Appendix H
Telescope Operation Impact on Cable Tensions

1.0 Introduction

The suspended structure of the Arecibo Telescope consists of a fixed platform supporting several moving parts used to steer the telescope (Figure 1, Figure 2). When the telescope is operating, the displacement of the moving parts shifts the center of mass of the structure, generating tension changes in the cables supporting it. This appendix discusses the effect of telescope operation on the cable tensions.

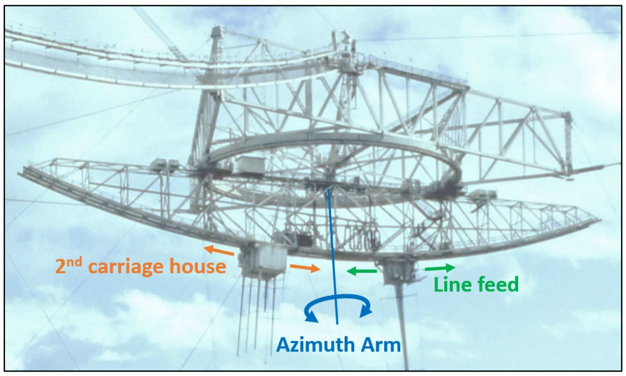

Figure 1: Moving parts of original telescope *(photo: Manfred Niermann, Wikipedia - CC BY-SA 4.0).*

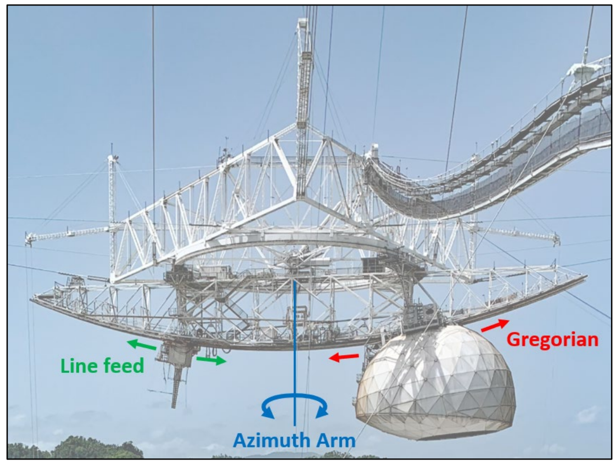

Figure 2: Moving parts of upgraded telescope, shown with line feed damage caused by Hurricane Maria *(photo: Mario Roberto Durán Ortiz, Wikipedia - CC BY-SA 4.0).*

2.0 Background

2.1 Original Structure

The moving parts of the original structure, completed in 1964, consisted of an azimuth arm that could rotate about the platform's central axis, and a line feed and second carriage house that could slide along the bottom of the azimuth arm (Figure 1). The line feed and second carriage house were relatively light compared to the rest of the structure and, as explained to us by the Arecibo Observatory (AO) staff, they were typically positioned symmetrically on both sides of the azimuth arm. As a result, the center of mass of the original structure did not move significantly during telescope operation.

2.2 Upgraded Structure

The second upgrade of the structure was completed in 1997 and, among other changes, replaced the second carriage house with the Gregorian (Figure 2). Weighing 200 kilopound (kip), the Gregorian was significantly heavier than the second carriage house (35 kip). This introduced a load imbalance on the azimuth arm, and to mitigate it a counterweight was added at the tip of the azimuth arm opposite to the Gregorian. However, since the counterweight was fixed while the Gregorian could move, the center of mass of the upgraded structure still moved during telescope operation.

2.2.1 Parameters and Operation Modes

The configuration of the upgraded telescope at any given time is defined by three angular parameters (Figure 3):

- The **azimuth arm angle** is the horizontal angle between the north direction and the longitudinal direction of the azimuth arm. The azimuth arm angle is zero when the span of the azimuth arm that supports the Gregorian points north. The azimuth arm can complete up to two revolutions (720 degrees) in the same direction before turning back.

- The **Gregorian angle** is the angle between the vertical axis of the telescope and a radius of 420 feet passing through the focal point of the Gregorian. The center of mass of the Gregorian is approximately two degrees downhill of the focal point and 430 feet from the center of rotation. The Gregorian angle is zero when positioned at the center of the azimuth arm, and the maximum Gregorian angle of 20 degrees is reached when it is at the tip of the azimuth arm.

- The **line feed angle** is the angle between the vertical axis of the telescope and the axis of the line feed. The line feed angle is zero when the line feed points straight down, and the maximum line feed angle of 20 degrees is reached when the line feed is at the tip of the azimuth arm.

