Thornton Tomasetti

Appendix D
Cable System Condition History

1.0 Introduction

The Arecibo Telescope collapsed after several cables failed at the top of Tower 4. The cable system had been inspected and maintained several times over the 57-year lifespan of the structure, with broken wires discovered on some of the cables and movement observed at some of the auxiliary cable sockets. The cable system had also been upgraded with vibration dampers and a moisture control system.

This appendix reviews the history of the cable system's condition as depicted in documents provided by Arecibo Observatory (AO) and retrieved from the Cornell University (CU) archives. As shown in Figure 1, these documents include AO's regular maintenance records (Figure 2, Figure 3) and reports from occasional inspections performed by AO or the Engineer of Record, Ammann & Whitney (AW).

This appendix focuses on the telescope's cables and cable sockets and does not address the condition of the suspended structure, towers, or primary reflector. Each aspect of the cable system's condition (paint, wire breaks, socket slip, moisture exclusion, and vibration) is considered in a separate section.

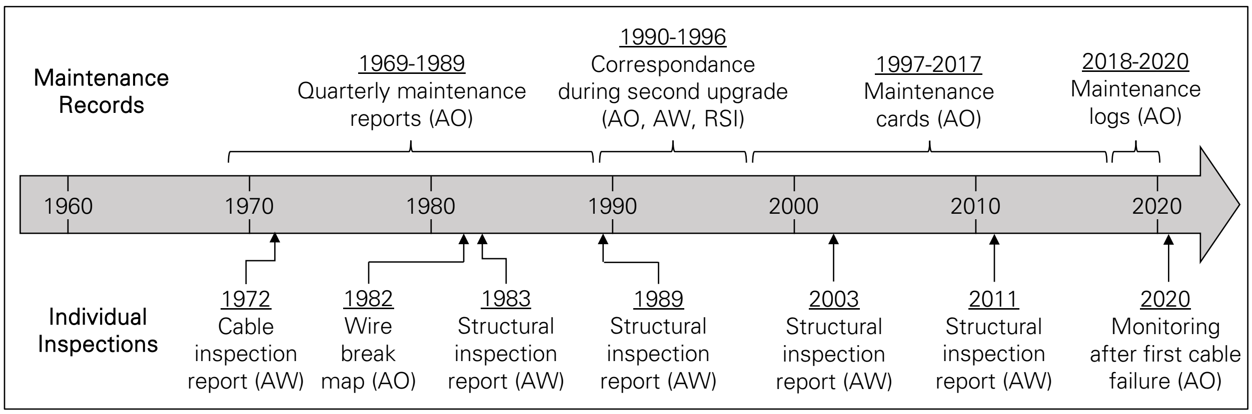
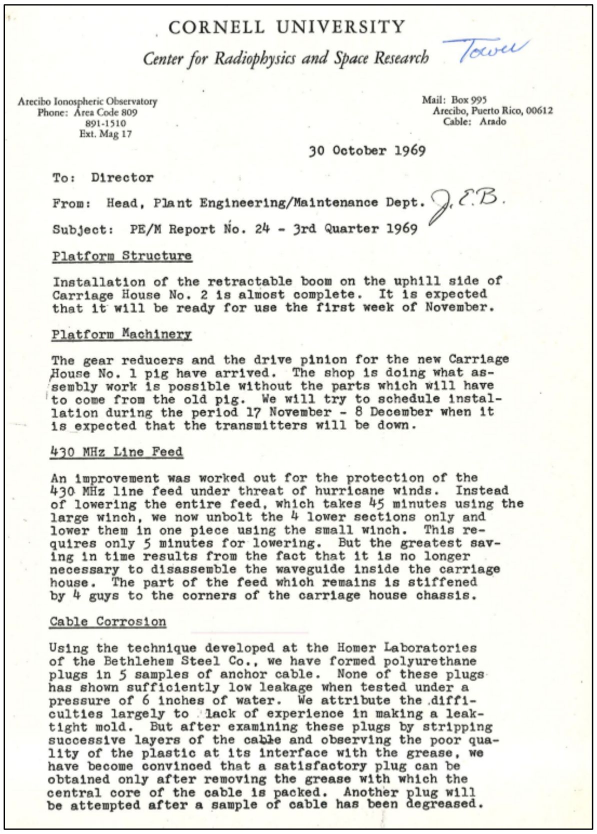


Figure 1: Primary documents reviewed relevant to condition of cable system.



CORNELL UNIVERSITY

Center for Radiophysics and Space Research Tower

Arecibo Ionospheric Observatory
Phone: Area Code 809
891-1510
Ext. Mag 17

Mail: Box 995
Arecibo, Puerto Rico, 00612
Cable: Arado

30 October 1969

To: Director

From: Head, Plant Engineering/Maintenance Dept. J.E.B.

Subject: PE/M Report No. 24 - 3rd Quarter 1969

Platform Structure

Installation of the retractable boom on the uphill side of Carriage House No. 2 is almost complete. It is expected that it will be ready for use the first week of November.

Platform Machinery

The gear reducers and the drive pinion for the new Carriage House No. 1 pig have arrived. The shop is doing what assembly work is possible without the parts which will have to come from the old pig. We will try to schedule installation during the period 17 November - 8 December when it is expected that the transmitters will be down.

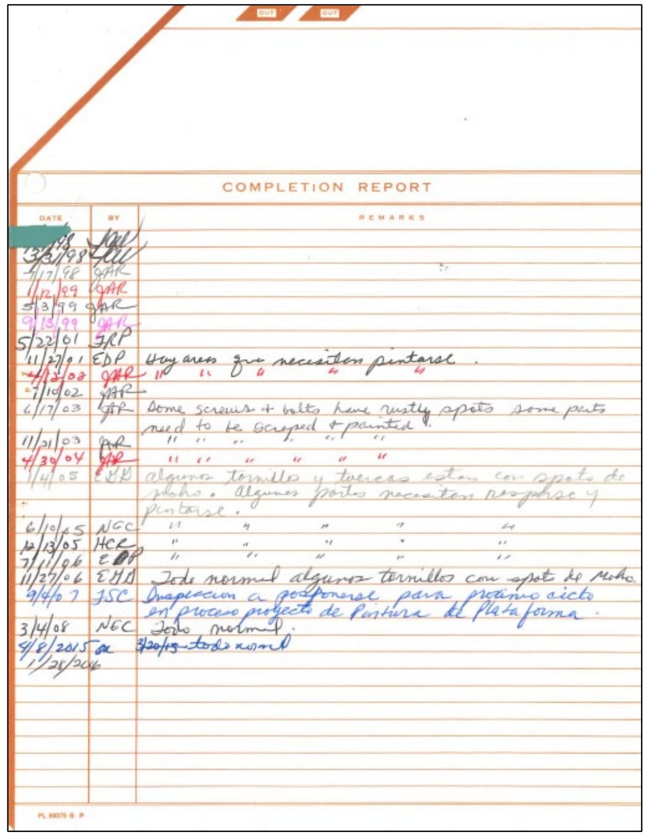
430 MHz Line Feed

An improvement was worked out for the protection of the 430 MHz line feed under threat of hurricane winds. Instead of lowering the entire feed, which takes 45 minutes using the large winch, we now unbolt the 4 lower sections only and lower them in one piece using the small winch. This requires only 5 minutes for lowering. But the greatest saving in time results from the fact that it is no longer necessary to disassemble the waveguide inside the carriage house. The part of the feed which remains is stiffened by 4 guys to the corners of the carriage house chassis.

Cable Corrosion

Using the technique developed at the Homer Laboratories of the Bethlehem Steel Co., we have formed polyurethane plugs in 5 samples of anchor cable. None of these plugs has shown sufficiently low leakage when tested under a pressure of 6 inches of water. We attribute the difficulties largely to lack of experience in making a leak-tight mold. But after examining these plugs by stripping successive layers of the cable and observing the poor quality of the plastic at its interface with the grease, we have become convinced that a satisfactory plug can be obtained only after removing the grease with which the central core of the cable is packed. Another plug will be attempted after a sample of cable has been degreased.

Figure 2: Example of first page of quarterly inspection and maintenance report produced from 1969 to 1989 *(courtesy of NAIC Arecibo Observatory, a facility of the NSF).*



COMPLETION REPORT

DATE	BY	REMARKS
3/31/98		
4/17/98	GAR	
1/12/99	GAR	
5/3/99	GAR	
9/13/99	GAR	
5/22/01	JRP	
11/27/01	EDP	Hay areas que necesitan pintarse.
4/2/02	GAR	" " " " "
7/10/02	GAR	
6/17/03	GAR	Some screws + bolts have rusty spots some parts need to be scraped + painted.
11/21/03	GAR	" " " " "
4/30/04	GAR	" " " " "
1/4/05	EHD	algunos tornillos y tuercas estan con spots de moho. Algunas partes necesitan raspado y pintarse.
6/10/05	NGC	" " " " "
10/13/05	HCR	" " " " "
7/11/06	EDP	" " " " "
11/27/06	EHD	Todo normal algunos tornillos con spot de Moho.
9/4/07	JSC	Inspeccion a posponerse para proximo ciclo en proceso proyecto de Pintura del Plataforma.
3/4/08	NEC	Todo normal.
4/8/2015		3/20/13 todo normal
1/21/2016		

Figure 3: Example of maintenance card system used from 1997 to 2017 *(courtesy of NAIC Arecibo Observatory, a facility of the NSF).*

2.0 Cable Paint

The telescope's cables are made of galvanized steel wires, which were painted to protect against corrosion. The paint's anti-corrosive role is two-fold: it covers the surface of the outer wires to protect them from corrosion, and it seals any gap between the outer wires to prevent water from seeping into the cable and corroding the inner wires.

