Arecibo Observatory: *Failure Event Sequence*

Presentation Requested by

The Committee on Analysis of Causes of Failure and Collapse of the 305-Meter Telescope at the Arecibo Observatory

January 25, 2022

Ashley VanderLey – Senior Advisor for Facilities(AST/MPS)

AST POs:

Joe Pesce (thru April 1, 2018)
Ashley VanderLey (thru Spring 2021)*
Alison Peck (current)

AST Division Director (includes Fall 2020): Ralph Gaume (expert)

AGS POs:

John Meriwether (Expert)
Carrie Black (2018 – 2020)
Robb Moore (includes Fall 2020)
Roman Makarevich (current)

NASA Planetary Defense Coordination Office:

Lindley Johnson
Kelly Fast

AGS Section Head (Oct 2017 – March 2021): Mike Wiltberger

DACS: Jeff Leithead (2018 - 2021), Taína Muñoz-Mulero (current, G/AO during competition and transition)

Challenging time period:

Thank you to Arecibo Observatory Staff for their dedication and diligent work. Also thank you to engineering firms, expert reviewers, and consultants.

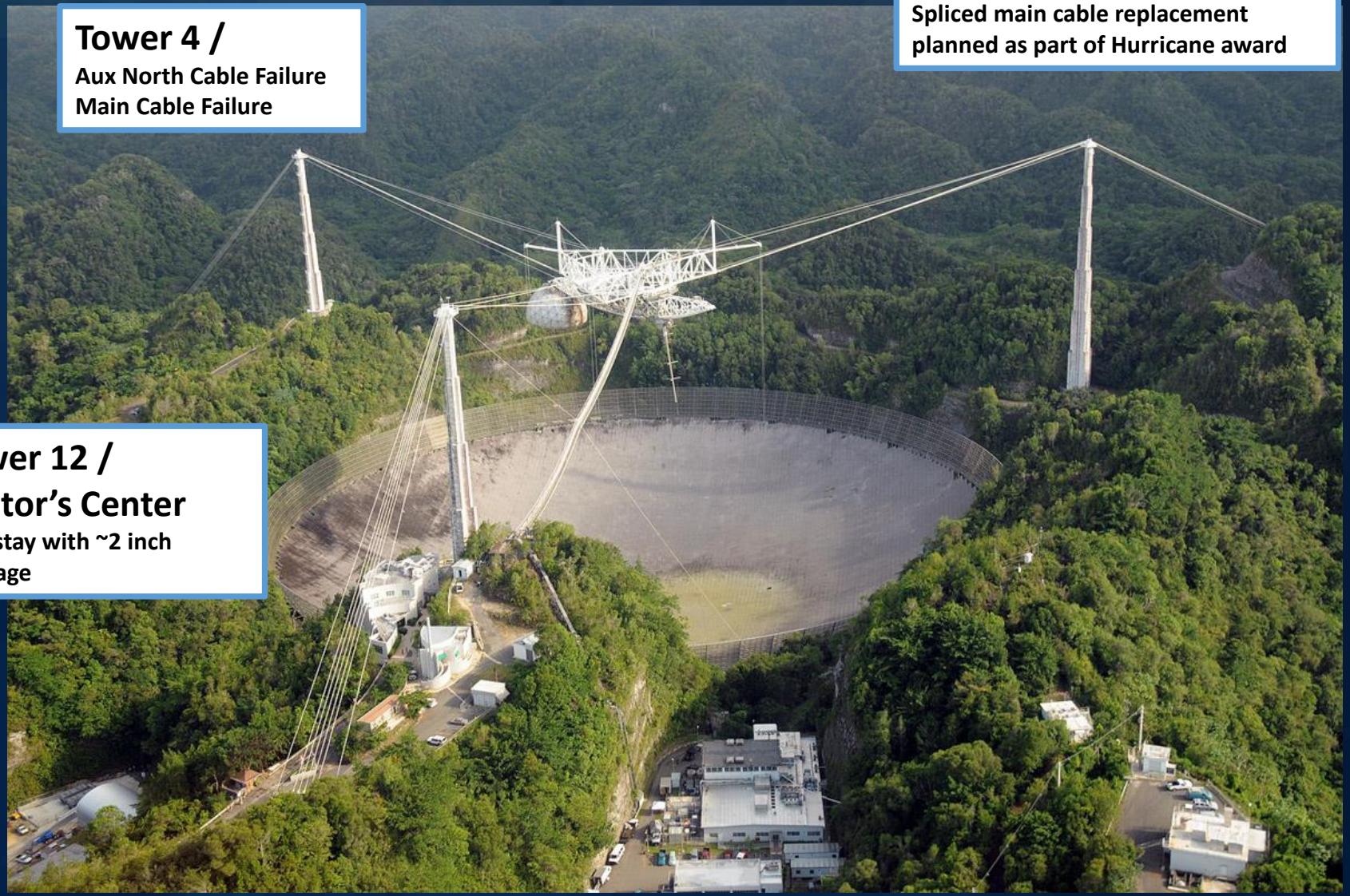
We are grateful that the rigor and care put into the analysis led to an outcome that *was not worst-case scenario*. The platform collapsed, but there were no (physical) injuries or death.

