are shown in Figure 10 for Tower 4 and Figure 11 for Tower 8. In both cases, the majority of the tower section remains at the same average temperature of 77.5°F, and only the surface of the concrete experiences a temperature cycle. Each day, the average temperature varies by 0.9°F at the top of Tower 4 and by 0.7°F at the bottom of Tower 8. These temperature ranges cause the towers to expand and contract by less than 0.05 inch, which has a negligible impact on the hundreds of feet of cables connected to the towers.

Table 3: Concrete properties for heat transfer analysis.

Thermal conductivity	2.25 W/m/°C
Specific heat	916 J/kg/°C
Mass density	7850 kg/m^3
Surface emissivity	0.9
Convective heat transfer coefficient with air	25 W/m^2/°C
Thermal expansion coefficient	1.0 x 10^{-5}/°C

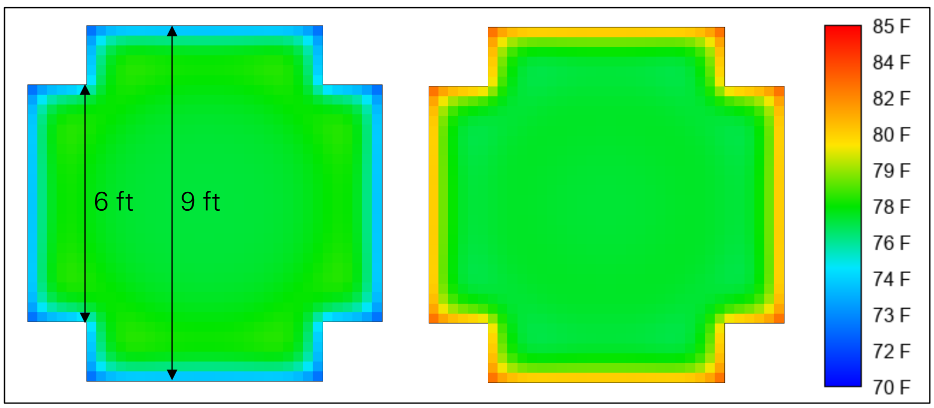

Figure 10: Midnight (left) and noon (right) concrete temperature at top of Tower 4.

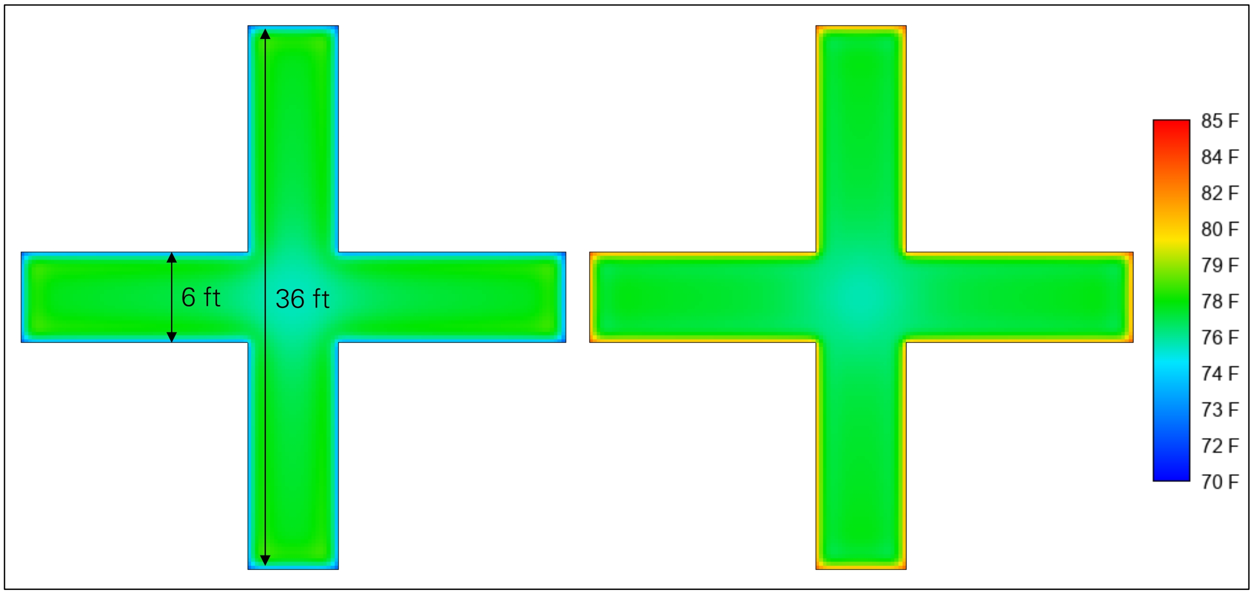

Figure 11: Midnight (left) and noon (right) concrete temperature at bottom of Tower 8.

