

Appendix E

Cable Failures and Telescope Collapse

- 1.0 Introduction 1
- 2.0 Before M4N Failure 1
- 3.0 M4N Failure..... 3
 - 3.1 Wire Breaks 3
 - 3.2 Socket Condition..... 4
- 4.0 Between M4N and M4-4 Failure 4
 - 4.1 Wire Breaks 4
 - 4.2 Socket Condition..... 7
- 5.0 M4-4 Failure 9
 - 5.1 Wire Breaks 9
 - 5.2 Socket Condition..... 10
- 6.0 Between M4-4 Failure and Collapse.....10
 - 6.1 Wire Breaks 10
 - 6.2 Socket Condition..... 15
- 7.0 Collapse15
 - 7.1 Top of Tower 4 15
 - 7.2 Overall Structure..... 18

1.0 Introduction

After a first cable failed on August 10, 2020, the cable system was frequently inspected by the Arecibo Observatory (AO) staff until the collapse on December 1, 2020. Those inspections were visual and mostly performed with drones to keep personnel at a safe distance from the damaged structure. This appendix compiles some of the inspection photos and still images of videos provided by AO to show the visible damage that developed in the cable system between first cable failure and collapse. The appendix is limited to observations. We relied on these observations to perform an analysis of the cable failures, which is presented in Appendix O.

The structural damage observed between the cable failure and collapse consists of cable wire breaks, cable socket deformation, and full cable failures. Damage was only observed among the original main cables supporting the telescope's platform from Tower 4 (the M4 cables), and most of the damage occurred near the top of Tower 4 (Figure 1).

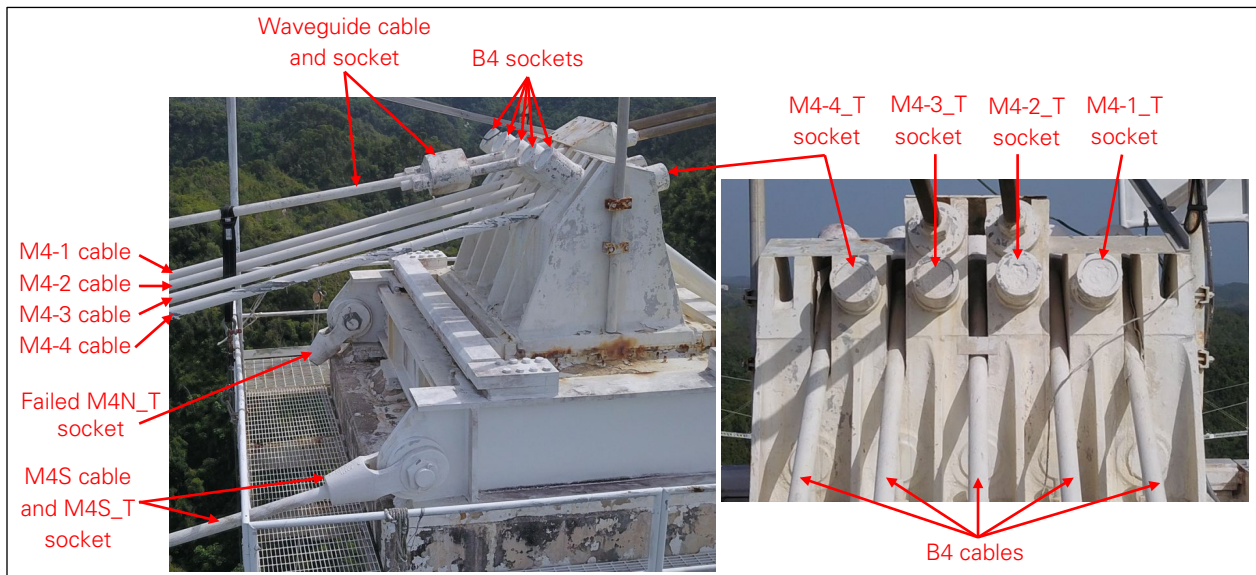


Figure 1: Cables and sockets at top of Tower 4 after M4N failure, looking northeast (left) and northwest (right)
(photos: NAIC Arecibo Observatory, a facility of the NSF).

Each of the M4 cables is a single strand of 168 steel wires, and in some of the cables multiple wires fractured before the entire cable failed. From the drone photos, we determined the number of wire breaks by counting the wires visibly loose and based on the paint damage on the cable surface. Only the wire breaks in the outer layer of the cable are counted, as any wire break in the inner layers would not be visible on the drone photos.

2.0 Before M4N Failure

According to the AO inspection records, a total of eight wire breaks were observed on the M4-2 and M4-4 cables between 1967 and 1989 (Table 1). Drone photos taken after the M4N failure (Figure 2, Figure 3) are consistent with those records, as they show protruding wires and/or clamps on the two cables. The clamps were likely installed to keep the broken wires tight with the rest of the cable. However, we noted

that clamps had been installed at the tower end of the M4-1 cable (Figure 3), while there is no record of any wire break at that location (Table 1).

Table 1: Wire breaks in Tower 4 original main cables on record before M4N failure.

	M4-1	M4-2	M4-3	M4-4
Tower End	none	none	none	6/30/1975 1/15/1983 1/3/1989
Platform End	none	12/5/1969 8/26/1970	none	6/22/1967 6/24/1972 1/15/1983

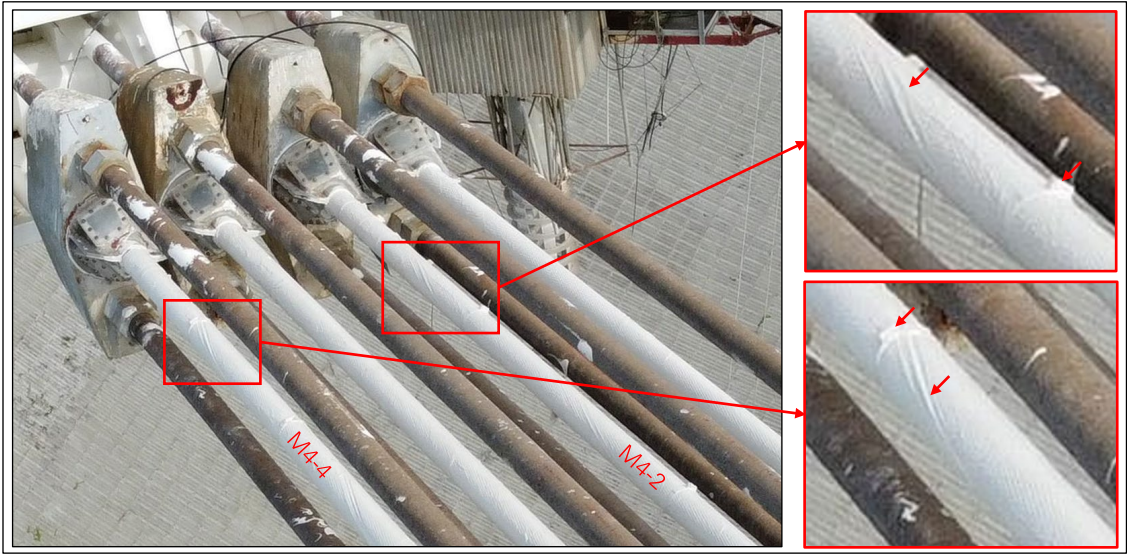


Figure 2: Clamps and evidence of previous wire breaks on M4-2 and M4-4 near platform
(photo: NAIC Arecibo Observatory, a facility of the NSF).



Figure 3: Clamps on M4-1 and M4-2 near Tower 4, likely installed after previous wire breaks.
The paint damage on M4-4 corresponds to fresh wire breaks following the M4N failure.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)

3.0 M4N Failure

Cable M4N pulled out of its socket at the top of Tower 4 on August 10, 2020. This section describes the damage discovered in the other cables over the next few days.

3.1 Wire Breaks

Shortly after the M4N failure, four wire breaks were observed in M4-4 near Tower 4 (Figure 4). No wire break was observed in any other M4 cable or near the platform (Figure 5).