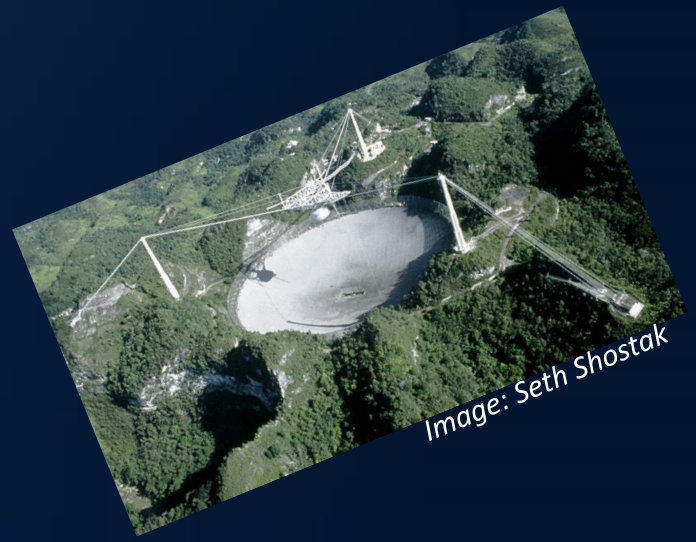
Thousands of hours were dedicated to planning stabilization and repair plans from August 10th to December 1st.

Tower 4 /
Aux North Cable Failure
Main Cable Failure

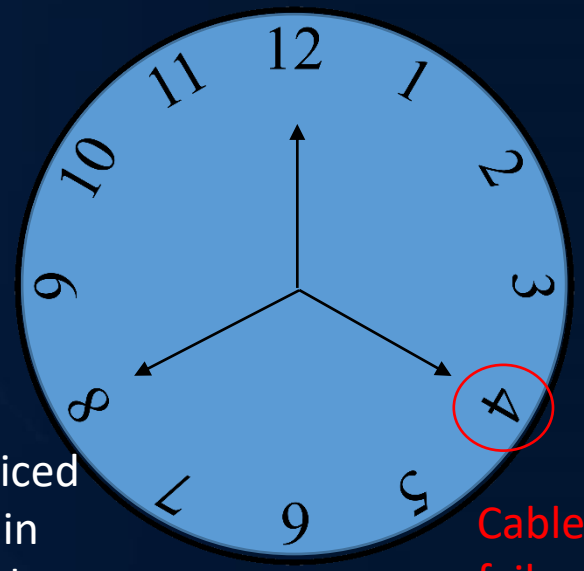
Tower 8 /
Spliced main cable replacement planned as part of Hurricane award