3.2 Steel Temperature Analysis

The daily temperature range was measured on the surface of six cable sockets in November 2020, with results ranging from 13.4°F to 18.9°F, depending on the socket (section 0 above). As confirmed by these measurements, the daily temperature range is expected to vary locally across the steel structure. For instance, the thicker cables and sockets heat up and cool down more slowly than the lighter steel angles of the platform trusses, and some of the steel surfaces are shielded from direct sunlight more often than others. The steel temperature, however, is not expected to vary significantly between different areas of the telescope, specifically between the cables tied to different towers. This is because the cables and the suspended structure stand higher than the surrounding hills (except for the lower end of the backstays), so that the incident sunlight is uniform over the entire steel structure during most of the day. In addition, the trusses of the suspended structure are too hollow to effectively shield one another from sunlight, and the narrow concrete towers cast only minimal shade on the structure. As a result, to determine the effect of temperature on the cable tensions, we assumed that the entire steel structure experiences the same daily temperature range.

We determined the daily temperature range in the steel from the tiedown tensions of the upgraded structure. The total tiedown tension is known to increase by approximately 60 kip at night as the steel cools down and the tiedown jacks pull down to keep the platform at a constant elevation (section 0 above). Using a finite element model of the telescope structure (Figure 12), we determined the combination of steel temperature drop and jack pull down (two "variables") that results in a 60 kip total tiedown tension increase while keeping the platform elevation constant (two "equations").

The analysis results and the calculation of the daily temperature range in the steel are summarized in Table 4. We first set up the model in a reference state representing the daily high temperature, with the telescope stowed and the tiedowns taut. We then simulated two hypothetical scenarios: a steel temperature drop of 10°F without any jack movement, and a jack pull down of one inch without any steel temperature change. For both scenarios, the model provides the changes in tiedown tension and platform elevation. From these results, we calculated that to increase the tiedown tension by 60 kip while keeping the platform elevation constant, the steel temperature must decrease by 15.8°F while the jacks must pull down by 3.35 inches.

The average daily temperature range in the steel is therefore 15.8°F, which is consistent with the temperature range of between 13.4°F and 18.9°F measured on the surface of six cable sockets in 2020 (section 0 above). It is also consistent with the average temperature range of 12.3°F in the air (section 2.1 above), as solar radiation heats up the steel to above the air temperature.

The tiedown jacks are not always active, for example when the telescope is not operating. From the previous analysis results, we calculated that without tiedown jacking, the platform rises by two inches at night (Table 4). The typical day-night cycles with and without tiedown jacking are illustrated in Figure 13 and Figure 14.