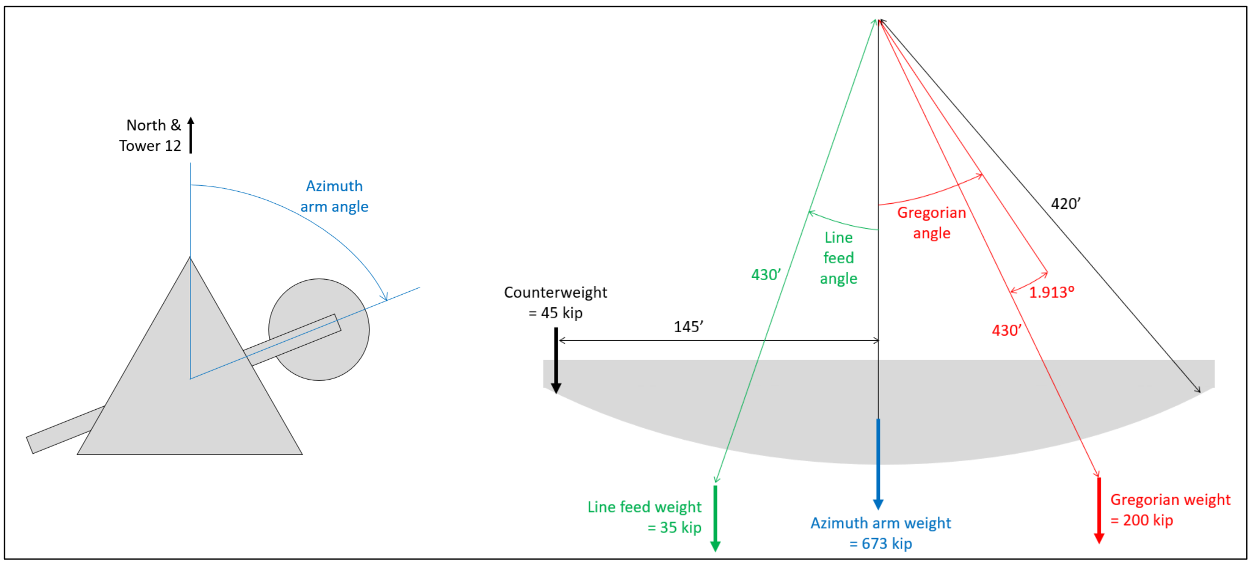

Figure 3: Upgraded telescope parameters and azimuth arm mass distribution.

The corners of the platform are connected to the ground with tiedown cables, and their tensions can be actively controlled with electro-mechanical jacks. However, this system is only used to mitigate the effect of temperature on the average elevation of the suspended structure (Appendix I), and the tiedown jacks are not actively adjusted for changes in the azimuth arm, Gregorian or line feed angles.

Depending on the type of observation or experiment being performed, the telescope operates in one of two general modes:

- In **standard** mode, the azimuth arm, Gregorian and/or line feed move slowly and typically complete less than 10 cycles per day. The standard mode is, for example, used to track a moving object that the telescope is observing.

- In atmospheric mode, the azimuth arm rotates more rapidly, at a rate of up to four revolutions per hour, with the Gregorian and line feed fixed at a given angle. This mode is used for studies of the Earth's atmosphere.

Before and during high wind events, the telescope is placed in a predetermined stowed position, which corresponds to an azimuth arm angle of 258 degrees, a Gregorian angle of 8.5 degrees, and a line feed angle of 8.9 degrees. Pins are then inserted between the fixed platform and the moving parts for the duration of the wind event.

2.2.2 Operation Data

A telescope operation data log was provided by AO. Covering the period from June 2004 to August 2020, the log includes the azimuth arm, Gregorian and line feed angles as well as the tension in each tiedown, all recorded every second. One week of data is shown in Figure 4 as an example, where the difference between the standard and atmospheric modes is clearly visible. The data log indicates that over the past 16 years, the telescope was operating in standard mode for approximately 85 percent of the time and in atmospheric mode for approximately five percent of the time, while for the remaining 10 percent of the time the telescope was not operating.