Tower 12 /
Visitor's Center
Backstay with ~2 inch slippage





Visitor's Center



Spliced main cable

Cable failures

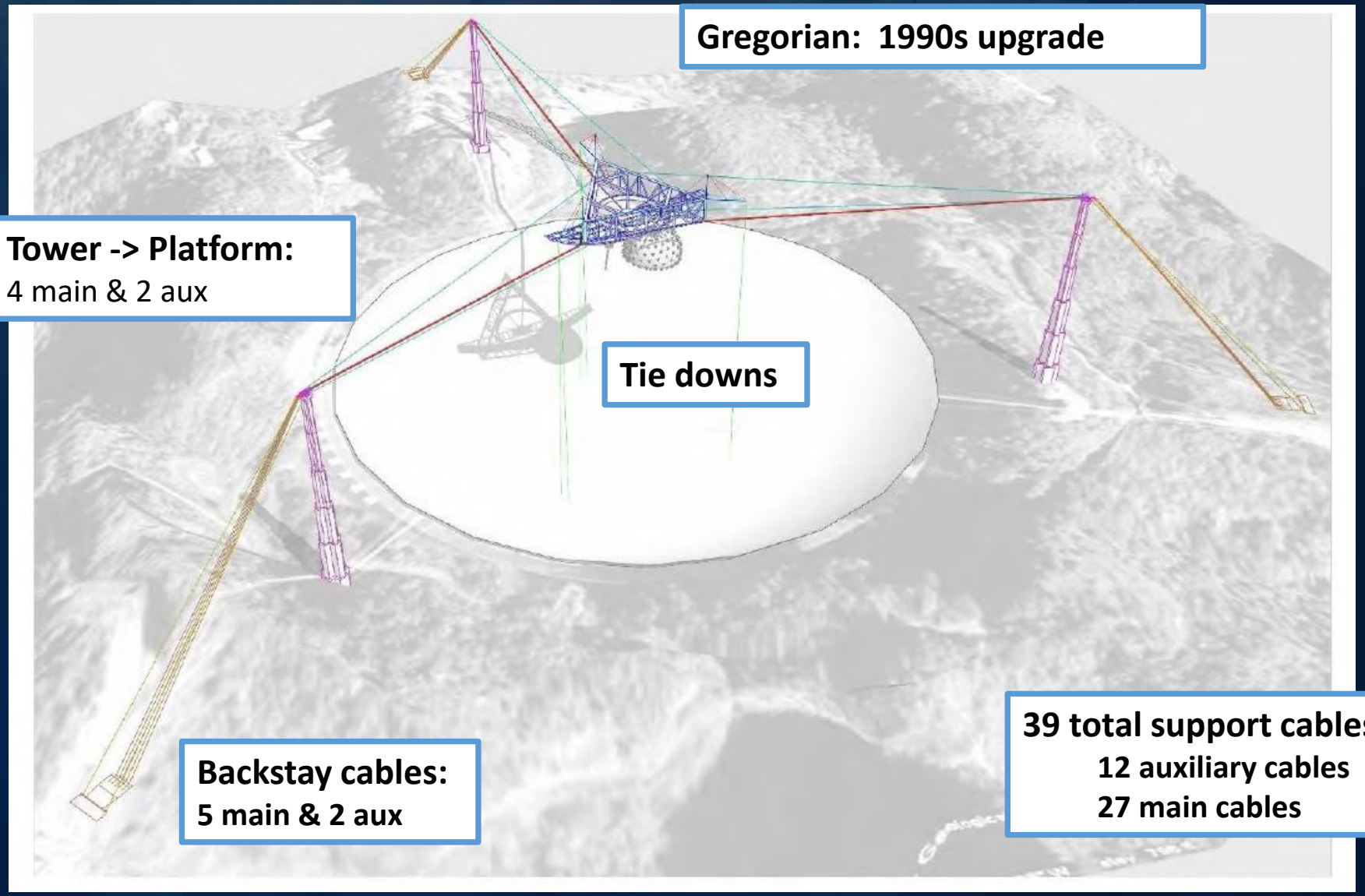
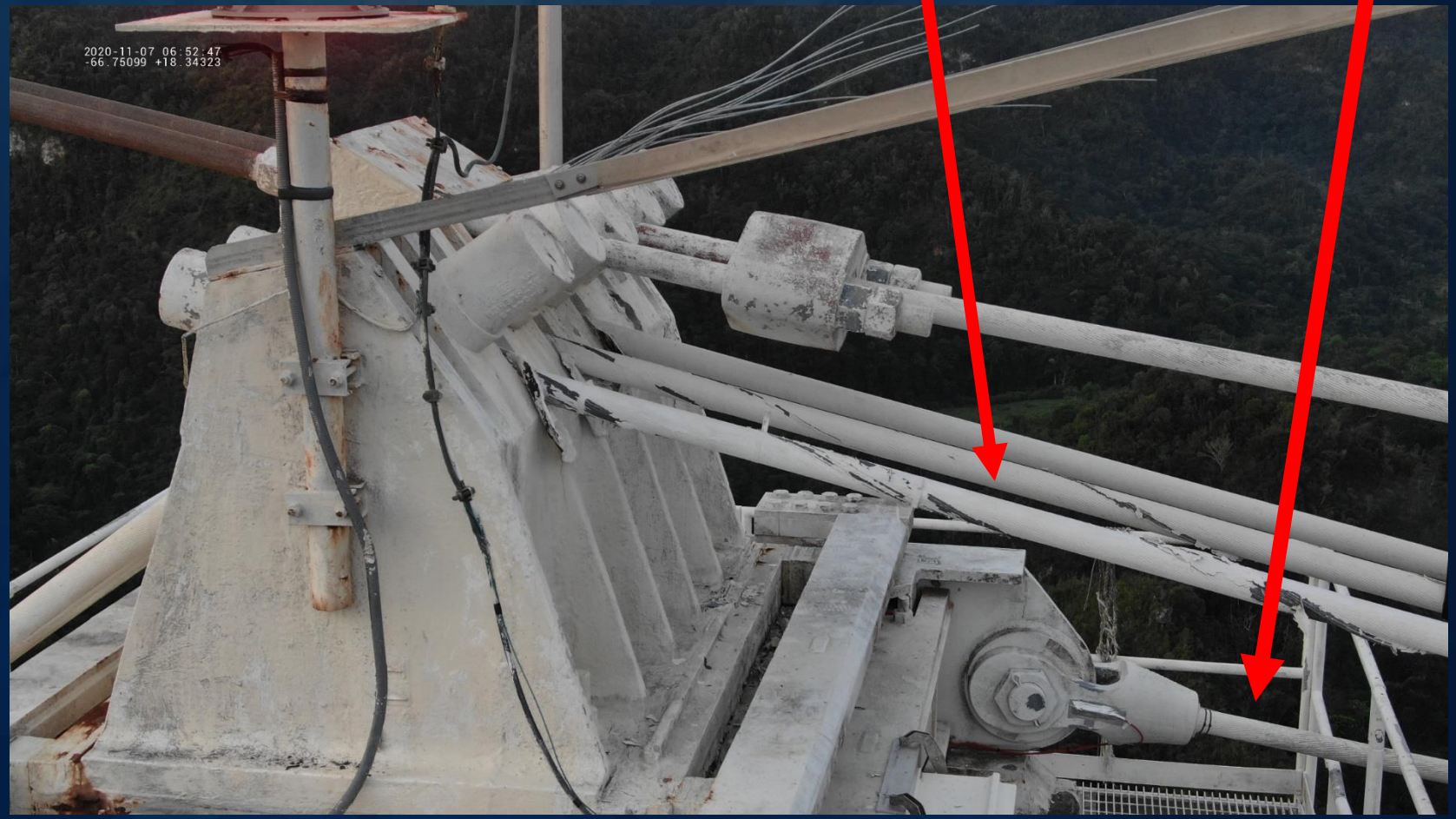