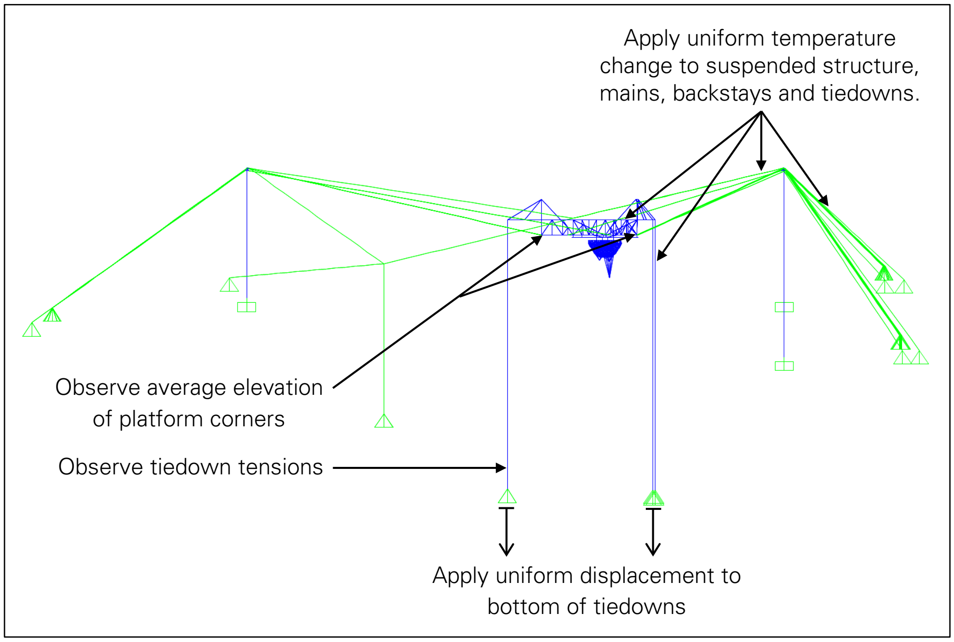

Figure 12: Finite element model (SAP2000) setup for steel temperature analysis.

Table 4: Calculation of steel temperature change from analysis results.

Case	Difference with Reference Case			
	Steel Temperature [°F]	Tiedown Jack Length [in]	Platform Elevation [in]	Total Tiedown Tension [kip]
Reference = Daily high temperature (daytime)	0	0	0	0
Cool down steel by 10°F	- 10	0	+ 1.27	+ 25
Pull down 1 inch on tiedowns	0	-1.00	- 0.60	+ 6
Daily low temperature (nighttime)	- 15.8	- 3.35	**0**	**+ 60**
Daily low temperature without tiedown jacking	- 15.8	0	+ 2.01	+ 40

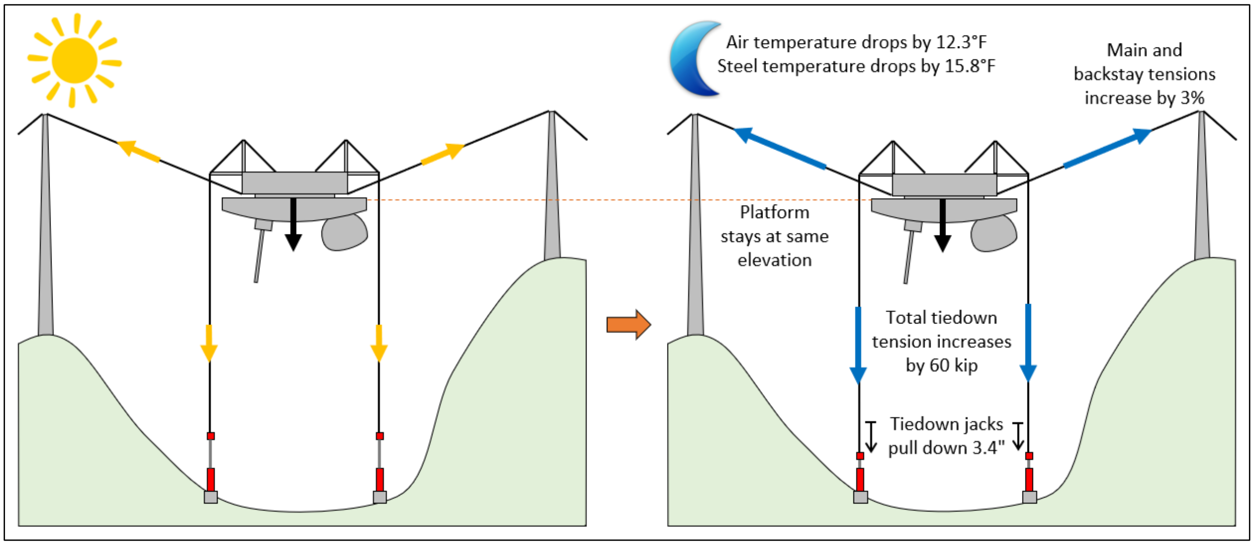

Figure 13: Typical day-night cycle in upgraded structure with tiedown jacking.