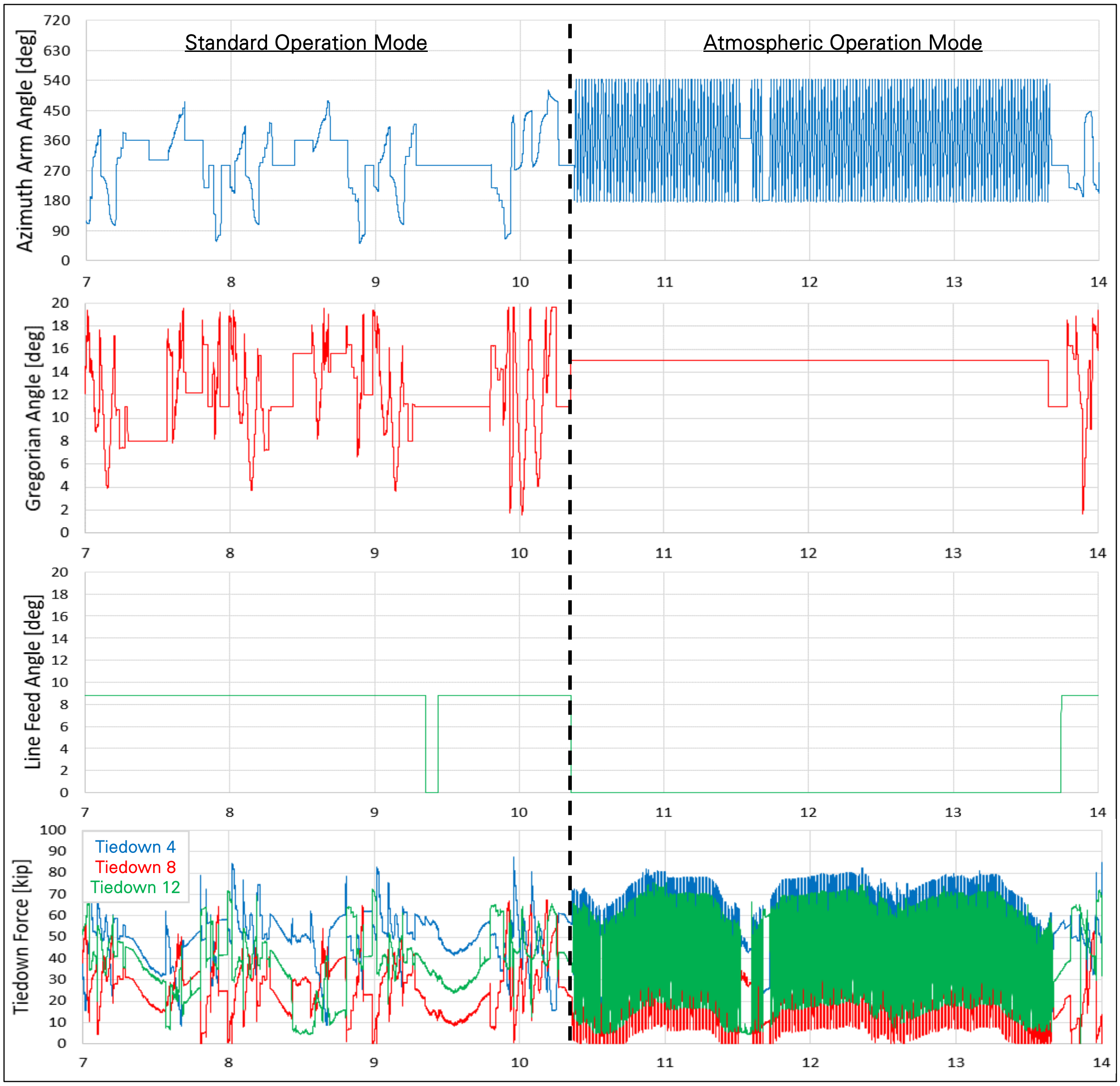

Figure 4: One week of telescope operation data (12/7/2012 to 12/14/2012).

3.0 Analysis Method

We performed a structural analysis of the telescope during operation to determine the maximum tensions and the number of tension cycles experienced by the cable system. The models used for this analysis is detailed in Appendix F.

3.1 Load Application to Model

The combined weight of the moving parts is transferred to the fixed platform at two points where the azimuth arm is suspended from the ring girder. The position of these two points on the ring girder depends on the orientation of the azimuth arm, while the distribution of the suspended weight between the two points depends on the positions of the other moving parts (line feed and Gregorian or second carriage house). To analyze multiple configurations of the telescope, we removed the azimuth arm from the analysis model and replaced it with a pair of loads applied directly to the ring girder (Figure 5). The position and magnitude of each load could then be modified as needed to represent different positions of the moving parts.

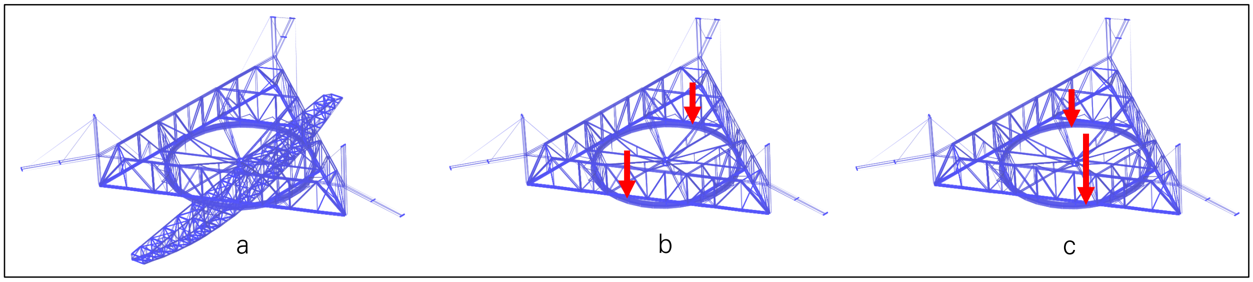

Figure 5: Modeling of telescope operation loads. (a) The azimuth arm is initially modeled as elements in the stowed position. (b) The azimuth arm elements are removed and replaced with loads on the ring girder. (c) The loads on the ring girder are moved and adjusted to represent movement of the moving parts.

3.2 Original Structure

In the original structure, the total weight of the azimuth arm, line feed and second carriage house is approximately 400 kilopound (kip). Since the line feed and second carriage house are relatively light and move symmetrically, the azimuth arm remains essentially balanced during telescope operation. In the analysis model, the total weight of the moving parts is therefore always transferred to the ring girder as two equal loads of 200 kip.

We simulated a full revolution of the azimuth arm while monitoring the change in cable tensions. The model was initialized so that the tiedown tensions are equal when the azimuth arm is stowed. As shown below in section 4.1, the results indicate that the rotation of the azimuth arm had a negligible impact on the cable tensions, and therefore no further analysis was performed on the original structure.

3.3 Upgraded Structure

The azimuth arm of the upgraded structure supports a 200-kip Gregorian on one side and a 35-kip line feed on the other. Part of the line feed fell off during Hurricane Maria in 2017, but the undamaged line feed weight of 35 kip is considered in our analyses. To reduce the weight imbalance on the azimuth arm, a 45-kip counterweight was installed at the tip of the azimuth arm opposite the Gregorian (Figure 3), with the counterweight fixed on the azimuth arm so that the azimuth arm is essentially balanced when the Gregorian and line feed are in stowed position. For other positions of the Gregorian and line feed, the azimuth arm is not balanced and transfers a moment to the platform, in addition to a total weight of 953 kip. The azimuth arm imbalance moment is shown in Table 1 for key configurations of the telescope.

To determine the minimum and maximum tensions that each cable can experience during telescope operation, we first simulated a full revolution of the azimuth arm with the maximum azimuth arm imbalance moment.

Table 1: Azimuth arm imbalance moment for key telescope configurations.