Image Credit: WJE response plan (1 SEP 2020)

Two cable systems: Main (3”) + AUX (3.25”)



different socket designs

Significant events 2017 – 2020

- **Hurricanes:** Fall 2017
- **Award transition to UCF:** April 1, 2018
- **Hurricane Repairs:** $14.3M appropriation
- **Earthquakes:** 2019 – 2020
- **COVID:** March 2020 - present
- **Auxiliary cable failure** – August 10, 2020
  - Planned stabilization (September)
  - Design for full repair (Proposal submitted in October)
- **Main Cable failure** – November 6, 2020
- **NSF announces decision to start planning decommissioning –** November 19, 2020
- **Collapse** – December 1, 2020
  - Transition to cleanup and forensic evaluation

Other relevant events

- Cornell named to operate/manage observatory - 1971
- Replacement of Tower 12 main cable backstay (6 wire breaks): 1981
- Gregorian Dome upgrade: 1992 - 1997
- Structural Surveys by Ammann & Whitney: 2003, 2011 (see slides 24-25)
- SRI named to operate/manage observatory – 2011
- 6.4 magnitude earthquake: damage noted to Tower 8 main cable; temporary repair implemented (January – March, 2014)

Arecibo Observatory Timeline

The following is a timeline of relevant events associated with the Arecibo Observatory.

Table 1. Arecibo Observatory Timeline

Date	Event
1960	Design and construction begins for the Arecibo Ionospheric Observatory[1]
Nov 1, 1963	Opening of the Arecibo Ionospheric Observatory
Oct 1, 1969	NSF assumes oversight of the observatory from the DOD[2]
Sep 1971	NASA joins with NSF to form the National Astronomy and Ionospheric Center (NAIC)[2]
1971	Cornell University named to operate/manage the observatory
1972-1974	Primary reflector receives new aluminum panel surface and S-band radar equipment installed[3]
Sep. 1981	Replacement of center backstay A12-3 due to six wire breaks[4]
1992-1997	Design and construction of Gregorian Dome upgrade and ionospheric radar line feed completed[5]

See also Table 6.1 in NESC report from the WJE September 2020 response plan

A few comments

- While transitions do raise questions of knowledge transfer, worth noting in transition to UCF, a majority of staff (including Director of facility) remained the same at the Observatory
  - Loss of any personnel can be problematic; some staff turnover
- 2011 structural survey showed no issue with aux cable socket
  - Did note condensation in compressed air end socket broken wires, some rust and poor paint conditions
- Funding was available for repairs if issues had been identified earlier; tasks for Hurricane Maria repairs were prioritized based on risk and importance for science (e.g., that is why main cable was top project)

Timeline

SRI management
2011 – 2018

RoD decision

NSF award to UCF
April 1, 2018 – March 31, 2023
20.15M

Congress appropriates **$14.3M** for Hurricane damages – "restoring to world class capabilities"

Hurricanes Irma & Maria – significant damage Fall 2017 wind gusts in excess of 100 mph

COVID (2020 – present)

August 10, 2020
Unexpected cable/socket failure

Earthquakes (2019 – 2020)

November 6, 2020
Unexpected main cable failure

December 1, 2020
Platform collapse

Hurricanes Maria and Irma

Hurricane Repairs

Hurricanes Irma & Maria – significant damage Fall 2017 wind gusts in excess of 100 mph

$2M awarded to UCF Summer 2018 / completed: Focused on repairs identified to be most time-critical