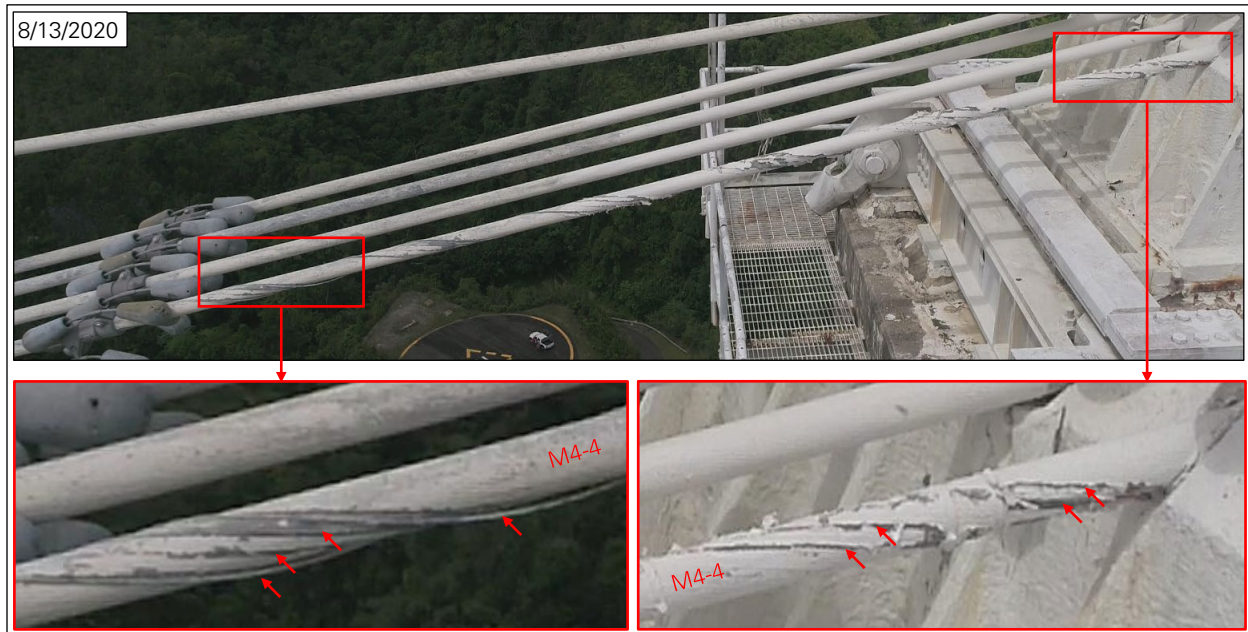


Figure 4: M4 cables near Tower 4 on August 13, 2020. Four wires are broken in M4-4, and no wire is broken in the other three cables. (Photo: NAIC Arecibo Observatory, a facility of the NSF.)

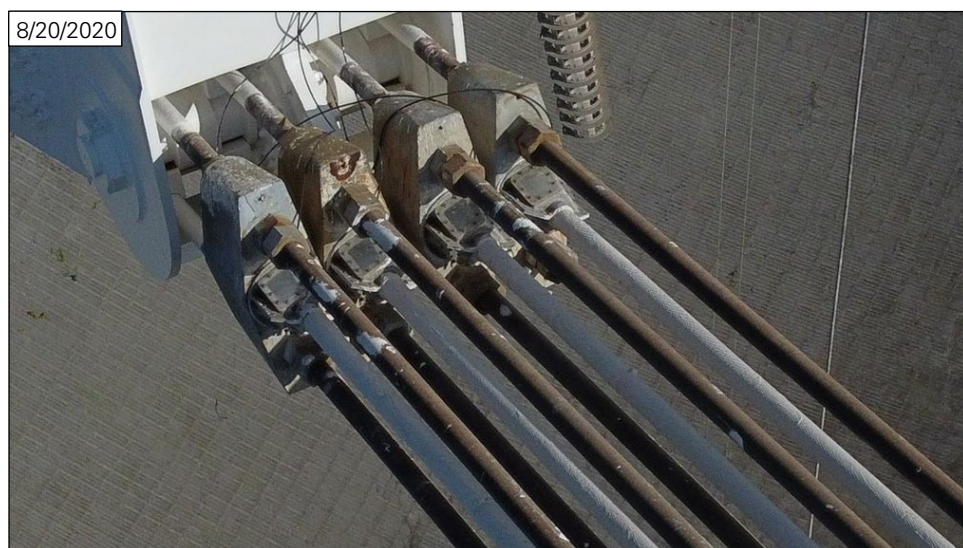


Figure 5: M4 cable near platform on August 20, 2020. No wire is broken. (Photo: NAIC Arecibo Observatory, a facility of the NSF.)

3.2 Socket Condition

The back end of the M4 sockets at Tower 4 is shown in Figure 6 after the M4N failure. On socket M4-2_T, a circular crack is visible on the surface of the zinc casting, and the central part of the casting has moved inwards. On socket M4-4_T, the surface of the casting also appears to be deformed with the central part moving inwards, but to a lesser extent than for M4-2_T. It is unknown whether these deformations occurred before or during the M4N failure.

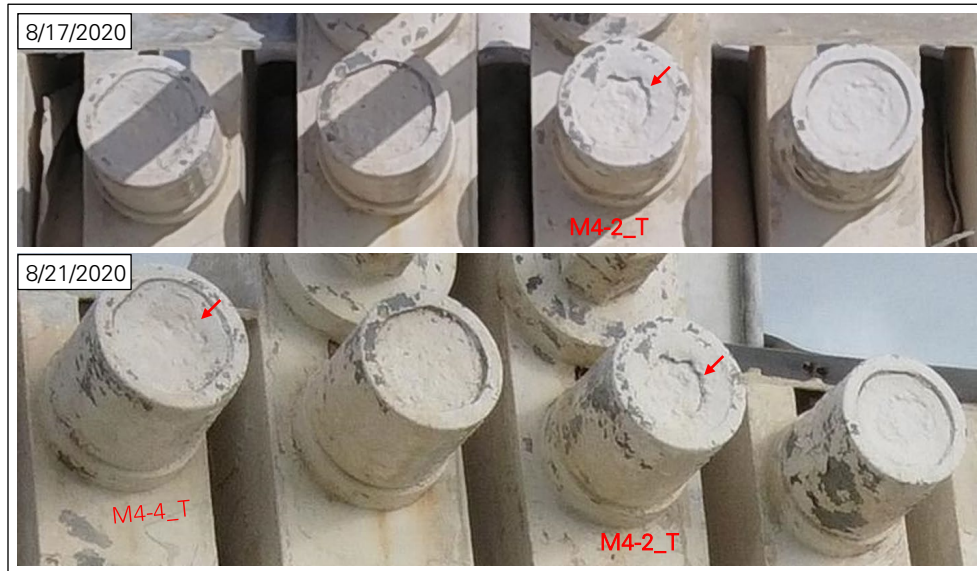


Figure 6: M4 sockets at Tower 4 after M4N failure
(photos: NAIC Arecibo Observatory, a facility of the NSF).

4.0 Between M4N and M4-4 Failure

AO inspected the structure on a regular basis in the three-month period between the M4N failure on August 10, 2020, and the M4-4 failure on November 6, 2020

4.1 Wire Breaks

The failed M4N_T socket was removed from the top of Tower 4 on September 23, 2020 for forensic analysis. During the operation, AO took close-up photographs of the M4 cables. The photographs show four broken wires on M4-4 (Figure 7), and one broken wire on M4-1 (Figure 8). The M4 cables were then repainted at the top of Tower 4 (Figure 9).

A new wire break was discovered on M4-2 on October 15, 2020 (Figure 10), and new paint damage was observed on M4-4 on October 19, 2020 (Figure 11). This paint damage, however, appears to be due to the movement of wires already broken. No more changes were observed by 10/30/2020 (Figure 12, Figure 13), which is a week before the failure of M4-4.

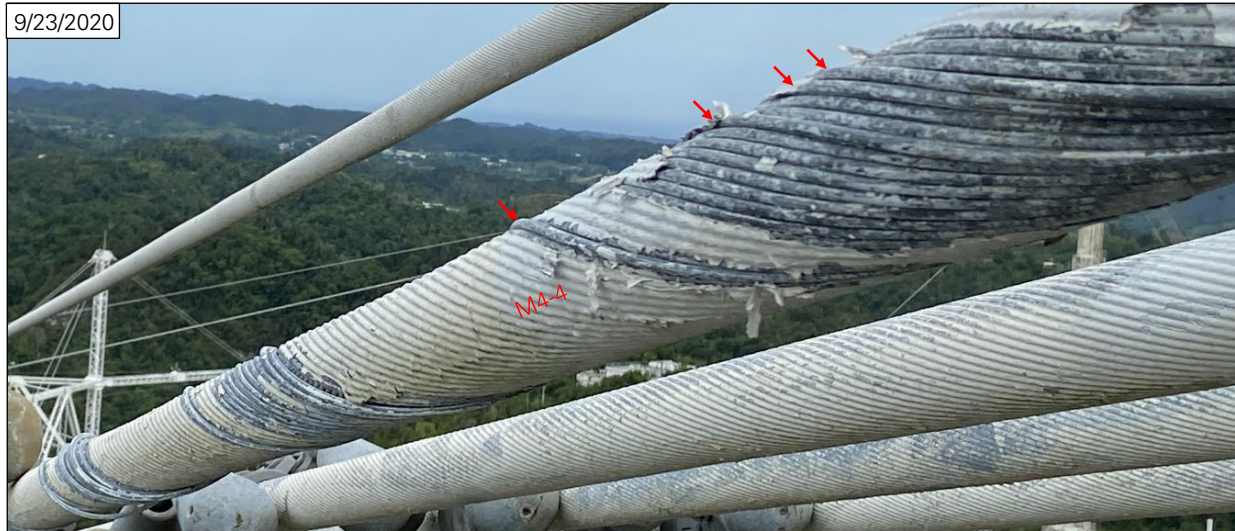


Figure 7: Close-up view of M4-4 near Tower 4 on September 23, 2020. Four wires are broken.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)

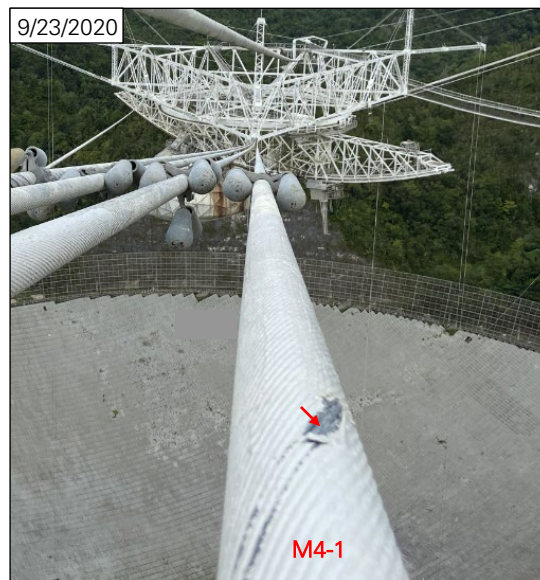


Figure 8: Close-up view of M4-1 near Tower 4 on September 23, 2020. A wire is broken.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)



Figure 9: M4 cables freshly repainted near Tower 4 on October 1, 2020
(photo: NAIC Arecibo Observatory, a facility of the NSF.)