AO's maintenance records indicate that the original cables (installed in 1963) were fully repainted between 1973 and 1974, and again between 1984 and 1988, while the auxiliary cables (installed in 1995) were fully repainted in 2003.

The condition of the cable paint was reviewed by AW during each inspection of the structure, and their conclusions are summarized in Table 1. The paint appears to have remained in good condition from the telescope's construction to its second upgrade, which is consistent with AO's maintenance records indicating that the cables were repainted at least twice during that period. However, during the first inspection after the second upgrade in 2003, AW noted that the paint on the original cables had deteriorated (Figure 4) to the point that the cables had started to corrode. After the next inspection in 2011, AW reported that the condition of the original cables remained unchanged, and it is unknown whether the cables had been repainted between the two inspections. The paint on the auxiliary cables appears to have remained in good condition after their installation during the second upgrade.

Table 1: Cable paint condition as described in inspection reports.

Source	Quotes	Notes
1972 cable inspection report[A]	"In general, the cables were found to be in good condition."	
1983 structural inspection report[B]	"The white exterior paint is kept in excellent condition."	
1989 structural inspection report[C]	"Examination of the cables at the end sockets and with binoculars over the central portion disclosed no changes from the last inspection (1982)."	
2003 structural inspection report[D]	Original backstays: "The paint exhibits varying degrees of peeling, cracking, flaking and discoloration … Exposed individual wires are visible at many locations where the paint has deteriorated … The galvanizing on the wires has begun to oxidize in some locations, initiating the first phase of rusting of the wire … The paint condition of the backstays is rated as poor." Auxiliary backstays: "The paint on the auxiliary backstays remains flexible and in good condition overall … The paint condition of the auxiliary backstays is rated as good." Auxiliary mains: "The paint condition of the auxiliary main cables is rated as good." Recommendation: "The [original] backstay cables and the [original] main cables should be cleaned, inspected for wire breaks, and painted along their entire lengths."	The cables were subject to close-up inspection at the cable ends, and inspected with binoculars from the ground, the platform and the top of Tower 4 and Tower 12.
2011 structural inspection report[E]	Original backstays: "The backstay paint condition was rated as poor by the 2003 survey and there is no change in status." Auxiliary backstays: "The paint condition on the auxiliary cables was rated as good in the 2003 survey, and there is no change in status." Original mains: "The main cable paint condition was rated as poor in the 2003 survey, and there is no change in status." Auxiliary mains: "The paint condition of the auxiliary main cables was rated as good in the 2003 report and there is no change in status." Recommendation: "As a priority, all of the original project cables should be painted."	The cables were subject to close-up inspection at the cable ends, and inspected with binoculars from the ground, the platform and the top of the towers.

[A] Ammann & Whitney. *Report on Inspection of Cable System*. September 1972. Report retrieved from Cornell University archives.
[B] 1983. Report retrieved from Cornell University archives.
[C] Ammann & Whitney. *Arecibo Mini Inspection*. May 1989. Report retrieved from Cornell University archives.
[D] Ammann & Whitney. *Structural Condition Survey 2003*. May 2003. Report retrieved from Cornell University archives.
[E] Ammann & Whitney. *Structural Condition Survey 2011*. March 2011. Report retrieved from Cornell University archives.

Figure 4: Original backstay B12-5 near anchor in 2003. Clamps and missing paint indicate a broken wire. Paint is also cracked between other wires *(photo: Ammann & Whitney[1]).*

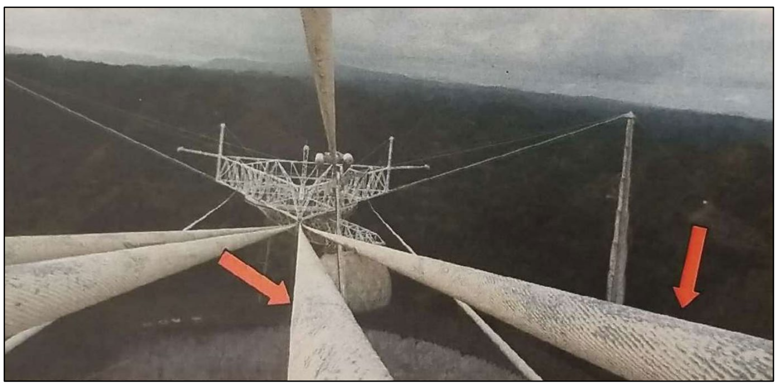


Figure 5: Paint deterioration on original mains at top of Tower 12 in 2011 *(photo: Ammann & Whitney[2]).*

3.0 Cable Internal Moisture

AO's maintenance records indicate that by the late 1960s, a water intrusion problem had been identified in the structure's cables. It was observed that the cable ends near the sockets were not fully airtight, allowing moist air and rainwater to enter the cable and corrode the wires from the inside. Several attempts to seal the cable ends with polyurethane plugs were made in 1969 and 1970, but this method was eventually abandoned because the plastic material failed to fully penetrate and bond to the cable.

As an alternative to sealing off the cable ends, AO implemented a moisture exclusion system that pushed dry air into the cable. As shown in Figure 6, the lower end of each cable was encased in an airtight sleeve just outside the cable socket, so dry air could be pushed into the sleeve and forced to enter the cable through the gaps between the wires near the socket. According to experiments

[1] Ammann & Whitney. *Structural Condition Survey 2003.* May 2003. Report retrieved from Cornell University archives.
[2] Ammann & Whitney. *Structural Condition Survey 2011.* March 2011. Report retrieved from Cornell University archives.

conducted in 1971, a pressure of one pound per square inch in the sleeve at the bottom of a cable was sufficient to cause airflow inside the cable and detect air escaping at the top of the cable.

Dry air sleeves were installed on the original cables in 1972. The system was later improved by adding moisture detectors in 1976 and replacing the sleeves in 1983 with larger windows to facilitate visual inspections. Despite occasional issues with the air compressors and dryers, the system appeared to function satisfactorily[3] through the 1980s and 1990s, and the auxiliary cables installed in 1995 were also equipped with similar dry air sleeves.

The maintenance and inspection documents include several reports, beginning in 2002, of condensation inside the dry air sleeves of some of the auxiliary cables (Figure 7 and Figure 8). The cause, extent and duration of the problem are not precisely known, although it affected backstays and main cables and persisted until at least 2011.

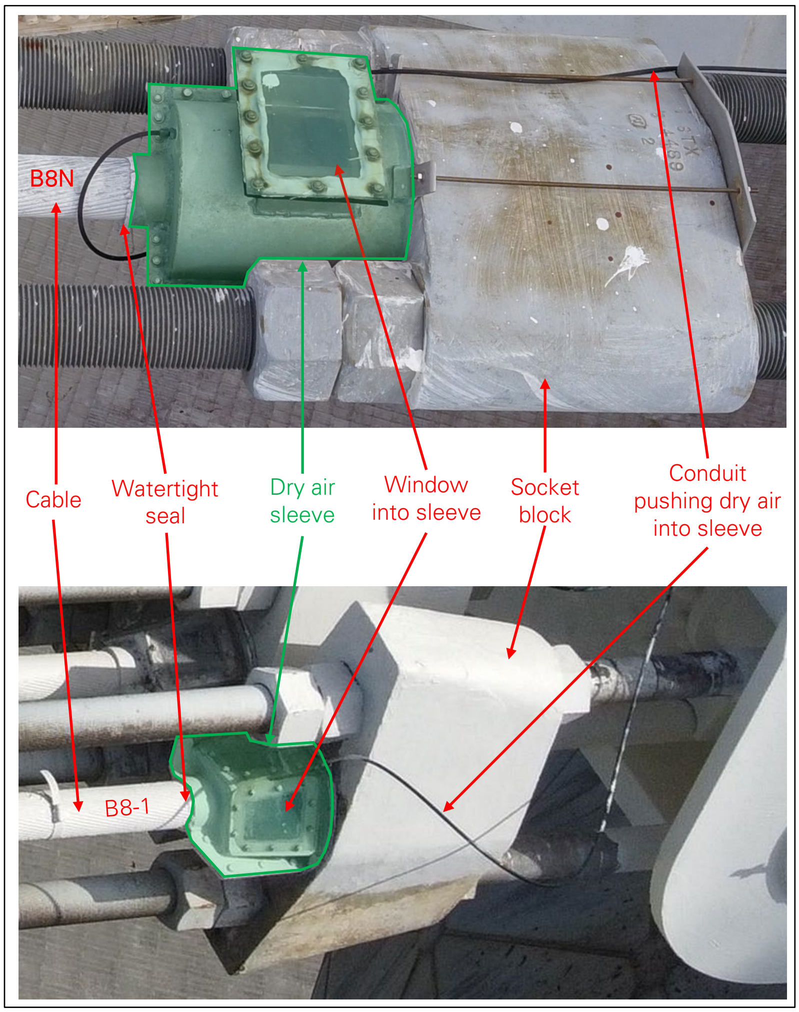


Figure 6: Moisture exclusion system on auxiliary main (B8N, top) and original main (B8-1, bottom) sockets in 2020 *(photos: NAIC Arecibo Observatory, a facility of the NSF).*

[3] Tor Hagfors (Arecibo Observatory). Letter to William McGuire (Cornell University). April 5, 1988. Correspondence retrieved from Cornell University archives.