Telescope Configuration	Gregorian Angle [deg]	Line Feed Angle [deg]	Azimuth Arm Imbalance Moment [kip·ft]	Azimuth Arm Weight Eccentricity [ft]
Maximum imbalance towards line feed	0	20.0	-14,540	-15.3
Stowed	8.5	8.8	1,000	1.1
Typical atmospheric mode	15.0	0	12,950	13.6
Typical standard mode	20.0	8.8	17,860	18.8
Maximum imbalance towards Gregorian	20.0	0	20,180	21.2

Then, to determine the amplitude and number of tension cycles actually experienced by the cables over time, we simulated four 10-day periods of actual telescope operation as recorded in the data log. Three of the 10-day periods were selected to represent the standard mode of operation, and the fourth 10-day period was selected to represent the atmospheric mode. Figure 6 to Figure 9 show the azimuth arm, Gregorian and line feed angles and the calculated azimuth arm imbalance moment for the four 10-day periods. The maximum azimuth arm imbalance moment is 17,860 kip·ft, which corresponds to a fully-extended Gregorian and a stowed line feed.

Prior to each analysis, we initialized the model so that the tiedown tensions are equal when the telescope is stowed.

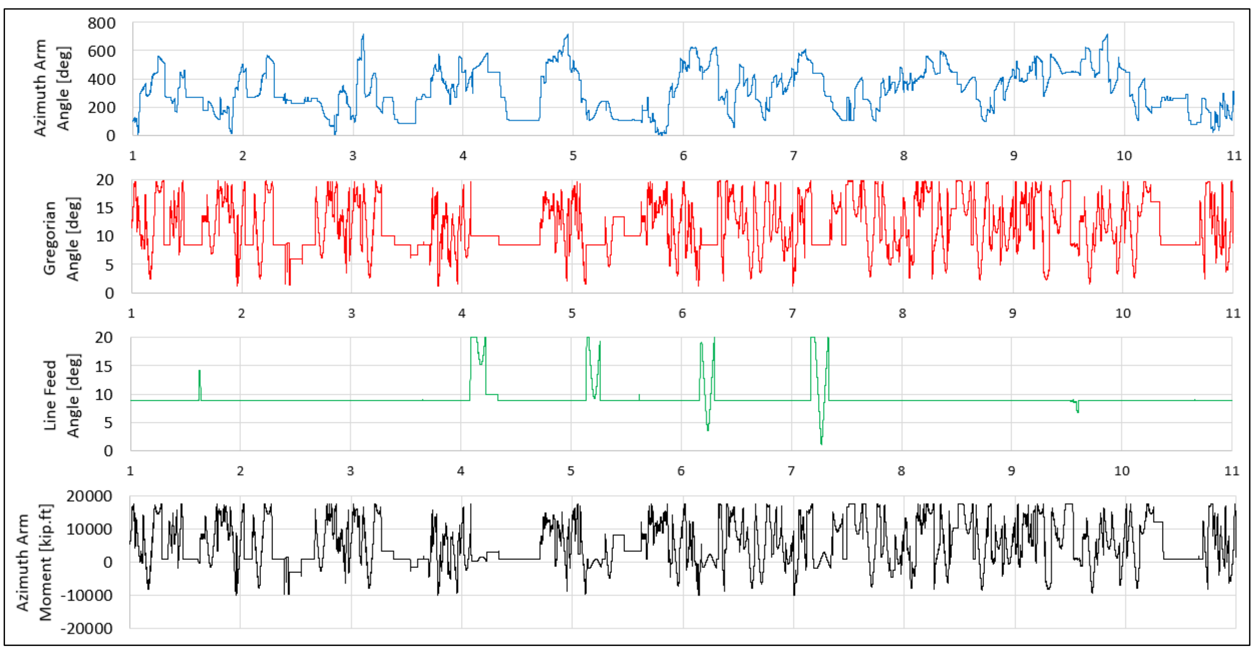

Figure 6: Ten days of telescope standard operation data (August 1-11, 2004).

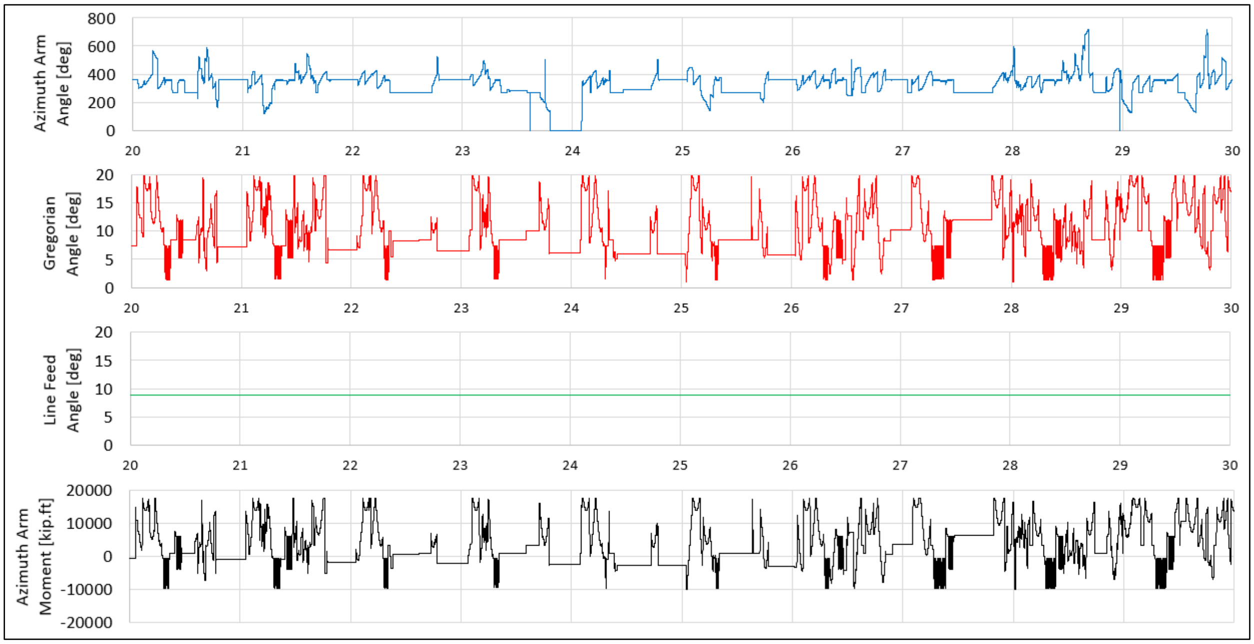

Figure 7: Ten days of telescope standard operation data (May 20-30, 2005).