- Generator rewinding
- Debris cleanup & Building repairs
- Electrical restoration
- Catwalk repair / Cable Car wheels replaced
- Procurement of material handler, three vehicles, water pump
- Cable replacement analysis and design

Hurricane proposal preparation

- 2018 – time for preparing full proposal and plans for remaining $12.3M repairs to restore scientific capabilities
- Spring 2019 – NSF held merit review panel for proposal
  - Included structural engineers to assess the main cable replacement
- Required a detailed project execution plan (NSF Core IPT and LFO provided input for this, especially for program management) and detailed plans for the cable replacement (to be put together by Louis Berger), then an RFP for the work

- NSF submitted waiver to OMB to permit $11.3M of $14.3M to be spent over 60 months instead of 24 months to permit time for careful evaluation and design of repairs

$12.3M awarded summer 2019 (timeline thru FY23):

- Completed Project Execution Plan (PEP)
- Major activities include 14 tasks (prioritized)

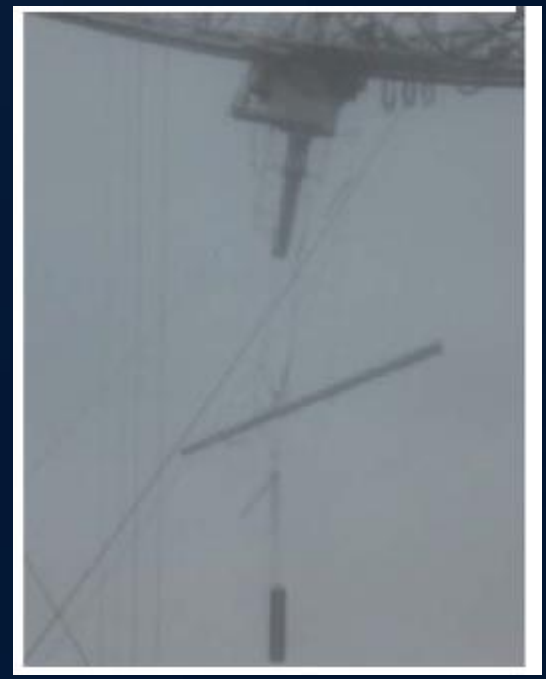
Tower 8 /
Spliced main cable replacement planned as part of Hurricane award

P01	Main Telescope Suspension Cable Replacement
P02	305M Primary Reflector Calibration
P03	Gregorian Dome Optics Alignment
P04	430 Line Feed Development
P05	Telescope Pointing Control & Data Taking
P06	S-Band Control System Upgrade
P07	Fiber Optic Cable Replacement
P08	Radio Frequency Interference & Evaluation
P09	430MHz & HF Transmitter Restoration
P10	Receivers Support Equipment
P11	Erosion Control
P12	Reference Antenna 12m
P13	Other Site Repairs
P14	Storage & Transmitter Lab

Hurricane damage related to cables/sockets

- **Tower 8 main cable:**
  - Only cable-related repair noted in post-Maria evaluation and funding requests; project execution plan prioritized highest-risk (replacing spliced cable)
  - Structural analysis, Main cable replacement design, and assistance in the cable replacement and construction administration to be overseen by WSP (acquired Louis Berger who acquired Ammann & Whitney)
  - Note a temporary fix had been performed in 2014 after another Earthquake

Hindsight 20/20: this splice was still intact after the collapse



Significant winds: line feed broke off! Catwalk required significant repairs.

Earthquakes

-Puerto Rico had an unprecedented number of earthquakes
-thousands since December 2019 in the Ponce region to the South