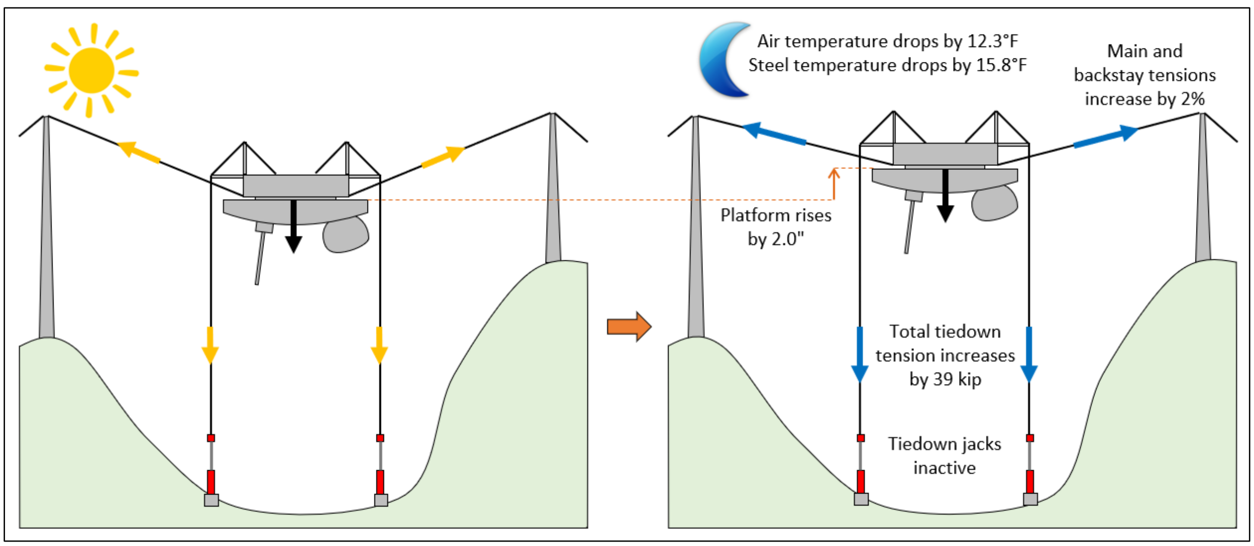

Figure 14: Typical day-night cycle in upgraded structure without tiedown jacking.

3.3 Cable Tension Analysis

To determine the effect of temperature changes on the cable tensions, we simulated a day-night cycle in the models of the original and upgraded structures. In both cases, the steel structure is assumed to cool down uniformly by 15.8°F at night (section 3.2 above) while the temperature of the concrete towers remains constant (section 3.1 above). Both analyses are performed with the telescope in stowed position.

In the original structure, each of the six inclined tiedowns is assumed to carry a tension of 11 kip when the temperature is at its maximum, which is the estimated tiedown tension after the first upgrade of the telescope in 1974. The inclined tiedowns of the original structure are not equipped with jacks and react passively to the temperature change. We applied the 15.8°F temperature drop to the steel in the model, and the cable tension results are presented in section 4.0 below.

In the upgraded structure, each tiedown cable is assumed to carry a tension of 10 kip when the temperature is at its maximum, for a total of 60 kip. This matches the daytime total tiedown tension in the earliest telescope monitoring data available to us (section 0 above). We considered the earliest data because the total tiedown tension decreases over the years. The tiedowns of the upgraded structure are equipped with jacks, and we determined that the jacks pull down by 3.35 inches as the structure cools down to keep the platform elevation constant (section 3.2 above). To simulate the day-night cycle, we applied the temperature drop and jack pull down simultaneously in the model. The cable tension results are presented in section 4.0 below.

4.0 Cable Tension Results

The results presented in this section describe the impact of the typical daily temperature cycle on the cable tensions. These results assume that the telescope does not move and experiences no other environmental loads.

4.1 Original Structure

In the original structure, the main and backstay tensions vary by approximately 2.5 percent during the daily temperature cycle (Figure 15), while the normalized stress range (ratio of cable tension change to cable minimum breaking strength) is approximately one percent (Figure 16). From a material fatigue perspective, these tension fluctuations are minimal.