Figure 10: New wire break in M4-2 on October 15, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).

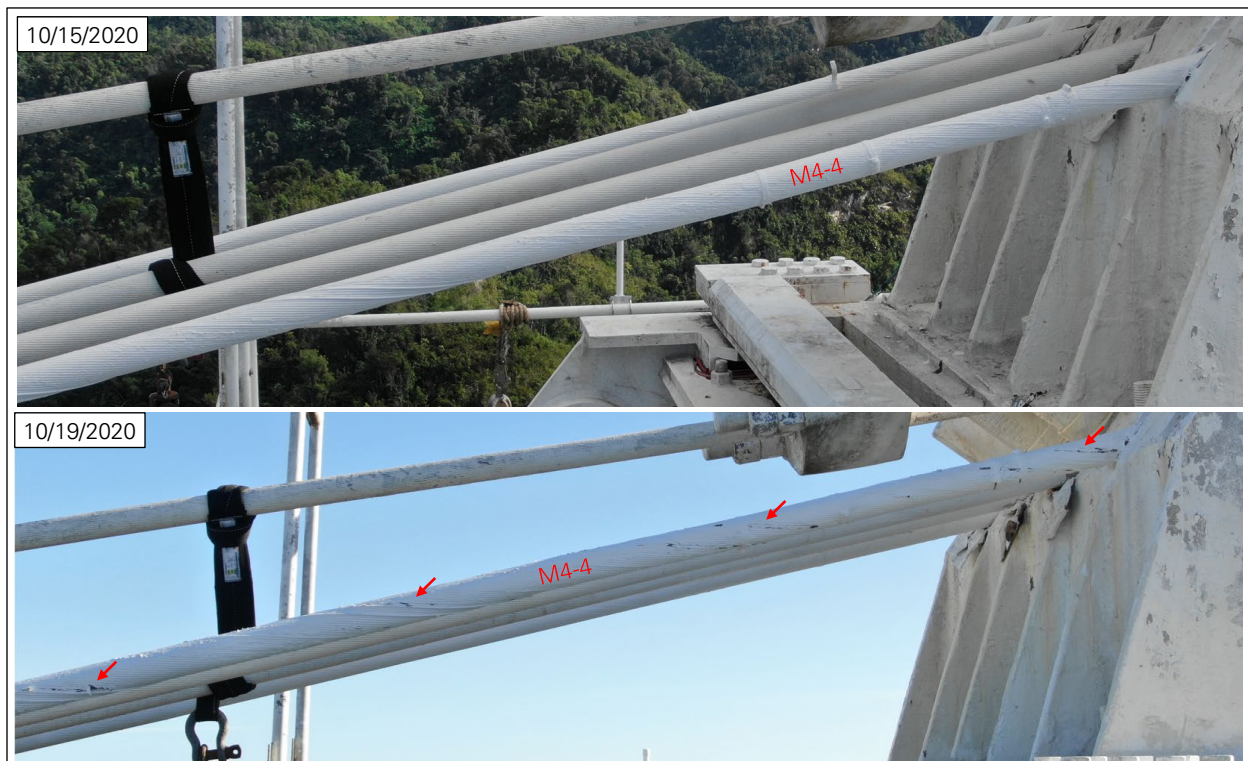


Figure 11: Broken wire movement in M4-4 on October 19, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 12: M4 cables near Tower 4 on October 30, 2020. No significant change is visible since October 19, 2020.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)



Figure 13: M4 cables near platform on October 30, 2020. No wire is broken.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)

4.2 Socket Condition

The crack in the zinc casting at the back of socket M4-2_T was sealed by October 1, 2020 (Figure 14). No significant change was observed on the sockets in October 2020 (Figure 15).

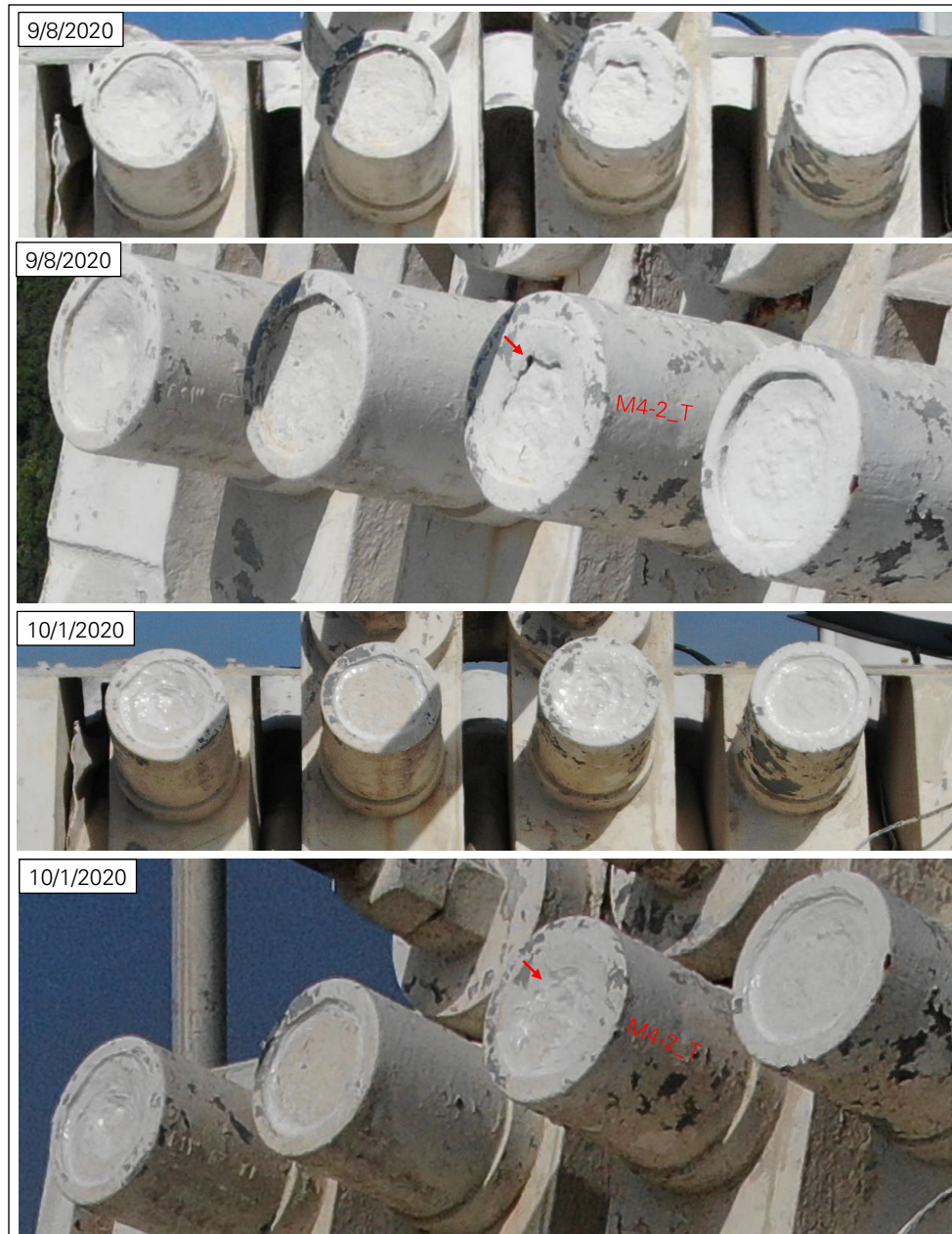


Figure 14: Sealant added at back of M4 sockets at Tower 4 by October 1, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 15: M4 sockets at Tower 4 on October 30, 2020. No significant change is visible since October 1, 2020.
(Photo: NAIC Arecibo Observatory, a facility of the NSF.)

5.0 M4-4 Failure

Cable M4-4 failed on November 6, 2020. This section describes the damage observed in the other M4 cables on the day of failure and the day after.