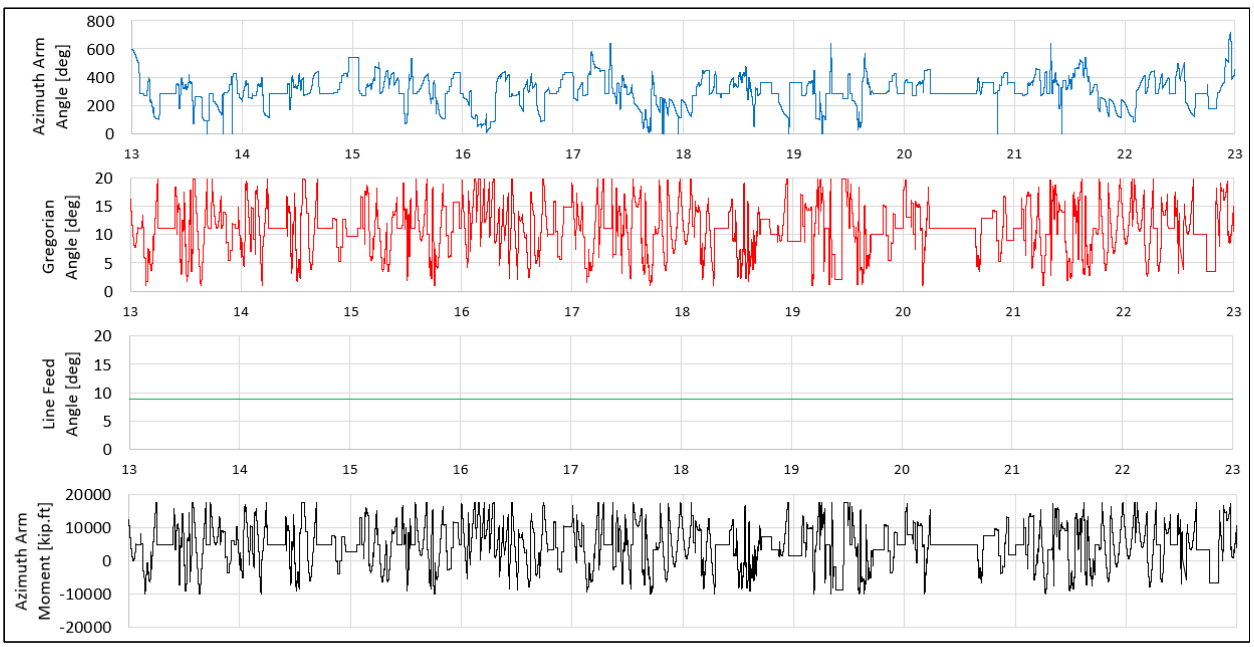

Figure 8: Ten days of telescope standard operation data (May 13-23, 2020).

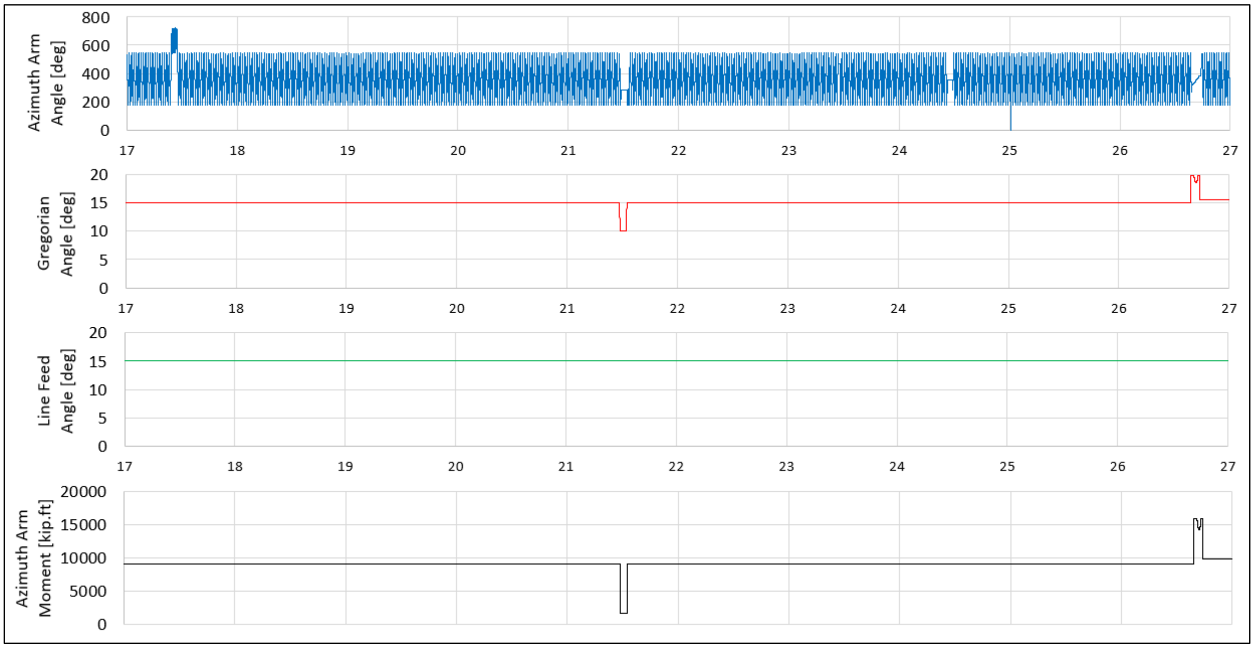

Figure 9: Ten days of telescope atmospheric operation data (January 17-27, 2008).