Figure 7: Condensation inside dry air sleeve of cable B4S (left) compared to typical condition of dry air sleeves (right) in 2003 *(photos: Amman & Whitney[4]).*

Figure 8: Condensation inside dry air sleeve on cable M4N in 2011 *(photos: Amman & Whitney[5]).*

4.0 Wire Breaks

Each cable of the Arecibo Telescope consists of a single strand of galvanized steel wires, with between 126 and 216 wires per cable depending on the cable and wire diameters.

It is not uncommon for individual wires to break in structural cables, even when the overall cable tension is less than the cable's minimum breaking strength. Wire breaks may be due to local propagation of cracks, corrosion, or friction between adjacent wires or with other surfaces. When a wire breaks, its tension gets redistributed to the remaining wires of the cable, generating a slight stress increase on each wire. A wire break in the outer layer of a strand can be detected visually through paint damage, loose

[4] Ammann & Whitney. *Structural Condition Survey 2003.* May 2003. Report retrieved from Cornell University archives.
[5] Ammann & Whitney. *Structural Condition Survey 2011.* March 2011. Report retrieved from Cornell University archives.

wire ends and/or high wires (a wire bulging out of the strand). A wire break inside the strand is usually not visible from the outside and can only be detected with an x-ray.

The AO maintenance records include reports of wire breaks discovered by the AO staff over time. As no x-ray reports were found about the wire breaks, we assume that the reported wire breaks only occurred in the cables' outer layer. In this appendix, these breaks are referred to as the *known wire breaks*, since other wires may have broken inside the cables and not been visible.

A map of the wire breaks discovered up to 1983 was published in a paper by Phoenix, Johnson and McGuire (Figure 9), with the map showing 20 known wire breaks. Six of these breaks were located at the ground end of cable B12-3, leading AO to replace that cable in 1981 as a precaution (Appendix C). According to the AO maintenance records and correspondence, eight additional wire breaks were discovered between 1982 and 2003 (Figure 10). The only new breaks on record after 2003 are located near the M8-4 cable splice: AW observed three breaks during a 2011 inspection, and nine additional breaks when re-inspecting the structure after a significant earthquake in January 2014 (Figure 11). As a precaution, a bypass was installed over the segment of cable with 12 breaks (Appendix C).

Overall, a total of 40 wire breaks had been reported in the cable system before the first cable failure on August 10, 2020. This is only 0.6 percent of the total number of wires in the telescope's cables. The number of breaks drops to 22 or 0.3 percent of the wires when excluding the B12-3 cable that was replaced and the M8-4 cable segment that was bypassed. Every known wire break is located near a socket at a cable end.

After discovering a wire break, the AO staff typically installed clamps on the cable to keep the broken wire in place. These clamps and the broken wires they hold remain visible after the cable is repainted (Figure 12). The numerous drone photos taken in 2020 after the first cable failure show evidence of past wire breaks at locations generally consistent with the breaks reported in the AO records. Past wire breaks could not be precisely counted from the drone photos, as some of the clamps appear to have been installed preventively while other clamps appear to have been removed or to have fallen from the cables.

The known wire breaks before the first cable failure are mapped in Figure 13, and the number of known breaks over time is plotted in Figure 14. A map of the cable clamps and clamp marks observed in 2020 is also presented in Figure 15.

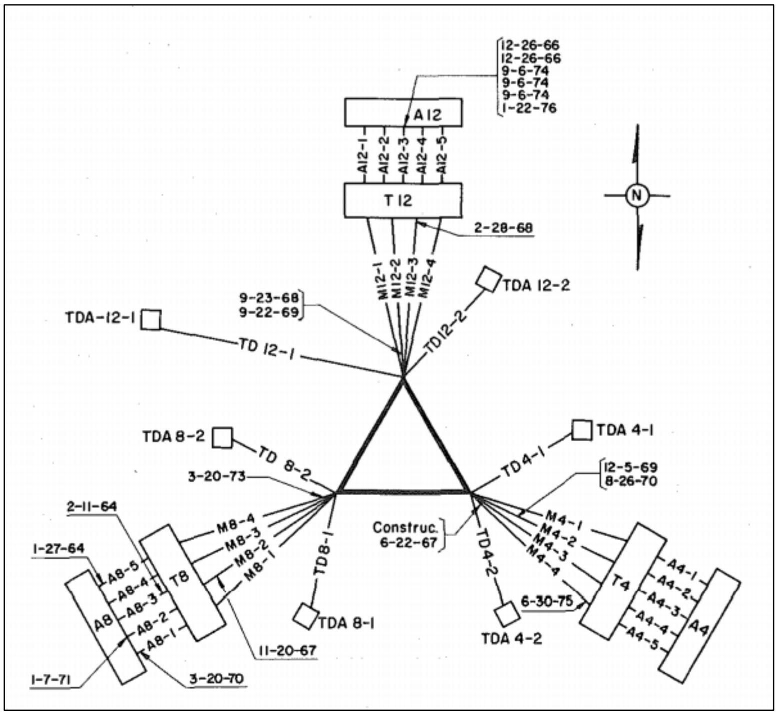


Figure 9: 1986 map of wire breaks *(image: Phoenix, Johnson, and McGuire[6]).*

Figure 10: Wire break at ground end on B4-1 discovered on December 12, 1996
(photo: NAIC Arecibo Observatory, a facility of the NSF).

[6] Phoenix, S.L., Johnson, H.H., and McGuire, W. "Condition of Steel Cable after Period of Service". *Journal of Structural Engineering*. 112(6). 1986.

Figure 11: Multiple wire breaks near M8-4 splice discovered on January 14, 2014
(photo: NAIC Arecibo Observatory, a facility of the NSF).

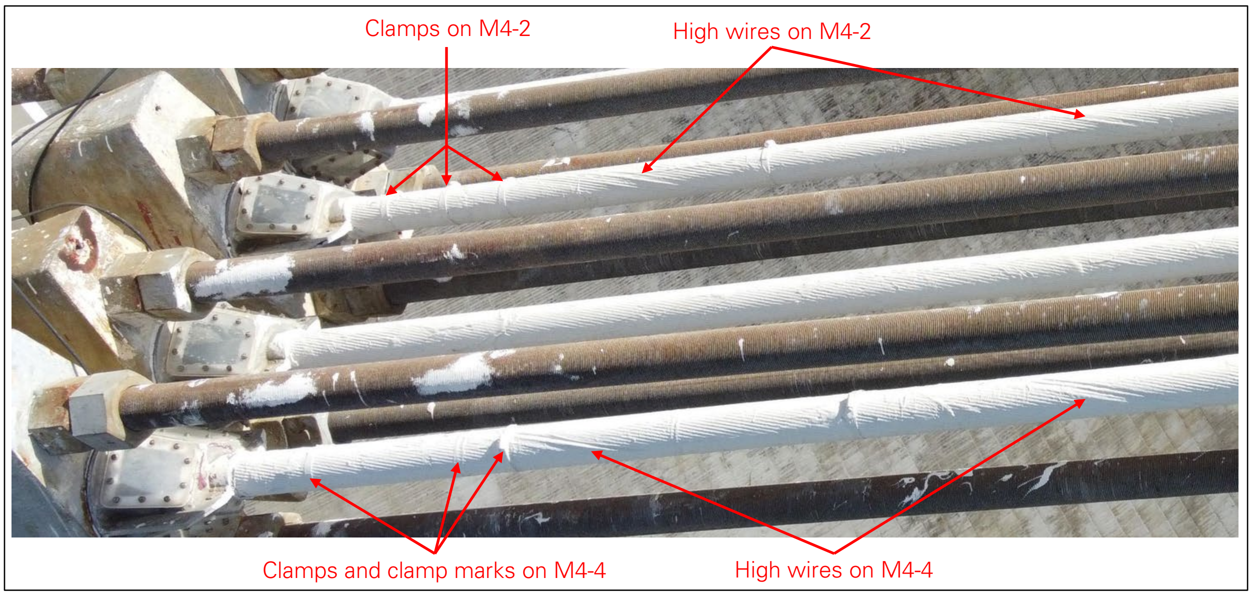


Figure 12: Evidence of past wire breaks at platform end of M4 cables
(photo: NAIC Arecibo Observatory, a facility of the NSF).