5.1 Wire Breaks

Shortly after the M4-4 failure, three new wire breaks were observed in M4-1 and a new wire break was observed in M4-2 near Tower 4 (Figure 16). Four wire breaks were also observed in M4-2 near the platform (Figure 17).



Figure 16: M4 cables near Tower 4 on November 6, 2020, with three new wire breaks in M4-1 and a new wire break in M4-2
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 17: M4 cables near platform on November 7, 2020. Four adjacent wires are broken in M4-2.
(Photos: NAIC Arecibo Observatory, a facility of the NSF.)

5.2 Socket Condition

The zinc casting of socket M4-4_T experienced significant deformation during the M4-4 failure or in the week preceding it, with the central part of the casting moving inwards (Figure 18). The M4-4 failure did not cause any visible change in the other three sockets (Figure 18).



Figure 18: M4 sockets at Tower 4 on November 8, 2020, and socket M4-4_T as recovered after collapse (top and bottom left photos: NAIC Arecibo Observatory, a facility of the NSF; bottom center photo: Socotec).

6.0 Between M4-4 Failure and Collapse

After the M4-4 failure, the remaining M4 cables were inspected at least once a day until the telescope collapsed.

6.1 Wire Breaks

Between the M4-4 failure and the collapse, seven and five new wire breaks were observed in the M4-1 and M4-2 cables respectively near Tower 4. The new wire breaks are shown in Figure 19 through Figure 27. No new wire break was observed in the M4 cables near the platform (Figure 28).

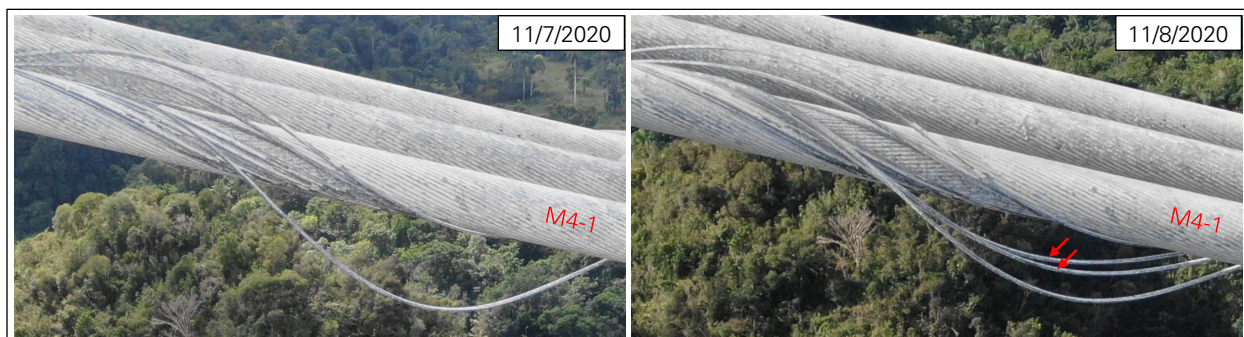


Figure 19: Two new wire breaks in M4-1 on November 8, 2020 (photos: NAIC Arecibo Observatory, a facility of the NSF).

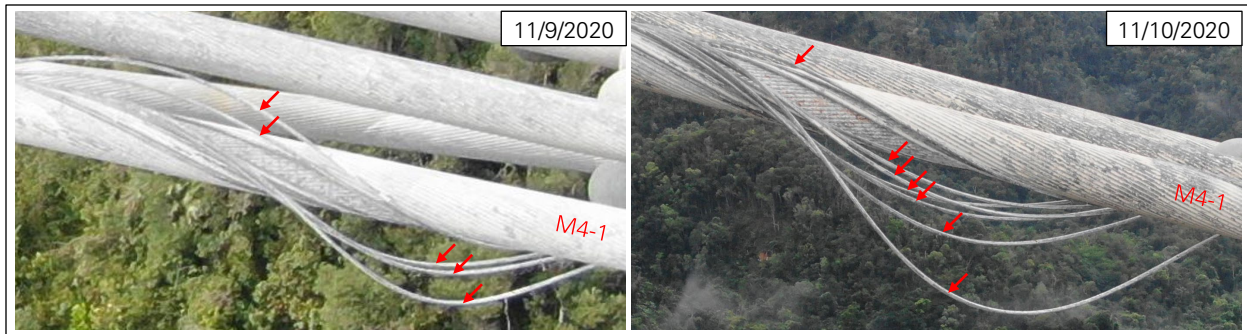


Figure 20: Two new wire breaks in M4-1 on November 10, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 21: New wire break in M4-2 on November 11, 2020. The break occurred away from the socket.
(Photos: NAIC Arecibo Observatory, a facility of the NSF.)



Figure 22: New wire break in M4-1 on November 13, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 23: New wire break in M4-2 on November 20, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).

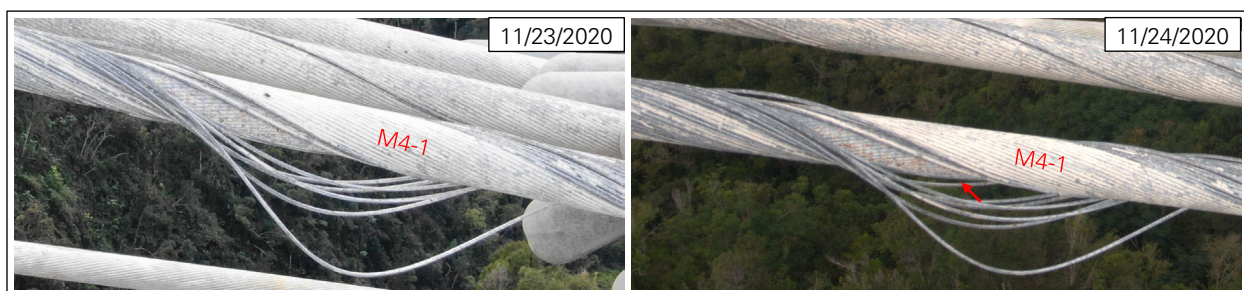


Figure 24: New wire break in M4-1 on November 20, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 25: New wire break in M4-1 on November 26, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 26: New wire break in M4-2 on November 29, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).



Figure 27: Two new wire breaks in M4-2 on December 1, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).

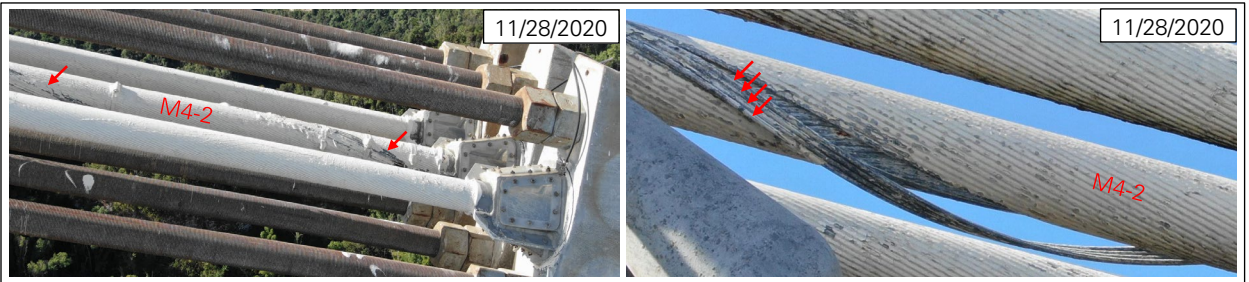


Figure 28: M4 cables near platform on November 28, 2020, with no visible change since November 7, 2020
(photos: NAIC Arecibo Observatory, a facility of the NSF).

The evolution of the number of wire breaks observed in the M4 cables near Tower 4 after the first cable failure is shown in Figure 29.

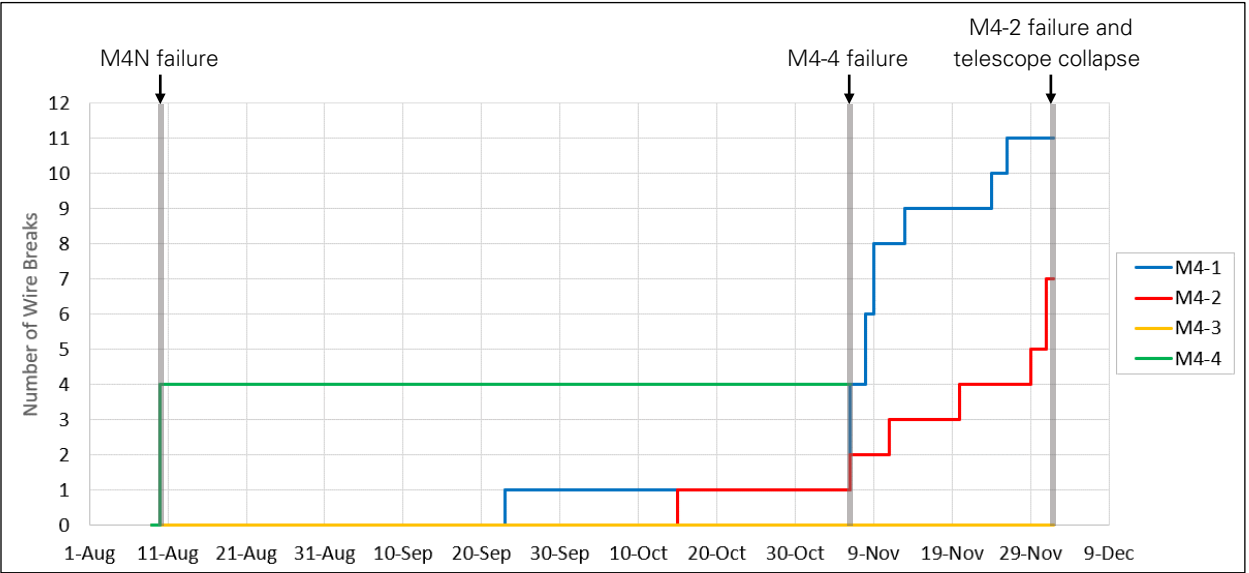


Figure 29: Count of wire breaks in M4 cables near Tower 4 between M4N failure and collapse.