4.0 Cable Tension Results

4.1 Original Structure

We analyzed the operation of the original structure by simulating a complete revolution of the balanced azimuth arm. As shown in Figure 10, the tensions in the main cables and backstays remain essentially constant for any azimuth arm orientation. This is because the center of mass of the azimuth arm remains centered on the platform. Figure 11 shows the tensions in the six original tiedowns, which vary by up to one kip as the azimuth arm rotates. The minimum safety factors in the cables and tiedowns during telescope operation are provided in Figure 12. The safety factor is calculated by dividing the cable's minimum breaking strength by the cable's maximum actual tension.

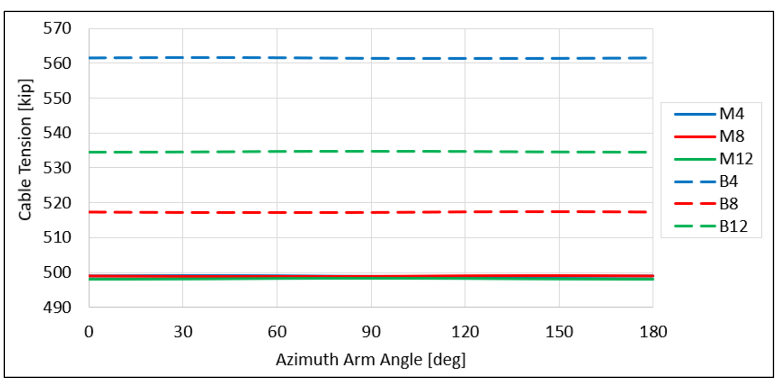

Figure 10: Tension in main and backstay cables for full revolution of azimuth arm in original structure.

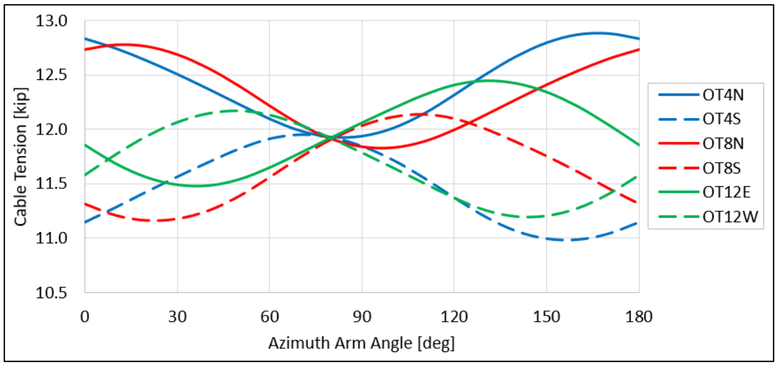

Figure 11: Tension in tiedown cables for full revolution of azimuth arm in original structure.

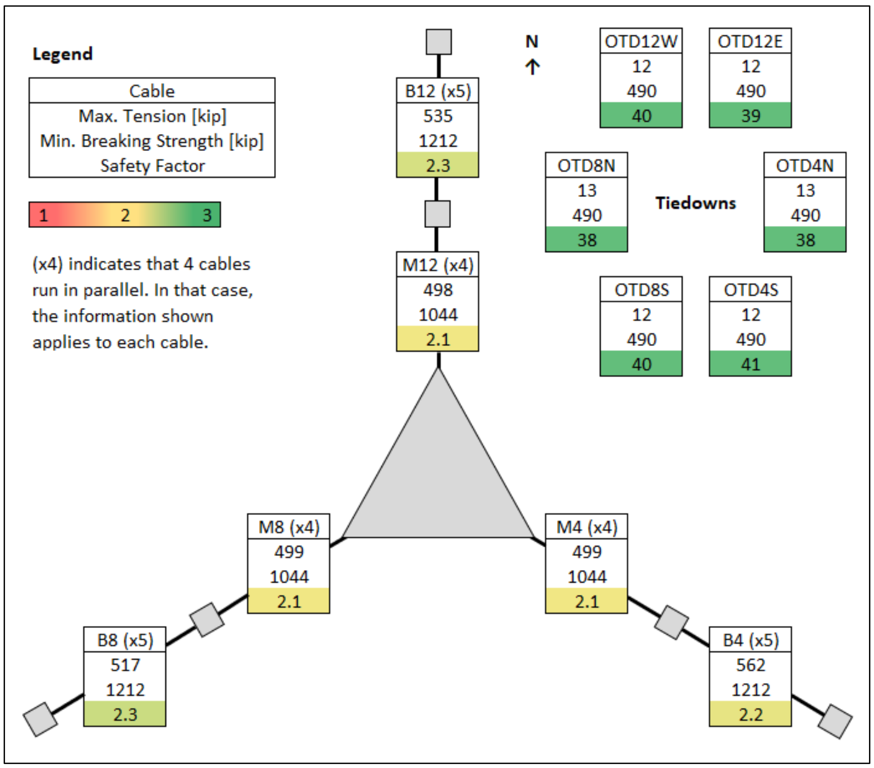

Figure 12: Minimum safety factor in cables for full revolution of azimuth arm in original structure.