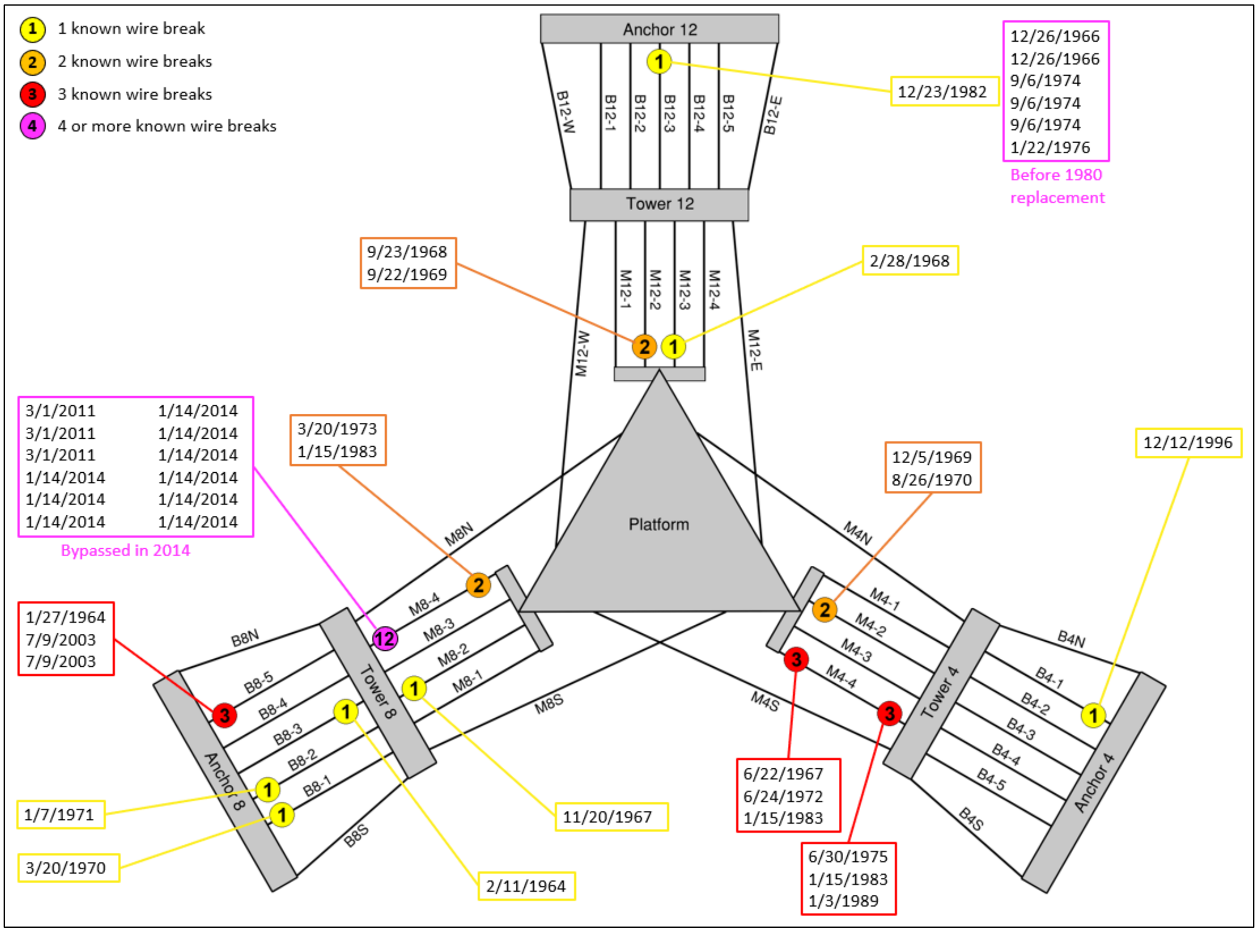


Figure 13: Known wire break locations and discovery dates before first cable failure.

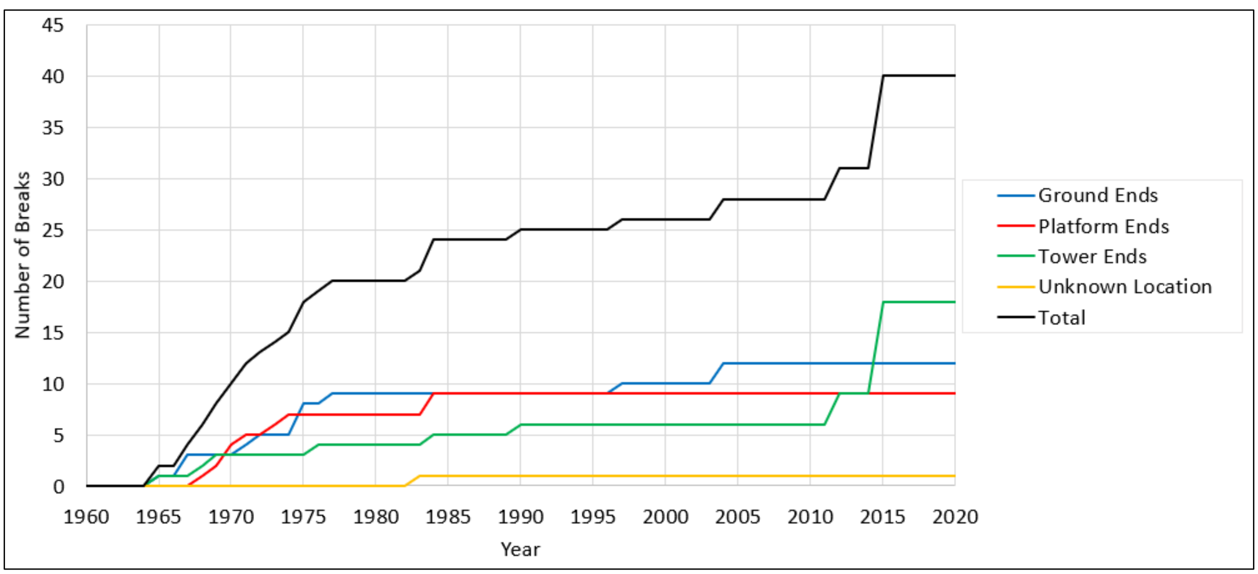


Figure 14: Count of known wire breaks up to first cable failure.

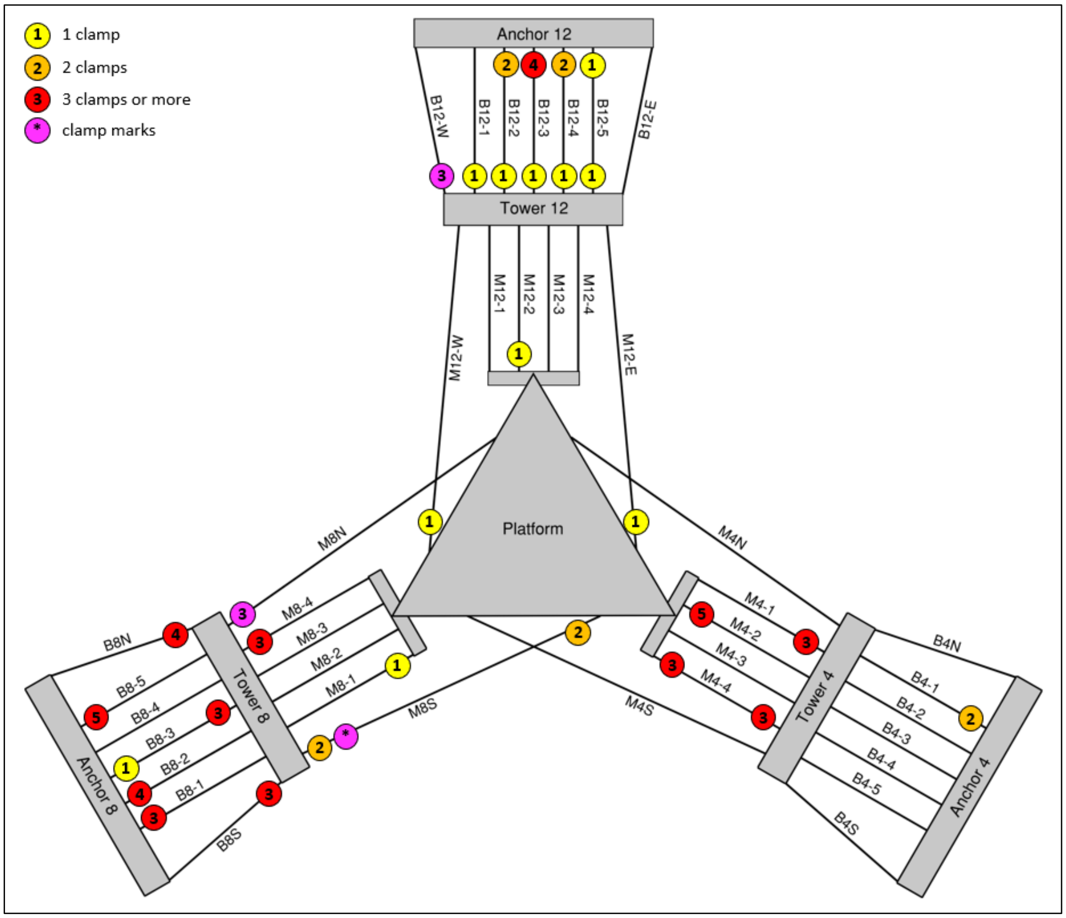


Figure 15: Cable clamps and clamp marks observed after first cable failure.