6.2 Socket Condition

The central part of the zinc casting of socket M4-2_T moved inwards after the M4-4 failure. As shown in Figure 30, a crack developed in the sealant that had been installed between the M4N and M4-4 failures.

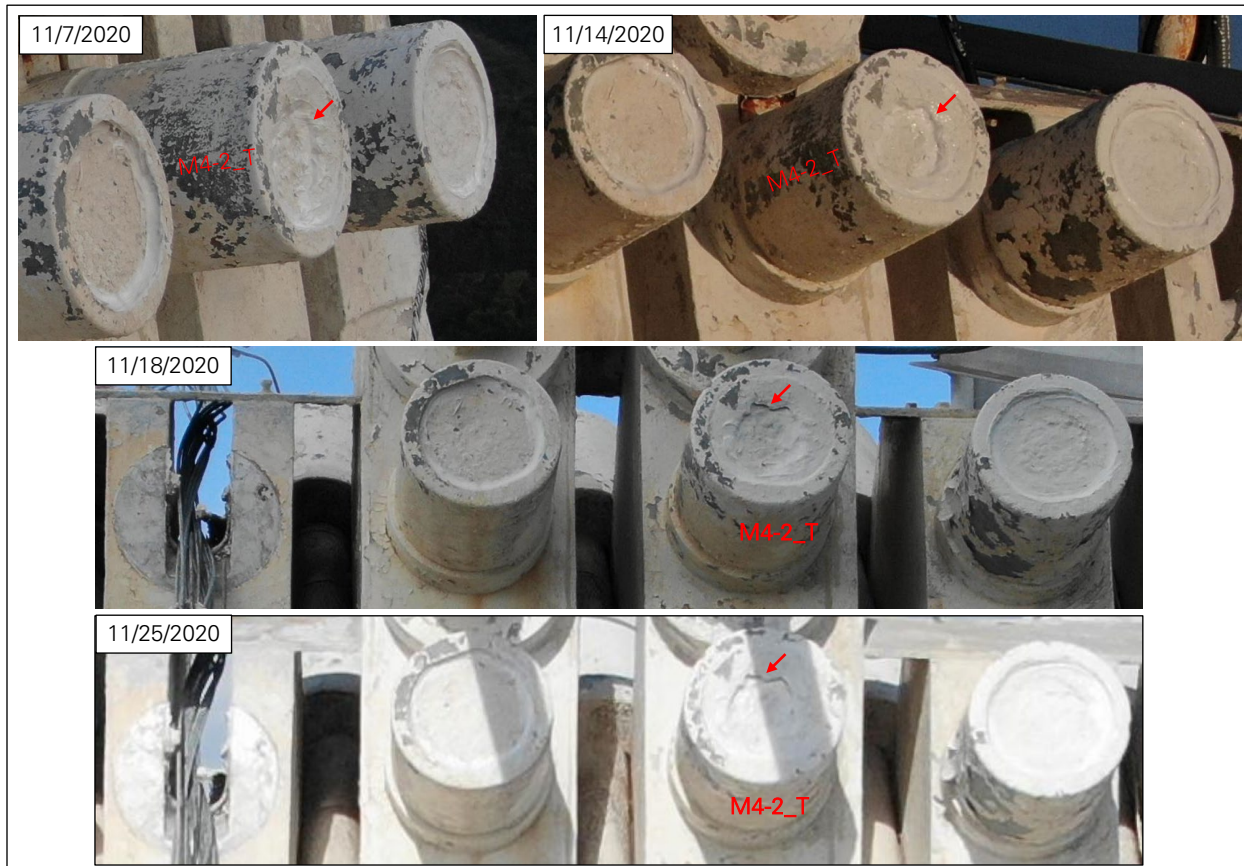


Figure 30: M4 sockets at Tower 4 after M4-4 failure. On socket M4-2, the central part of the zinc casting appears to move inwards, resulting in a new sealant crack. (Photos: NAIC Arecibo Observatory, a facility of the NSF.)

7.0 Collapse

The telescope collapsed on December 1, 2020, immediately after the failure of cable M4-2 at the top of Tower 4. This section describes the cable failure and the telescope collapse sequence as captured on video.

7.1 Top of Tower 4

The AO staff was performing a drone inspection of the top of Tower 4 when cable M4-2 failed and triggered the collapse of the telescope. Key frames of the video recorded by the drone are compiled on Figure 31 through Figure 33.

The M4-2 socket recovered after the collapse is shown in Figure 34. The central part of the zinc casting moved further inwards since the last known photo (November 25, 2020, Figure 30). This movement may have occurred suddenly when M4-2 failed.

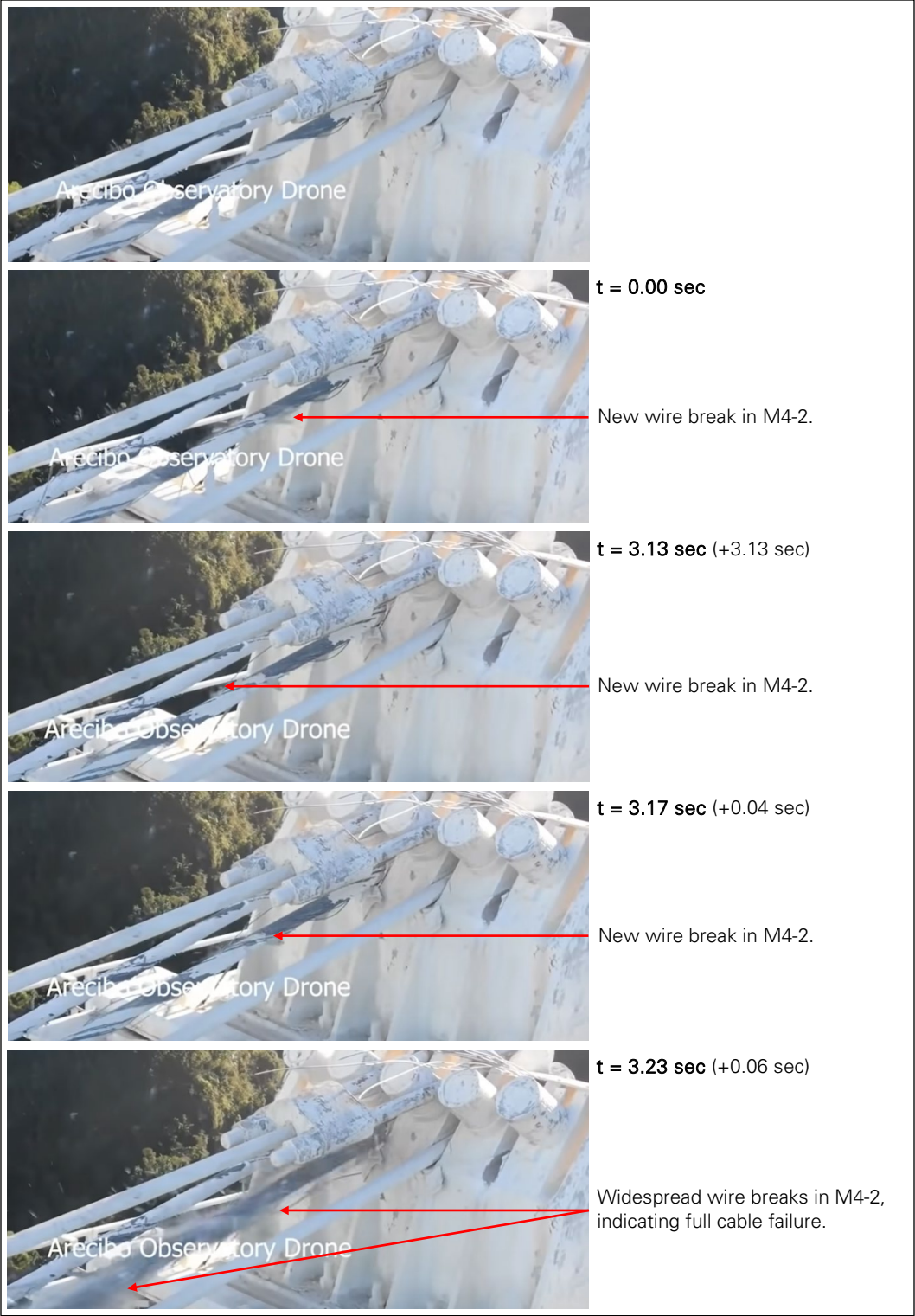


Figure 31: Still images of drone video of top of Tower 4 during telescope collapse: seconds 0.00 to 3.23 (video: NAIC Arecibo Observatory, a facility of the NSF).