4.2 Upgraded Structure

We first analyzed the operation of the upgraded structure by simulating a complete revolution of the azimuth arm with the maximum azimuth arm imbalance. During the azimuth arm revolution, each cable experiences a tension cycle. The tension range (peak-to-peak) is approximately 20 kip in the original main cables, and 50 kip in the auxiliary main cables (Figure 13). The tension range is negligible in the backstays (Figure 14), and 55 kip in the tiedowns (Figure 15). The corresponding cable safety factors and normalized stress ranges are shown in Figure 16 and Figure 17. The normalized stress range is calculated by dividing the cable's tension range by the cable's minimum breaking strength.

In a second analysis, we simulated three 10-day periods of telescope operation in standard mode. From the cable tension time history results, we counted the daily average number of tension cycles using the rainflow method. The results are compiled in Table 2, where the magnitude of a tension cycle is expressed as a normalized stress range. The magnitude and number of cycles are low from a fatigue perspective, with only eight cycles per day producing a normalized stress range of at least one percent in the auxiliary main cables, and only three cycles per day in the original main cables.

Finally, we simulated a 10-day period of telescope operation in atmospheric mode, and again counted the number of cable tension cycles, with the results summarized in Table 3. In this case, the only tension cycles causing a normalized stress range greater than one percent are in the auxiliary main cables, with approximately 90 cycles per day. This corresponds to the azimuth arm spinning at a rate of 22 degrees per minute, or one revolution every 16 minutes.

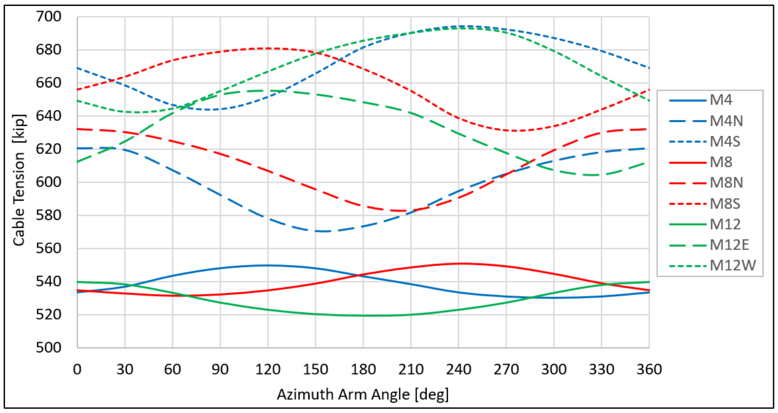

Figure 13: Tension in main cables for full revolution of azimuth arm with maximum azimuth arm imbalance in upgraded structure.

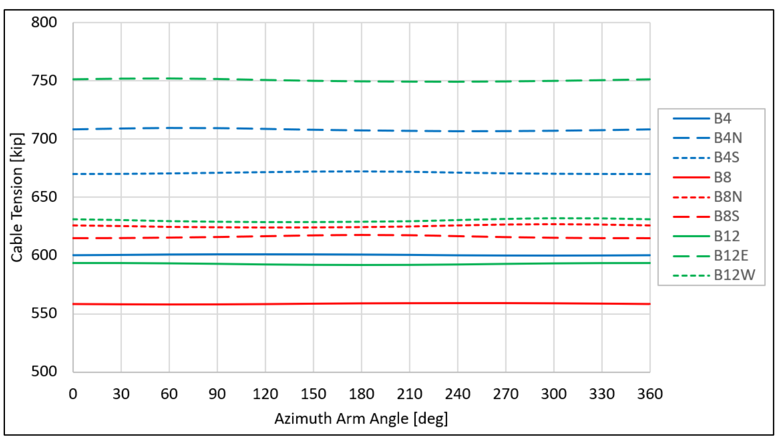

Figure 14: Tension in backstay cables for full revolution of azimuth arm with maximum azimuth arm imbalance in upgraded structure.

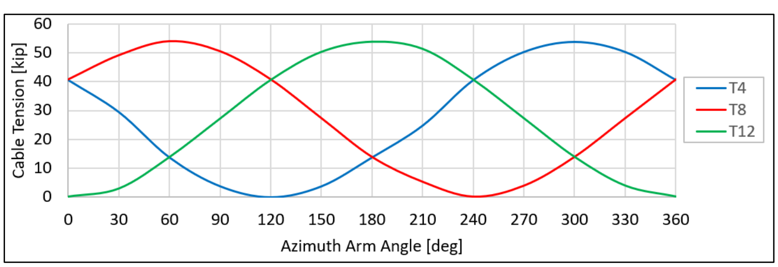

Figure 15: Tension in tiedown cables for full revolution of azimuth arm with maximum azimuth arm imbalance in upgraded structure.