5.0 Cable Slip

In this report, the *cable slip* refers to the distance that a cable end shifted with respect to its socket. In zinc-filled spelter sockets, the cable slip is typically measurable as the length of zinc extruded out of the socket (Figure 16).

Before breaking free on August 8, 2020, the end of cable M4N at the top of Tower 4 had slipped by more than one inch from its socket. This one-inch slip is approximately one-third of the cable's diameter and significantly more than typically observed in structural cables terminated with zinc-filled spelter sockets. We reviewed the telescope's maintenance and inspection records, as well as photographs, provided by AO to determine the history, extent, and severity of cable slip in the telescope structure. The available information is presented in this section.

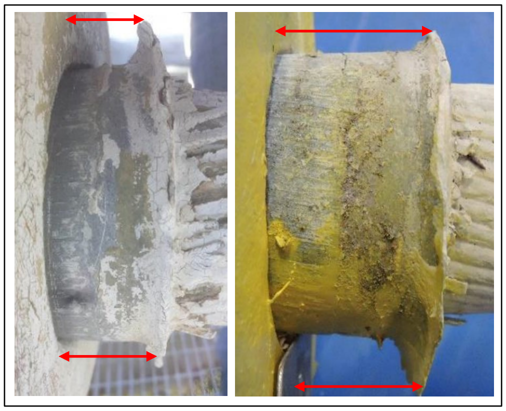


Figure 16: Cable slip at socket M4N_T (left) and B12W_G (right)
(photos: NAIC Arecibo Observatory, a facility of the NSF).

5.1 Inspection Reports

The structure's inspection reports (Table 2) only mention cable slip for the auxiliary cables, installed in 1995. A post-hurricane inspection performed by the AO staff in 1998 reported a 1/16-inch displacement at the auxiliary cable sockets, although it is not clear whether this refers to cable slip or some other type of displacement. AW reported a cable slip of up to ½ inch at all of the auxiliary cable sockets after their 2003 inspection, and no measurable change after their 2011 inspection.

Table 2: Auxiliary cable end slip conditions as described in inspection reports.

Source	Quotes
1998 post-hurricane damage assessment[A]	"In general, new cable connection at socket shows some displacement toward the inside of the socket in the order of 1/16"."
2003 structural inspection report[B]	Auxiliary backstays: "At the faces of the auxiliary backstays the zinc has separated away from the leading edge of the socket by up to ½". This condition was observed at all of the sockets for the auxiliary backstay cables and appears to have occurred during the fabricating or testing phase of the cable assemblies." Auxiliary mains: "As at the auxiliary backstays, the cast zinc has separated away from the leading edge of the sockets by up to ½". This condition was observed at the auxiliary cables."
2011 structural inspection report[C]	Auxiliary backstays: "The end socket ½" cast zinc leading edge separation was observed at all cables but has not measurably increased since reported in the 2003 survey." Auxiliary mains: "As noted in the 2003 report, the cast zinc has separated away from the leading edge of all the sockets by up to ½", a condition that remains unchanged."

[A] Arecibo Observatory. *Hurricane George*. September 25, 1998. Report retrieved from Cornell University archives.
[B] Ammann & Whitney. *Structural Condition Survey 2003*. May 2003. Report retrieved from Cornell University archives.
[C] Ammann & Whitney. *Structural Condition Survey 2011*. March 2011. Report retrieved from Cornell University archives.

5.2 Cable Slips Before Collapse

A map of the auxiliary cable slips at the time of collapse is provided in Figure 17. To determine the cable slips, we reviewed photographs taken in 2020 before the collapse and, when possible, took measurements on the sockets recovered after the collapse. The collapse does not appear to have significantly increased any of the cable slips.

The map indicates the ratio of the cable slip to the cable diameter, and sockets are flagged when this ratio is greater than one sixth. The one-sixth limit is based on the AASHTO M277[7] standard for testing wire ropes used in moveable bridges. Because the telescope's auxiliary cables had been loaded for 25 years when the structure collapsed and may therefore have experienced long-term creep effects that do not occur during short load tests, the comparison of the Arecibo cable slips to the one sixth limit is for reference only.

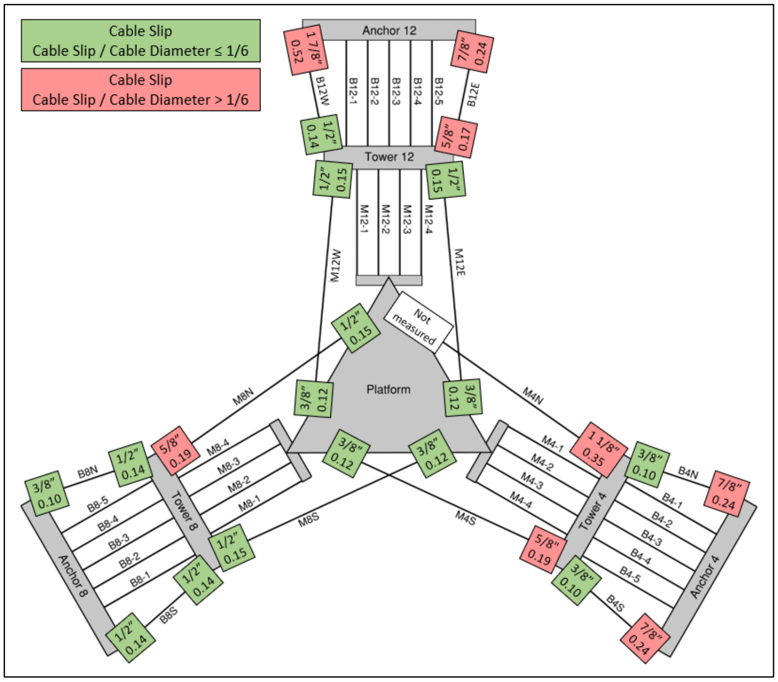


Figure 17: Cable slip at auxiliary sockets before collapse.

5.3 Photographs

The key available photographs of cable slip are compiled in this section, and include the latest drone photographs of the tower ends before collapse, as well as post-collapse photographs of the ground ends. A representative photograph is also provided for each time a cable end was photo-recorded up close by AO or WJE before the collapse.

[7] American Association of State Highway and Transportation Officials (AASHTO). *AASHTO M 277-06. Standard Specification for Wire Rope and Sockets for Movable Bridges*. 2019.

5.3.1 Auxiliary Main Tower-End Sockets

Socket M4N_T

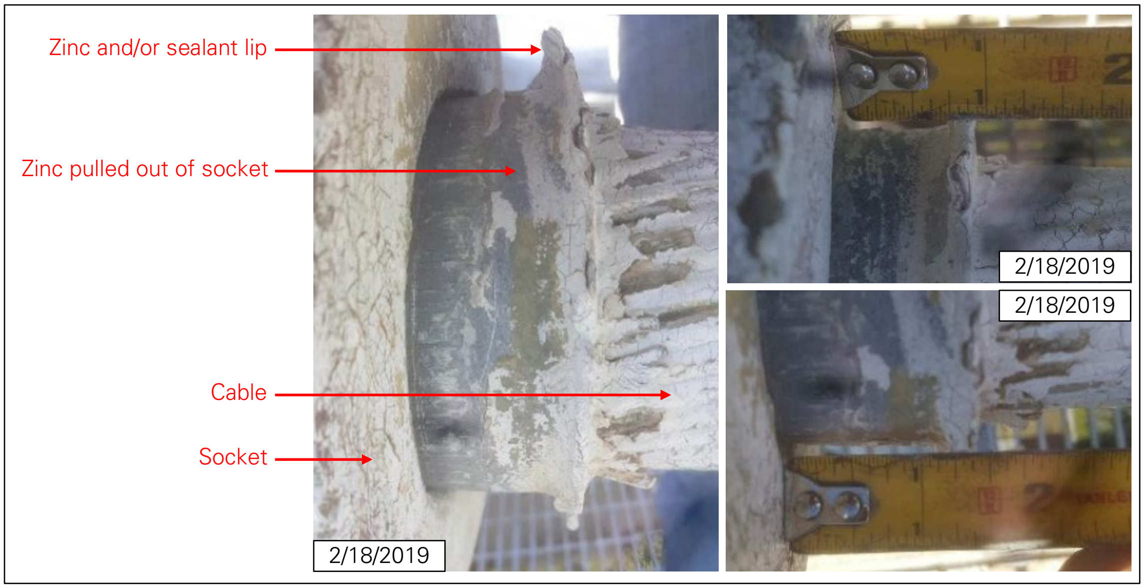


Figure 18: Cable slip at socket M4N_T. As seen from the north side (left) and measured on north (top right) and south (bottom right) sides of socket *(photos: NAIC Arecibo Observatory, a facility of the NSF).*

Socket M4S_T

Figure 19: Cable slip at socket M4S_T
(photo: Ammann & Whitney[8]).