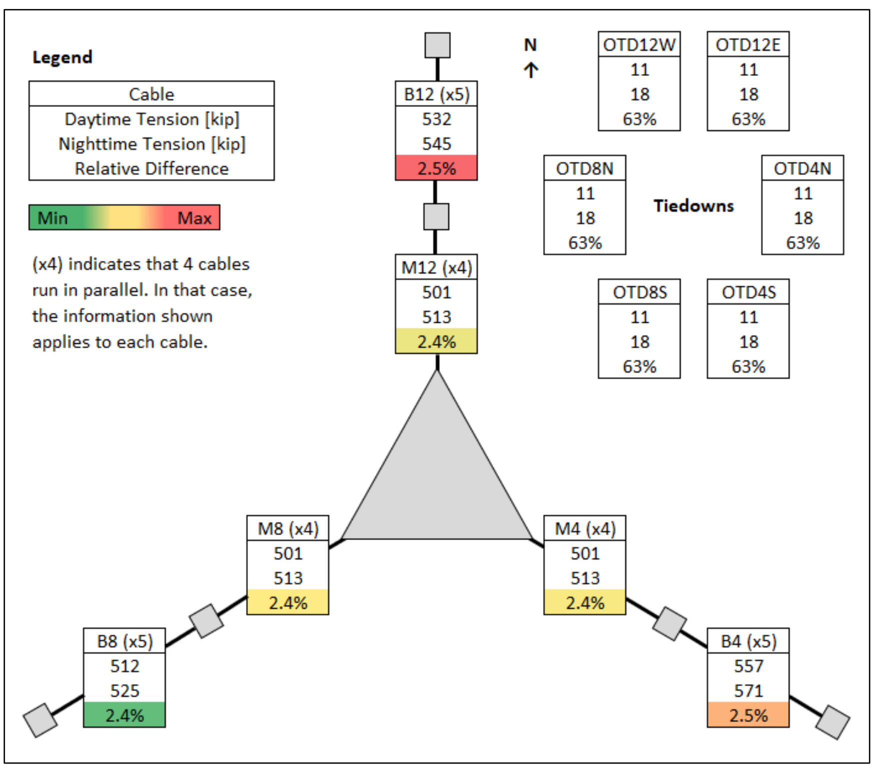

Figure 15: Cable tension change due to daily temperature cycle in original structure.

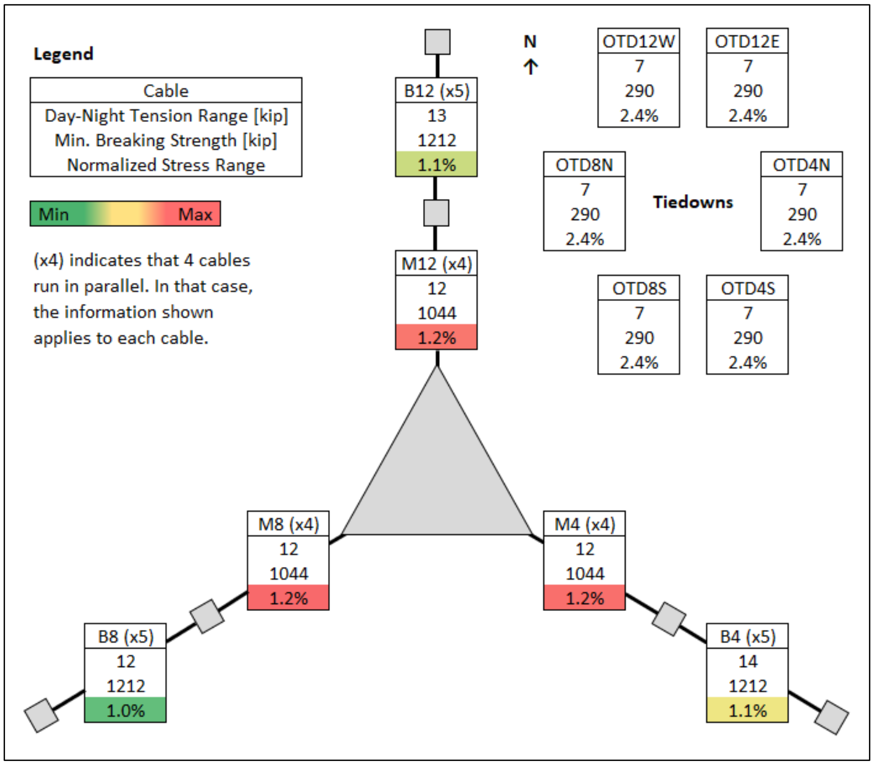

Figure 16: Cable normalized stress range due to daily temperature cycle in original structure.

4.2 Upgraded Structure

In the upgraded structure, the main and backstay tensions vary by approximately three percent during the daily temperature cycle (Figure 17), and the normalized stress range varies between one and two percent (Figure 18). While still low from a material fatigue perspective, the cable tension fluctuations are wider in the upgraded structure than in the original structure due to the tiedown jacks, which increase the tiedown tensions at night beyond the effect of the steel cooling down.