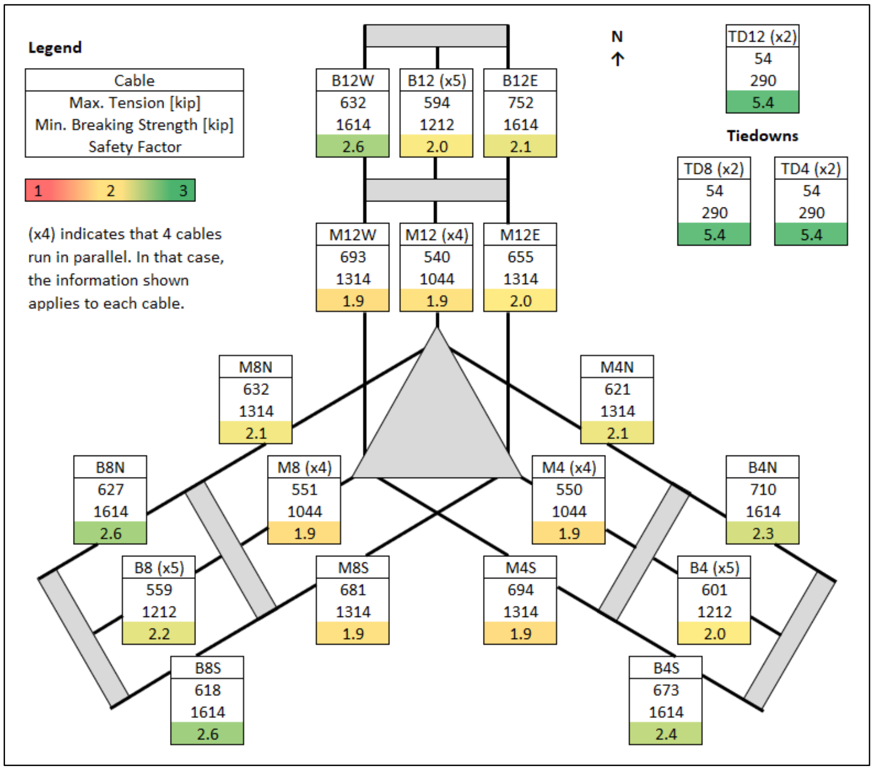

Figure 16: Cable safety factors for full revolution of azimuth arm with maximum azimuth arm imbalance in upgraded structure.

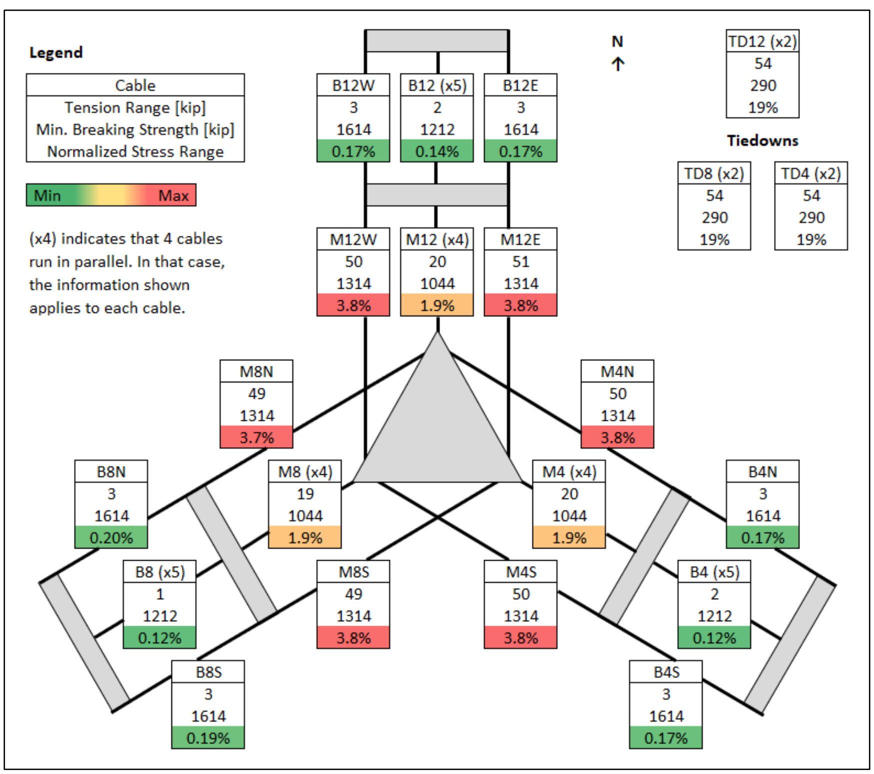

Figure 17: Cable normalized stress range for full revolution of azimuth arm with maximum azimuth arm imbalance in upgraded structure.

Table 2: Average number of cable tension cycles per day during standard telescope operation in upgraded structure.

	Normalized Stress Range (= Tension Range / Minimum Breaking Strength)						
	1-2%	2-3%	3-4%	4-5%	5-10%	10-15%	15-20%
M4	2.8						
M4N	4.4	2.2	0.4				
M4S	5.2	2.3	0.7				
M8	2.8						
M8N	4.7	2.0	0.4				
M8S	5.7	2.1	0.7				
M12	2.4						
M12E	4.8	2.2	0.6				
M12W	5.3	2.2	0.6				
Backstays							
T4	4.7	5.6	2.4	1.6	4.7	2.2	0.4
T8	6.5	4.3	2.3	2.0	4.3	2.1	0.6
T12	4.5	2.4	1.6	3.8	4.4	1.9	0.3

Table 3: Average number of cable tension cycles per day during atmospheric telescope operation in upgraded structure.

	Normalized Stress Range (= Tension Range / Minimum Breaking Strength)					
	1-2%	2-3%	3-4%	4-5%	5-10%	10-15%
M4	0.1					
M4N	88.5	1.3				
M4S	88.9					
M8	0.1					
M8N	89.5	0.1				
M8S	90.1	0.1				
M12	0.1					
M12E	88.3	1.3				
M12W	88.5	1.2				
Backstays						
T4	0.7	44.4		0.2	89.4	0.1
T8	0.6	44.6	0.1	0.1	89.4	0.1
T12			0.2	0.2	89.5	0.1