-earlier earthquakes from different geographic location

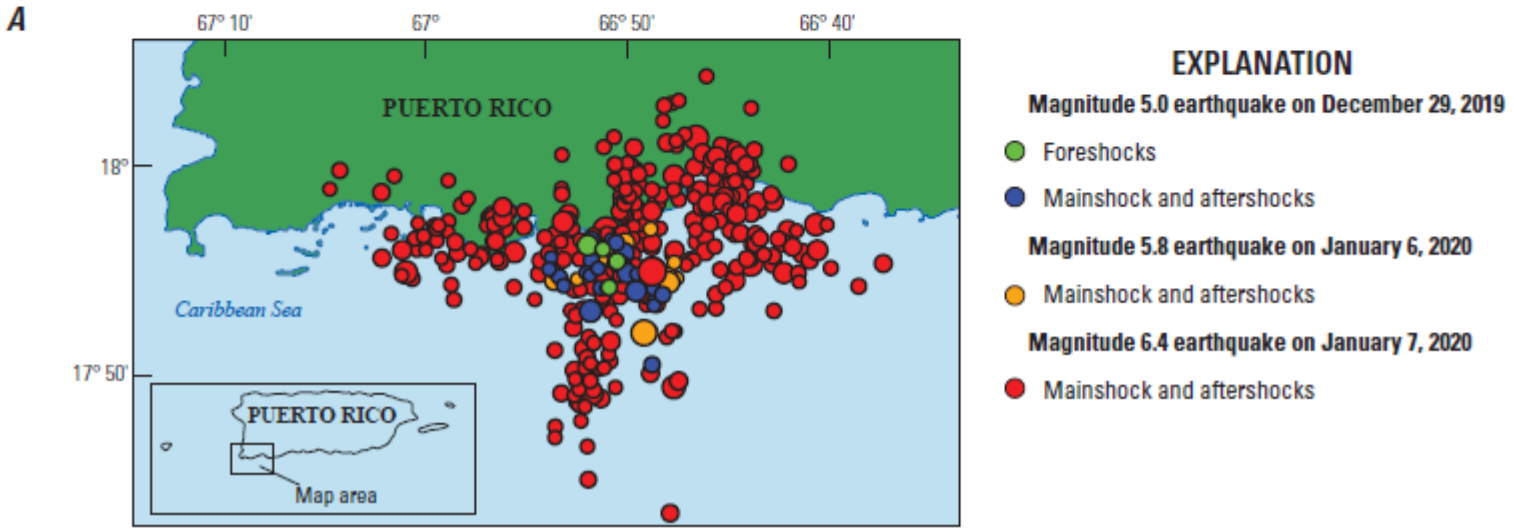
See USGS Report:
"Potential Duration of Aftershocks of the 2020 Southwestern Puerto Rico Earthquake" by Van Der Elst, Hardebeck and Michael

Table 1. Magnitude 5 and larger earthquakes between December 29, 2019[1], and January 17, 2020, recorded in the Advanced National Seismic System U.S. Geological Survey comprehensive catalog.

Date (UTC)	Time (UTC)	Magnitude	Latitude	Longitude	Depth[2], in kilometers
Dec. 29, 2019	01:06:00	5.0	17.885° N	66.864° W	6.0
Jan. 6, 2020	10:32:18	5.8	17.867° N	66.819° W	6.0
Jan. 7, 2020	08:24:26	6.4	17.916° N	66.813° W	10.0
Jan. 7, 2020	08:34:02	5.6	17.922° N	66.731° W	10.0
Jan. 7, 2020	08:50:45	5.0	17.953° N	66.677° W	10.0
Jan. 7, 2020	11:18:43	5.6	18.022° N	66.776° W	9.0
Jan. 10, 2020	22:26:25	5.2	17.935° N	66.883° W	9.0
Jan. 11, 2020	12:54:45	5.9	17.949° N	66.851° W	5.0
Jan. 11, 2020	12:56:22	5.2	17.824° N	66.795° W	10.0
Jan. 15, 2020	15:36:23	5.2	17.916° N	67.017° W	5.0

[1] Times and dates in this table are reported in the UTC time zone. Local time during these earthquakes is Atlantic Standard Time which is 4 hours behind UTC.

[2] Depths are poorly constrained for these earthquakes, which are occurring mostly offshore, far from seismic sensors.