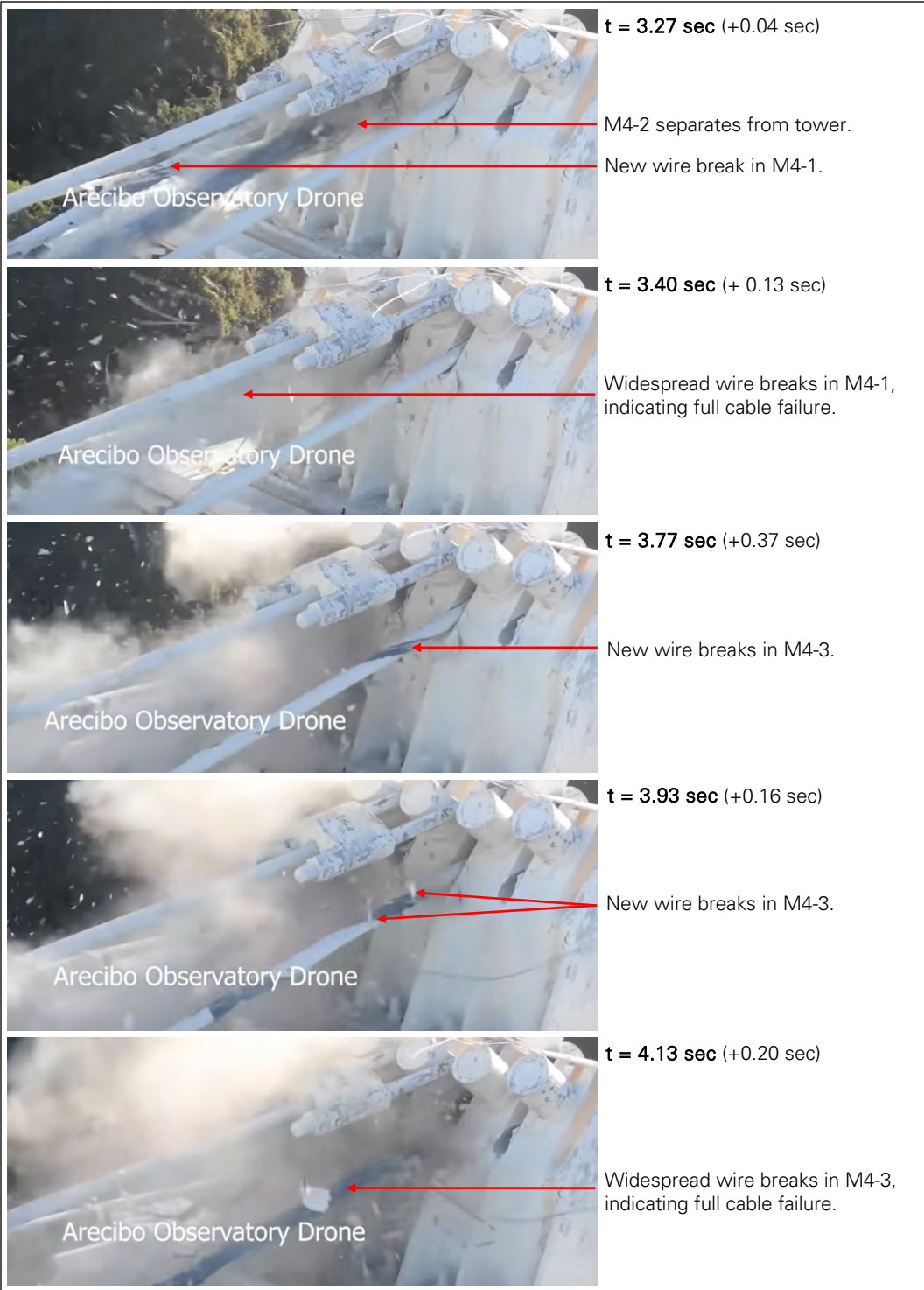


Figure 32: Still images of drone video of top of Tower 4 during telescope collapse: seconds 3.27 to 4.13 (video: NAIC Arecibo Observatory, a facility of the NSF).

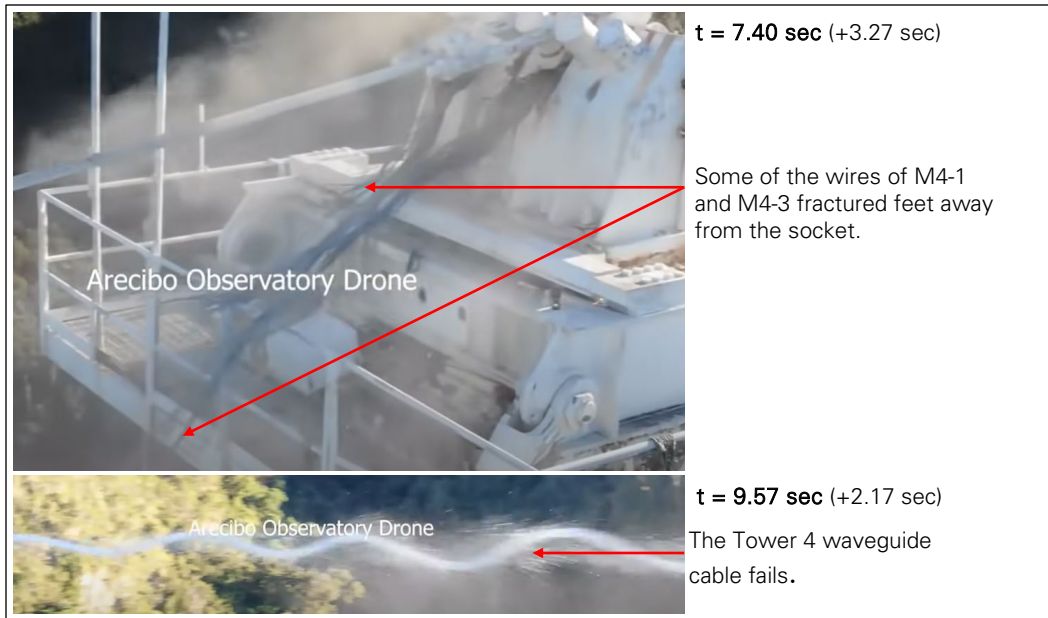


Figure 33: Still images of drone video of top of Tower 4 during telescope collapse: seconds 3.27 to 9.57 (video: NAIC Arecibo Observatory, a facility of the NSF).



Figure 34: Socket M4-2_T recovered after collapse.

7.2 Overall Structure

At the time of the collapse, a camera set up in the telescope's control room was recording the suspended structure. The collapse lasted approximately 15 seconds, between the M4-2 failure and the landing of the last cables and tower tops. Still images of the collapse video at one second intervals are shown in Figure 35 through Figure 40.