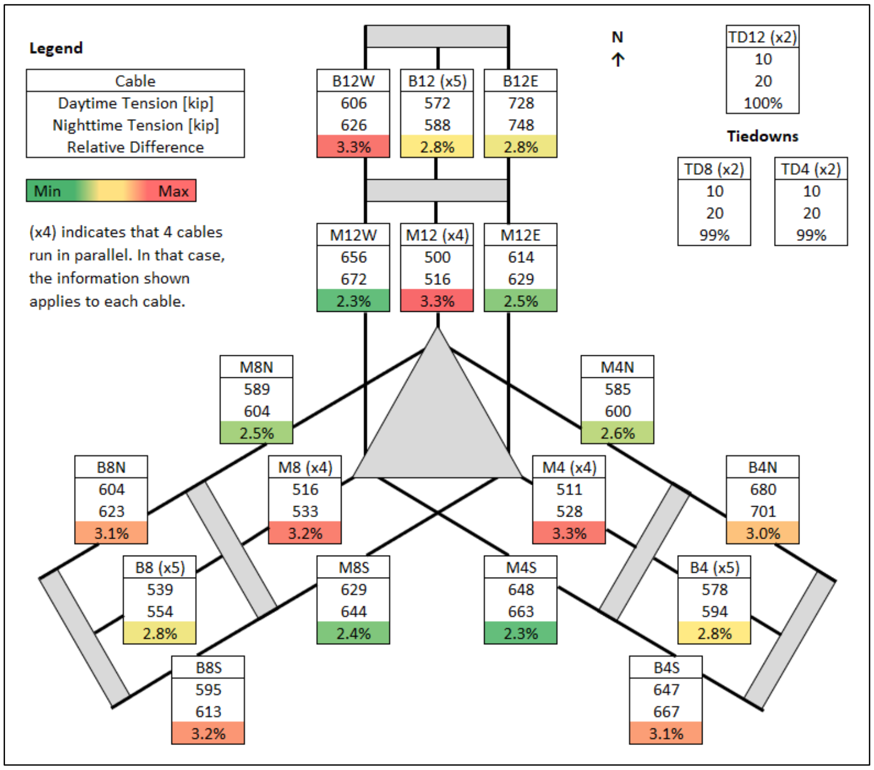

Figure 17: Cable tension change due to daily temperature cycle in upgraded structure.

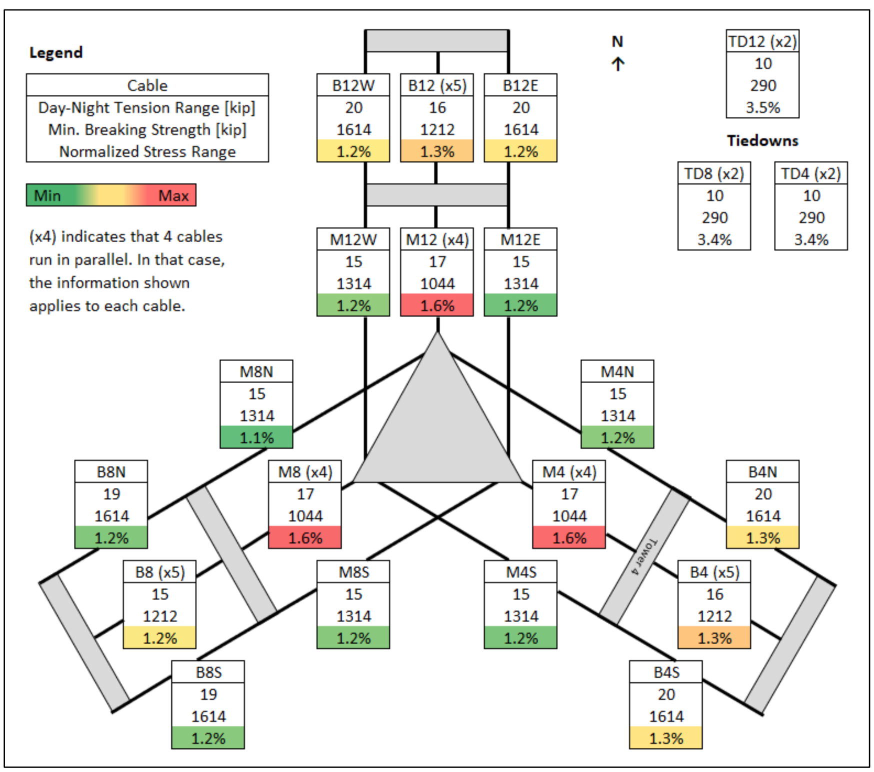

Figure 18: Cable normalized stress range due to daily temperature cycle in upgraded structure.