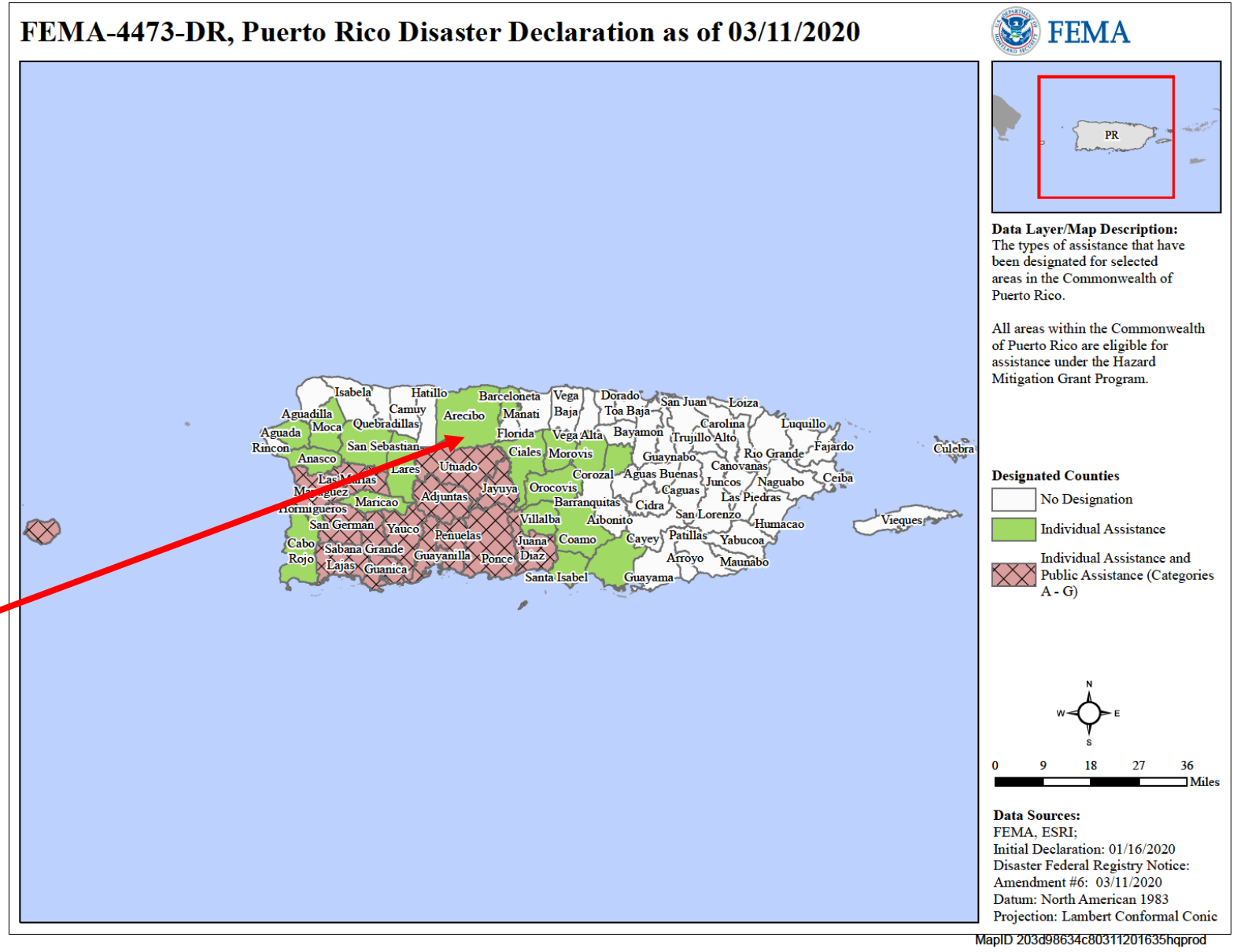


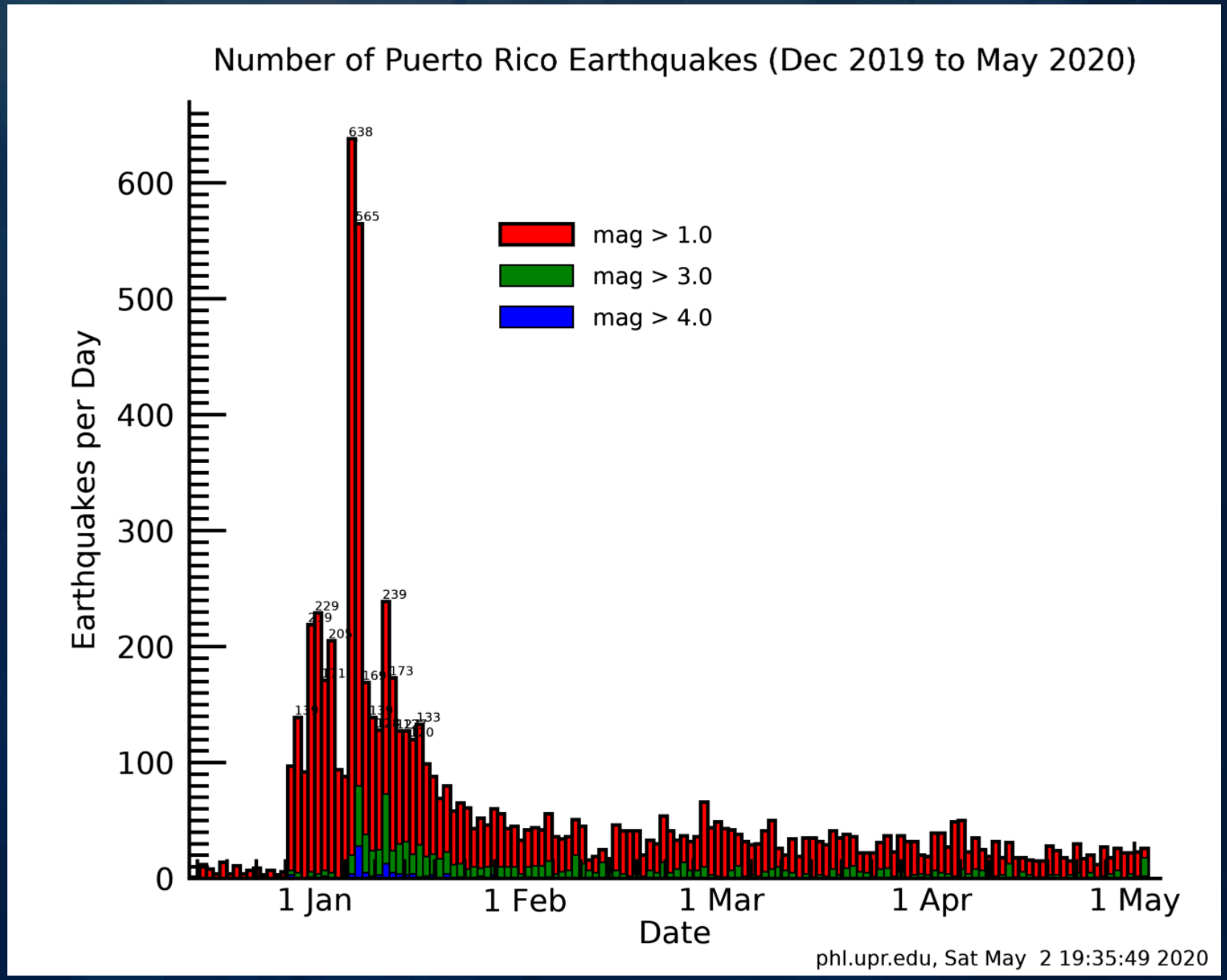
Puerto Rico Earthquakes were designated Disaster by FEMA (4473)