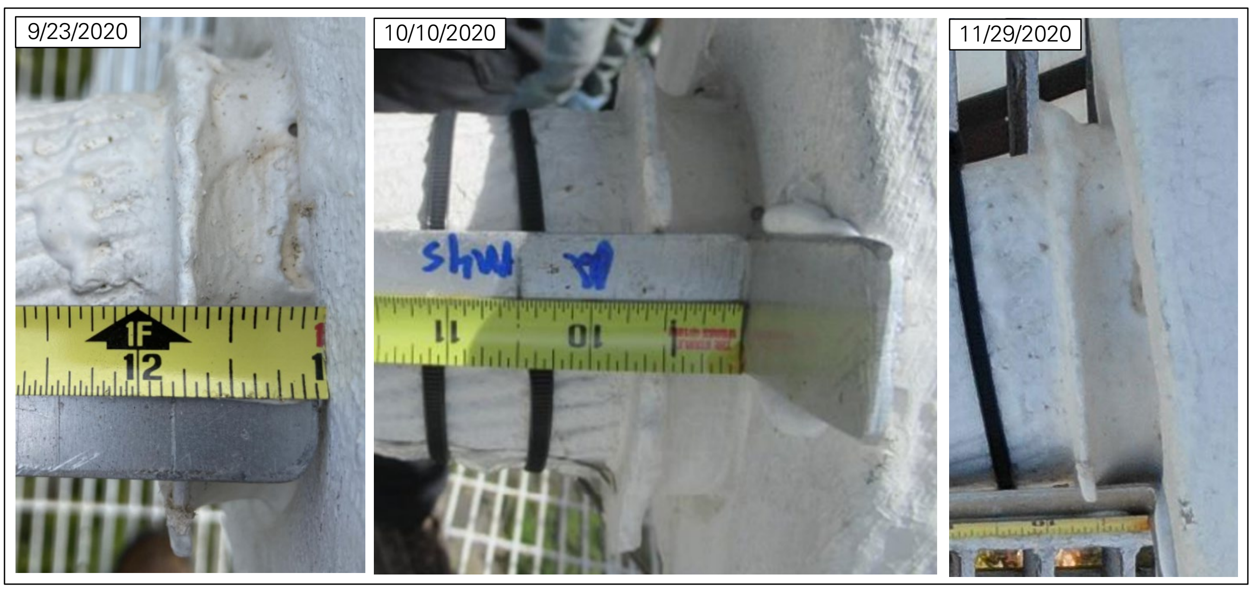


Figure 20: Cable slip at socket M4S_T
(left and center photos: WJE[9]; right photo: NAIC Arecibo Observatory, a facility of the NSF).

[8] Ammann & Whitney. *Structural Condition Survey 2003.* May 2003. Report retrieved from Cornell University archives.
[9] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

Socket M8N_T

Figure 21: Cable slip at socket M8N_T
(left and center photos: NAIC Arecibo Observatory, a facility of the NSF).

Socket M8S_T

Figure 22: Cable slip at socket M8S_T
(left photo: WJE[10]; center photo: NAIC Arecibo Observatory, a facility of the NSF).

[10] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

Socket M12E_T

Figure 23: Cable slip at socket M12E_T
(photos: NAIC Arecibo Observatory, a facility of the NSF).

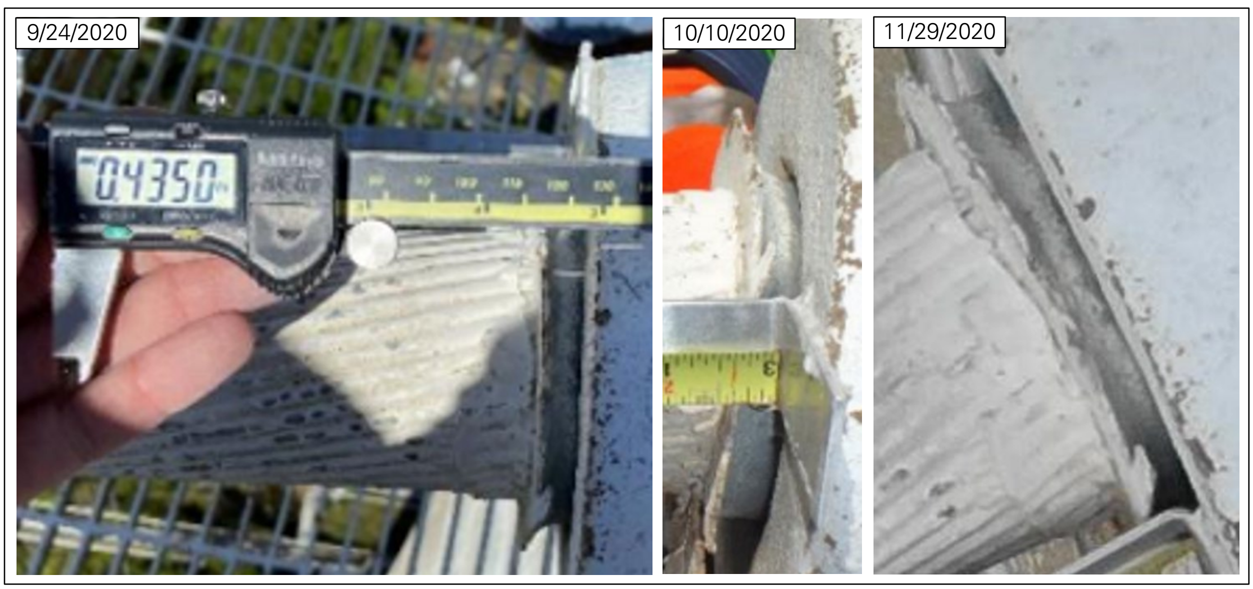


Figure 24: Cable slip at socket M12E_T
(left and center photos: WJE[11]; right photo: NAIC Arecibo Observatory, a facility of the NSF).

[11] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

Socket M12W_T

Figure 25: Cable slip at socket M12W_T
(left photo: NAIC Arecibo Observatory, a facility of the NSF; right photo: WJE[12]).

Figure 26: Cable slip at socket M12W_T
(left photo: WJE[12]; center photo: NAIC Arecibo Observatory, a facility of the NSF).

[12] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

5.3.2 Auxiliary Main Platform-End Sockets

Socket M4S_P

Figure 27: Cable slip at socket M4S_P.

Socket M8N_P

Figure 28: Cable slip at socket M8N_P.

Socket M8S_P

Figure 29: Cable slip at socket M8S_P.

Socket M12E_P

Figure 30: Cable slip at socket M12E_P.

Socket M12W_P

Figure 31: Cable slip at socket M12W_P.

5.3.3 Auxiliary Backstay Tower-end Sockets

Socket B4N_T

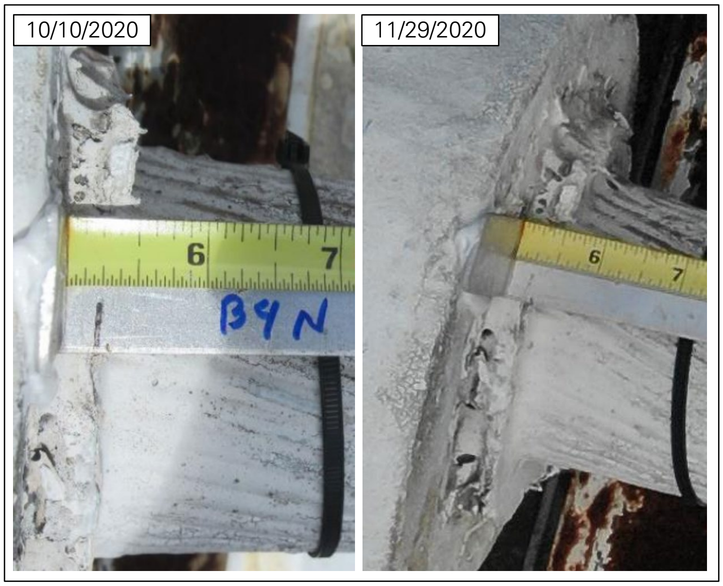


Figure 32: Cable slip at socket B4N_T
(left photo: WJE[13]; right photo: NAIC Arecibo Observatory, a facility of the NSF).