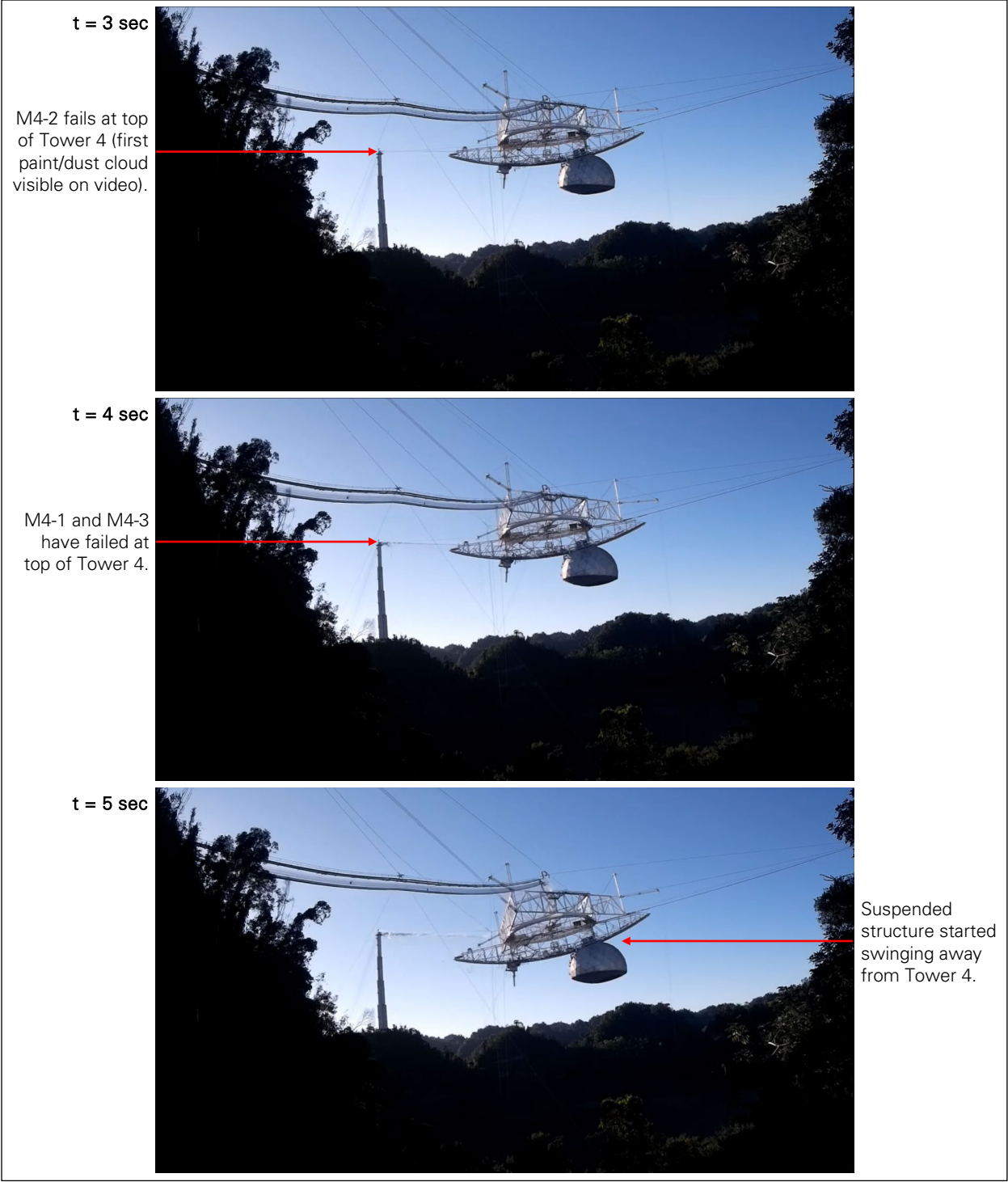


Figure 35: Still images of telescope collapse video: seconds 3 to 5
(video: NAIC Arecibo Observatory, a facility of the NSF).

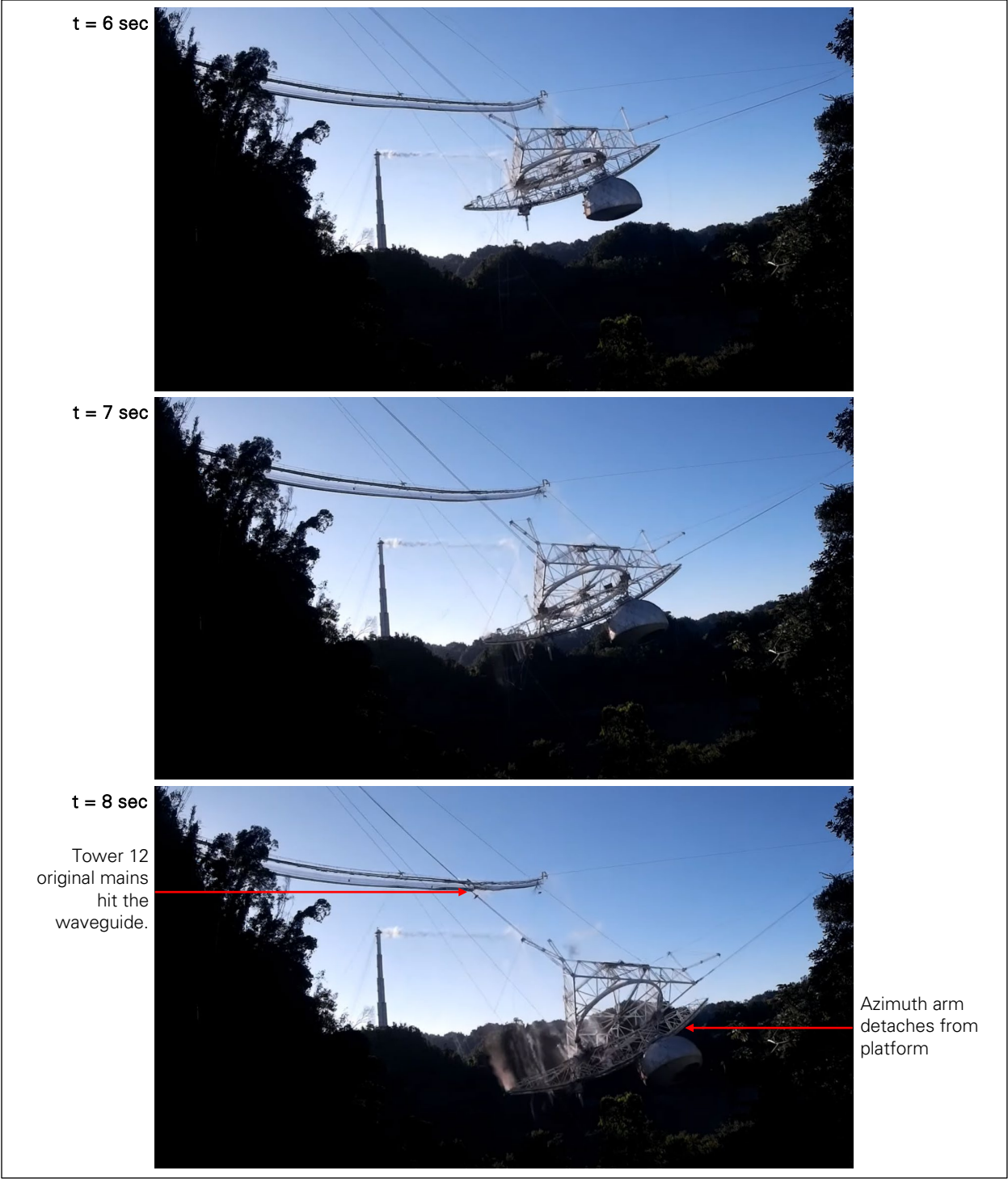


Figure 36: Still images of telescope collapse video: seconds 6 to 8
(video: NAIC Arecibo Observatory, a facility of the NSF).

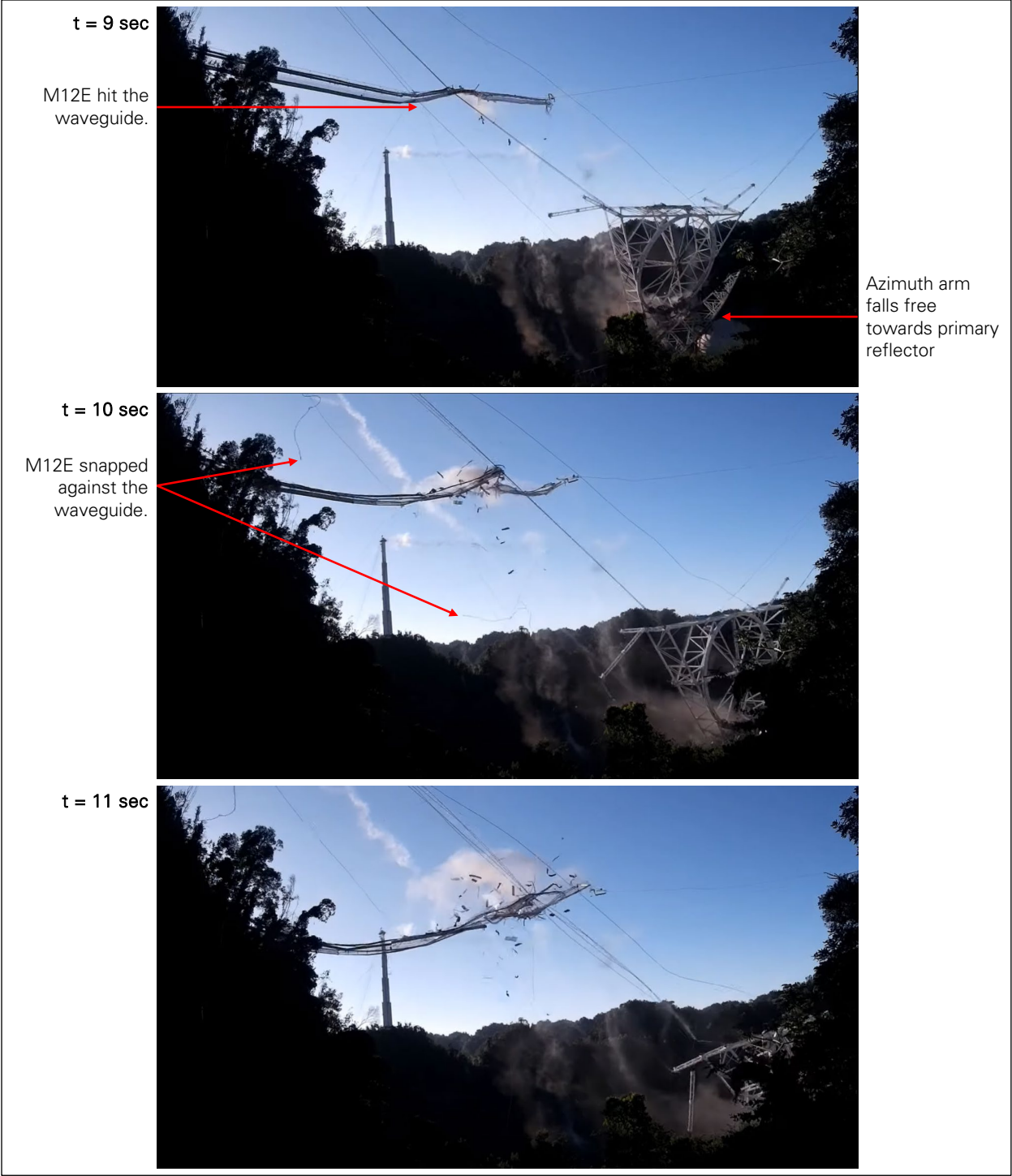


Figure 37: Still images of telescope collapse video: seconds 9 to 11
(video: NAIC Arecibo Observatory, a facility of the NSF).