Socket B4S_T

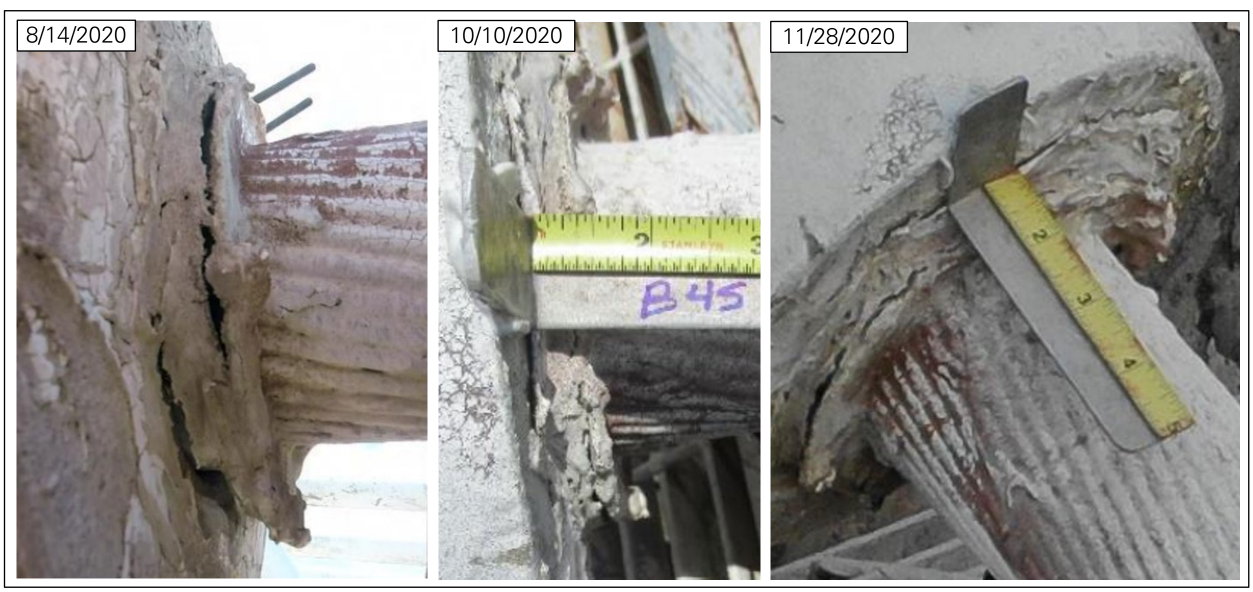


Figure 33: Cable slip at socket B4S_T
(left and right photos: NAIC Arecibo Observatory, a facility of the NSF; center photo: WJE[13]).

[13] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

Socket B8N_T

Figure 34: Cable slip at socket B8N_T
(photos: NAIC Arecibo Observatory, a facility of the NSF).

Socket B8S_T

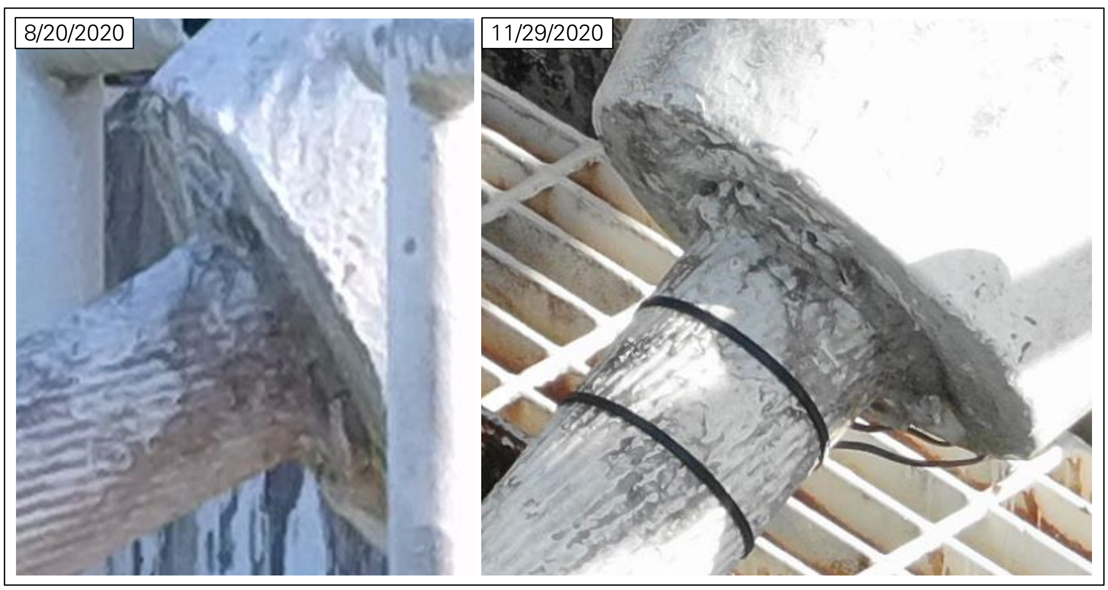


Figure 35: Cable slip at socket B8S_T
(photos: NAIC Arecibo Observatory, a facility of the NSF).

Socket B12E_T

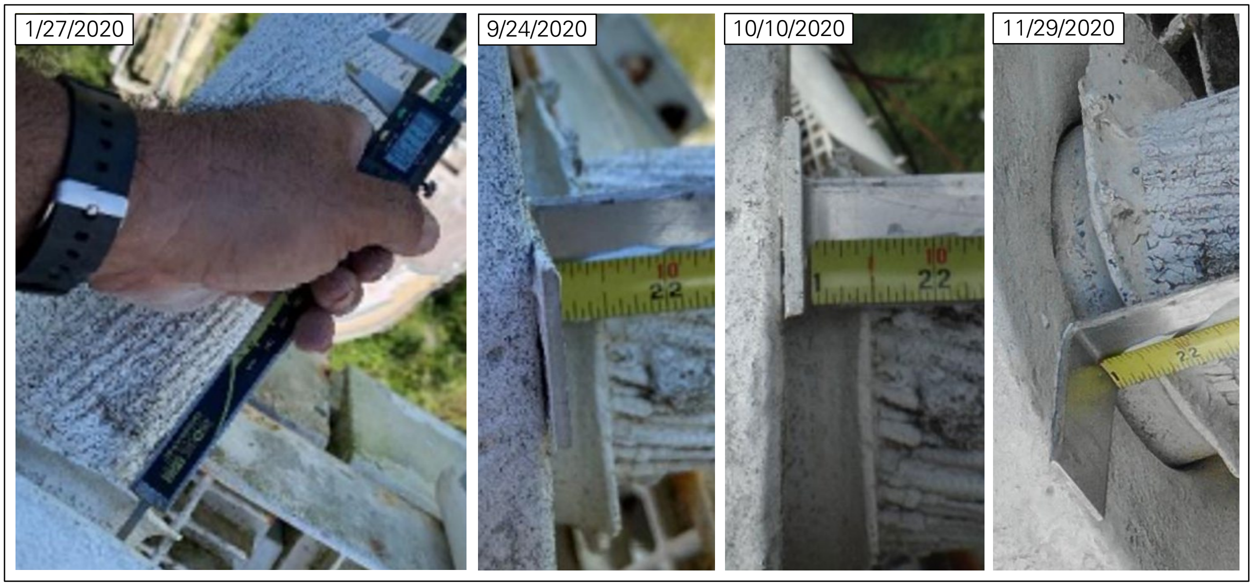


Figure 36: Cable slip at socket B12E_T
(left and right photos: NAIC Arecibo Observatory, a facility of the NSF; center photos: WJE[14]).

Socket B12W_T

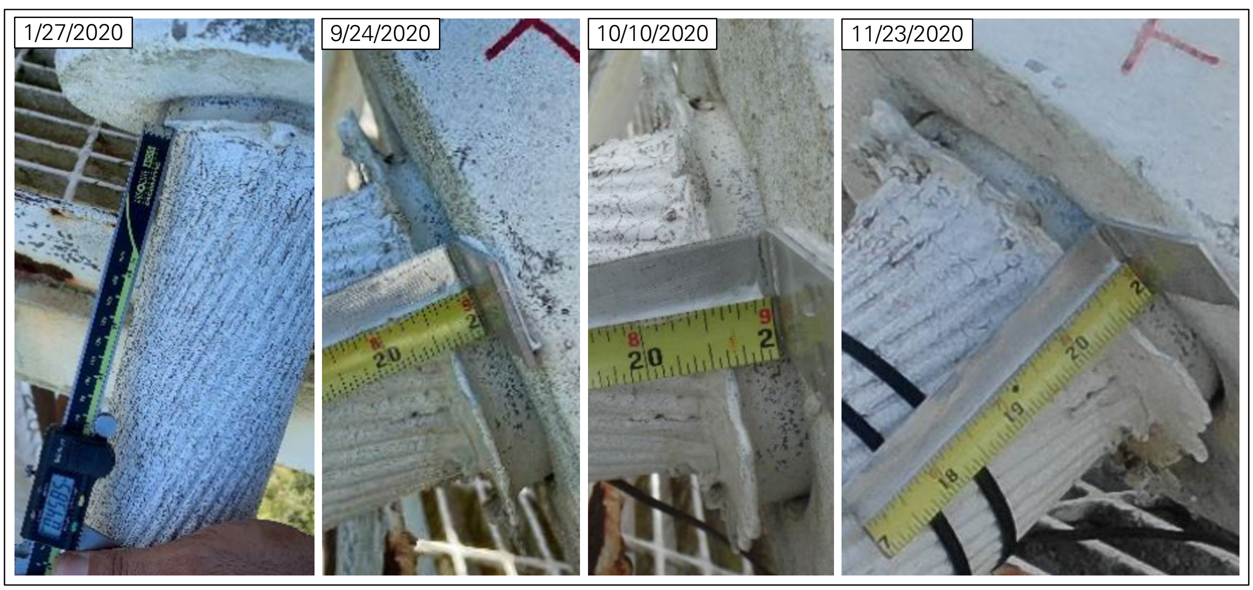


Figure 37: Cable slip at socket B12W_T
(left and right photos: NAIC Arecibo Observatory, a facility of the NSF; center photos: WJE[14]).

[14] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

5.3.4 Auxiliary Backstay Ground-end Sockets

Socket B4N_G

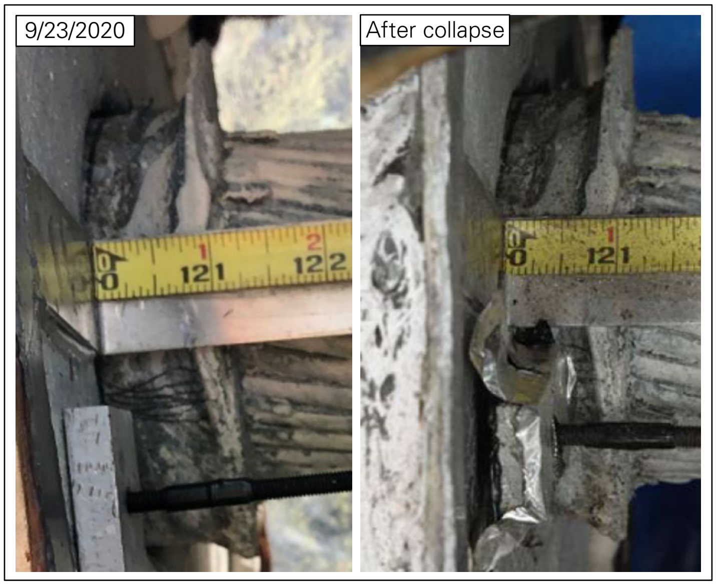


Figure 38: Cable slip at socket B4N_G
(left photo: WJE[15]).

Socket B4S_G

Figure 39: Cable slip at socket B4S_G.

[15] Wiss, Janney, Elstner Associates (WJE). *Auxiliary Main Cable Socket Failure Investigation.* June 21, 2021. Draft report provided by WJE.

Socket B8N_G

Figure 40: Cable slip at socket B8N_G.

Socket B8S_G

Figure 41: Cable slip at socket B8S_G.

Socket B12E_G

Figure 42: Cable slip at socket B12E_G.

Socket B12W_G

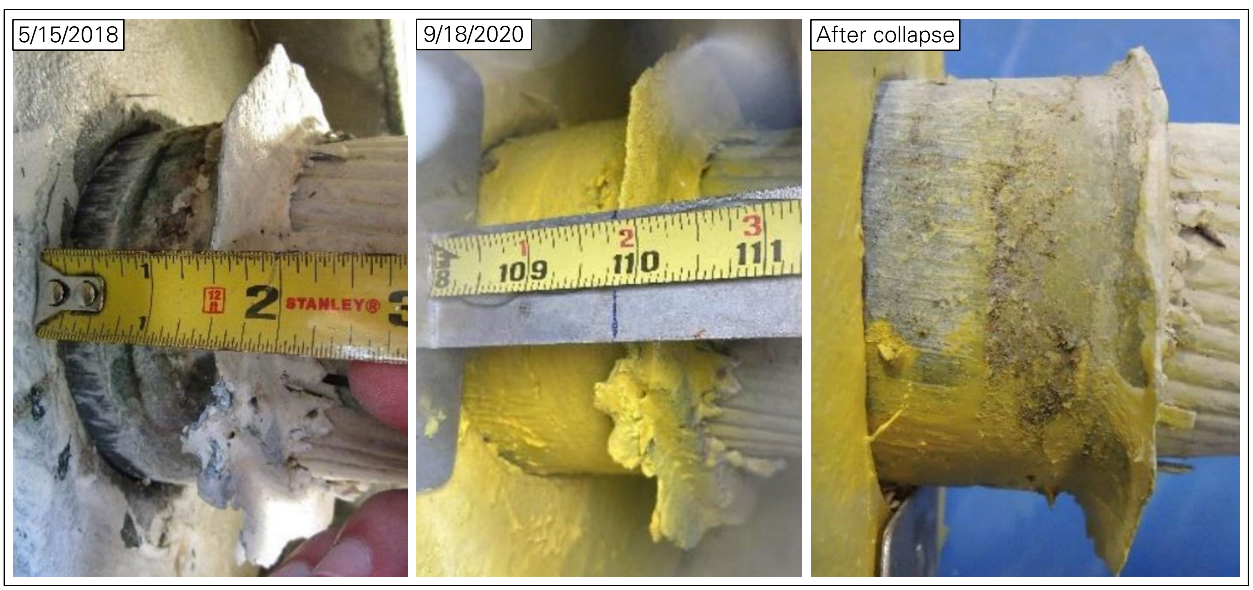


Figure 43: Cable at socket B12W_G
(left and center photos: NAIC Arecibo Observatory, a facility of the NSF).

6.0 Cable Vibrations

The main and backstay cables began experiencing wind-induced vibrations immediately after construction of the telescope in 1963, and Stockbridge dampers (Figure 44) were then installed to mitigate the vibrations.[16] As shown in Table 3, cable vibrations continued to be reported throughout the lifespan of the telescope, which led to upgrades and adjustments of the dampers. While we have not seen any data on the amplitude of the cable movement, AW did not consider that the vibrations were a concern from a structural standpoint. The vibrations also appear to have been relatively infrequent and may have occurred only under specific wind conditions. Finally, the initial installation and later adjustments of the damper system appear to have been effective.

Table 3: Cable vibrations mentioned in maintenance and inspection reports.

Source	Quotes
1970 maintenance report[A]	"While the dampers have been highly effective in reducing vibration of the cables, these vibrations still do occasionally occur. Since the installation of the dampers, there have been 2 or 3 guards' reports of vibrations. It is certain that the vibrations die out quickly after the excitation ceases."
1975 maintenance report[B]	"Main cable and anchor cable dampers were repositioned as specified by Ammann & Whitney."
1979 maintenance report[C]	"Vibration dampers were installed on the main platform suspension cables at tower four as recommended by Ammann & Whitney … Since the dampers were installed on 23 February, the cables have vibrated only once."
1983 structural inspection report[D]	"Stockbridge dampers were installed to minimize aeolian vibrations which, although never severe, had been observed." "Any evidence of vibration is reported."
1989 structural inspection report[E]	"There is still an ongoing vibration of the main cables which seems to be worse in the afternoon when the wind is choppy compared to the early morning hours." "Cable spacers made of energy absorptive material should be designed and installed on the main and backstay cables at third points. This should reduce the amplitude of the galloping vibrations."
2011 structural inspection report[F]	"From the top of T12, main cables M12-3 and M12-4 exhibited a slight to moderate amplitude of wind induced vibration. " "Auxiliary backstay A4 South and A12 West exhibited a slight wind induced vibration." "Cable dampers should be installed at Tower 12 for cables M12-3 and M12-4 and Anchorage A4 for cable M4S AUX."

[A] Arecibo Observatory. Quarterly maintenance report. April 1, 1970. Report provided by Arecibo Observatory.
[B] Arecibo Observatory. Quarterly maintenance report. December 8, 1975. Report provided by Arecibo Observatory.
[C] Arecibo Observatory. Quarterly maintenance report. May 2, 1979. Report provided by Arecibo Observatory.
[D] 1983. Report retrieved from Cornell University archives.
[E] Ammann & Whitney. *Arecibo Mini Inspection*. May 1989. Report retrieved from Cornell University archives.
[F] Ammann & Whitney. *Structural Condition Survey 2011*. March 2011. Report retrieved from Cornell University archives.

[16] Phoenix, S.L., Johnson, H.H., and McGuire, W. "Condition of Steel Cable after Period of Service". *Journal of Structural Engineering*. 112(6). 1986.

Figure 44: Stockbridge dampers near top (left) and bottom (right) of original M4 cables in 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).