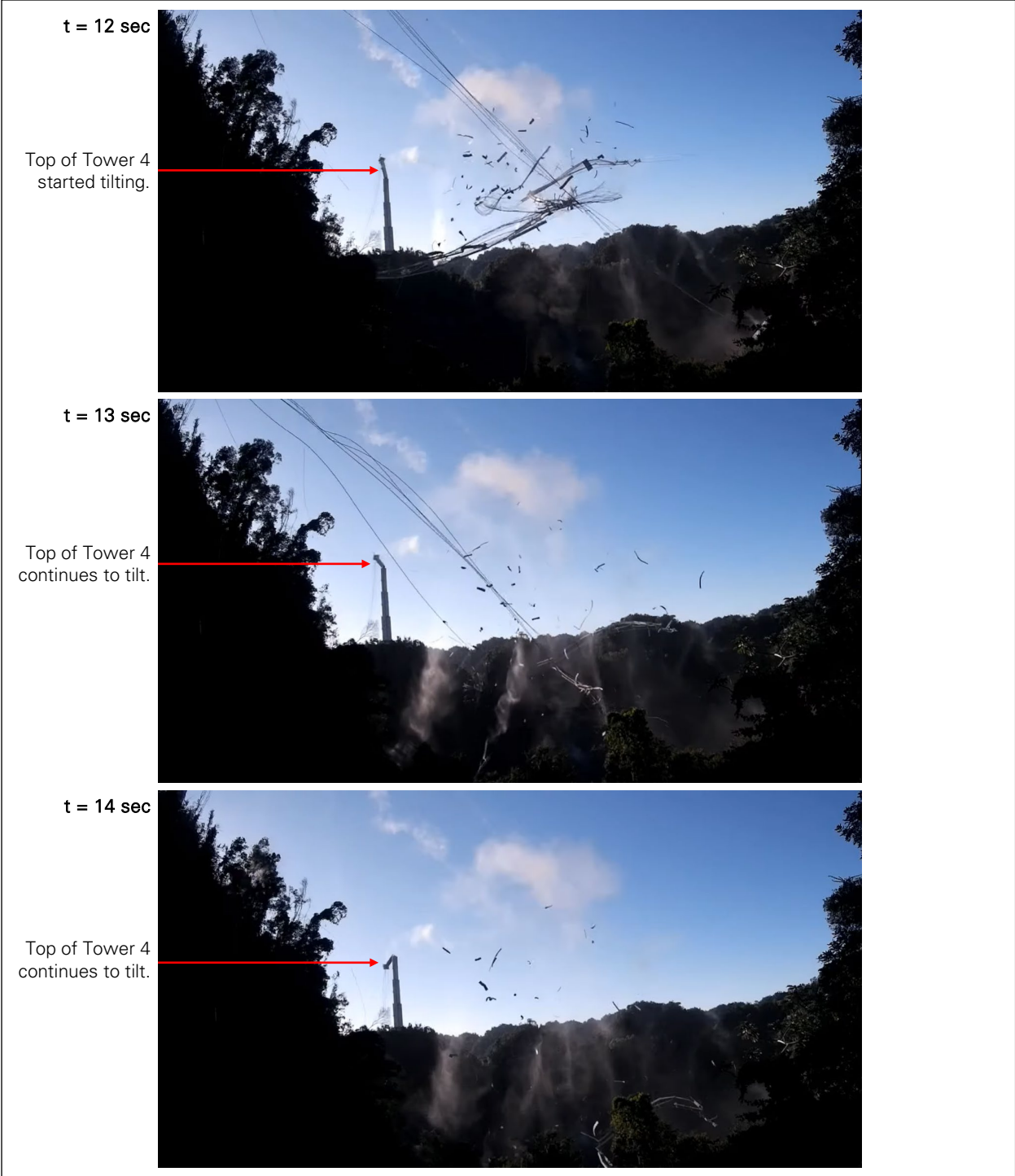


Figure 38: Still images of telescope collapse video: seconds 12 to 14
(video: NAIC Arecibo Observatory, a facility of the NSF).

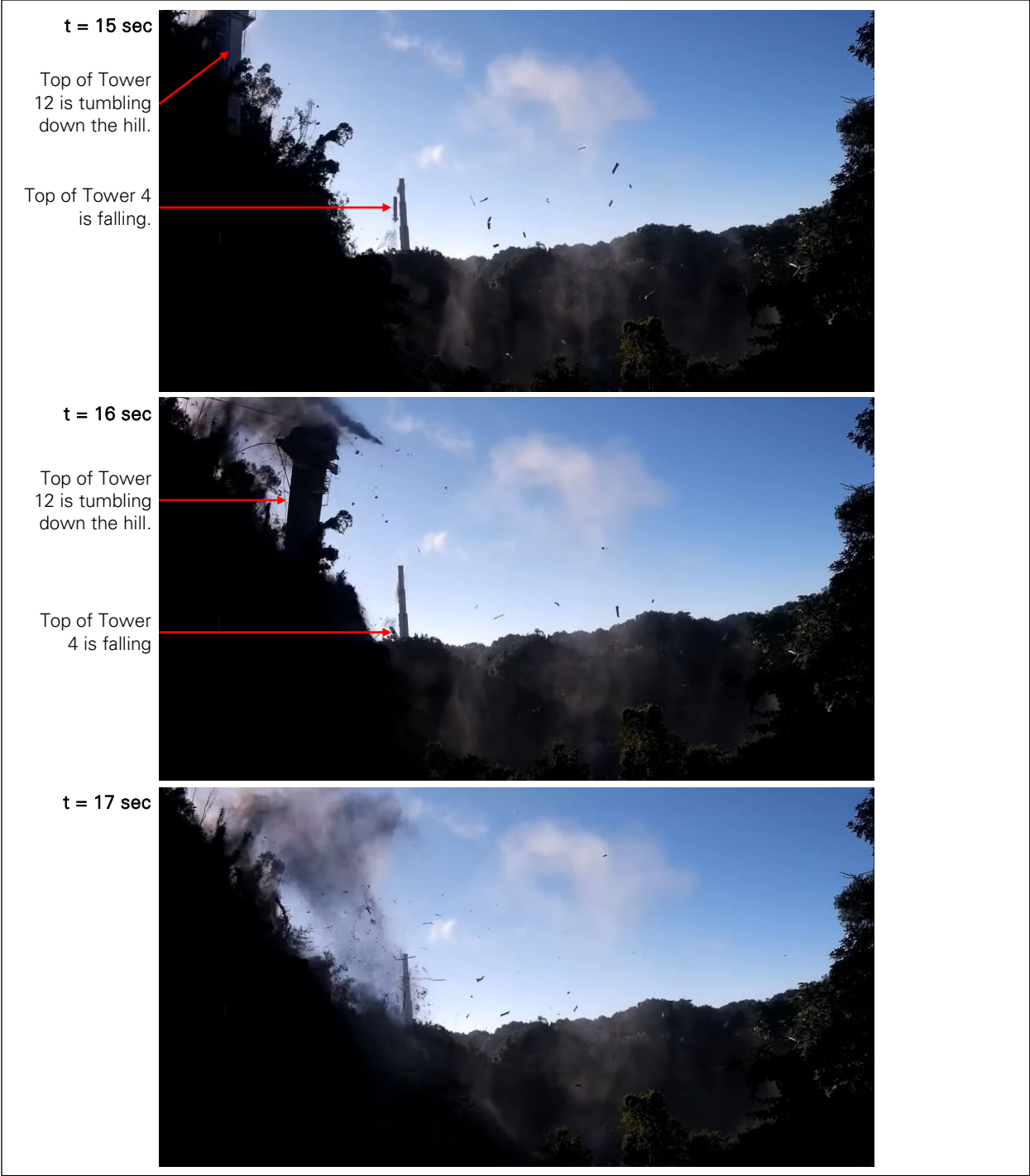


Figure 39: Still images of telescope collapse video: seconds 15 to 17
(video: NAIC Arecibo Observatory, a facility of the NSF).



Figure 40: Still images of telescope collapse video: seconds 18 to 19
(video: NAIC Arecibo Observatory, a facility of the NSF).