Incident Period: December 28, 2019 – July 3, 2020

Arecibo Observatory just North of area noted for Public Assistance

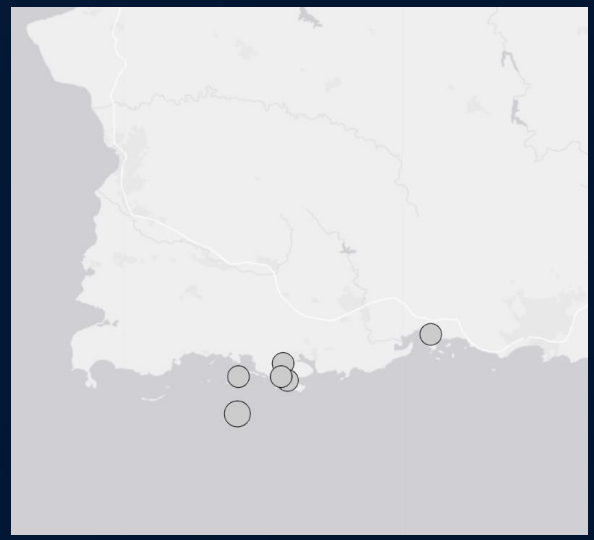
Source: fema.gov/disaster/4473





Earthquakes continued in June, July and August 2020:

e.g., August 6, 2020
23:27 Local Time
mag 4.8



Source: earthquake.usgs.gov

Proposed/Funded earthquake repairs

- Initial report (January 27, 2020) noted damage to vibration dampers, tie down blocks and slabs, potential for cracked platform steel components, and cracks in concrete buildings. Also concerns noted about site power infrastructure, and the need for more safety and inspection equipment, and structural analysis and modeling for resiliency

- $3.325M proposal submitted 2020 and awarded included tasks for acquisition and installation of new vibration dampers; purpose of dampers is to reduce vibration caused by external forces (wind or seismic events)
  - Existing dampers were damaged (bent) during earthquakes
  - Dampers on all main cable suspension locations (between platform and tower, and between tower and tower anchors)

Straight dampers (left);
bent dampers (below)

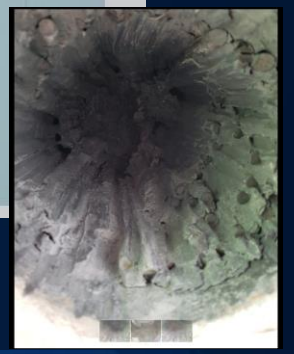
Cables not identified to be an issue

- As part of Feb 2020 visit to the site for their work on the spliced main cable replacement, NSF was informed that the structural engineers [WSP] were on site and performed inspection of the towers, cables, and platform primary structural elements. No additional damage was noted to have been found during those inspections.

Cable/socket failure (August 10, 2020; 3 am)

Cable that slipped out

Failed socket



-described by structural engineers to have failed "suddenly and without warning"

2003 and 2011 Structural Surveys (Ammann & Whitney)

3.2.4 Auxiliary Cables

The auxiliary cables were inspected visually and with binoculars from the feed platform and hands-on from the top of towers T4 and T12. No wire breaks or misswraps were observed. The intersection point at the platform elevation was viewed with binoculars for signs of chaffing and no deficiencies were observed. As at the auxiliary backstays, the cast zinc has separated away from the leading edge of the sockets by up to 1/2". This condition was observed at the auxiliary cables. The paint

condition of the auxiliary main cables is rated as good.

3.2.4 Auxiliary Main Cables

The auxiliary cables were inspected visually and hands-on from the feed platform and tops of the towers. Seized wire breaks near the top of T8 were observed on each aux main. As noted in the 2003 report the cast zinc has separated away from the leading edge of all the sockets by up to 1/2" a condition that remains unchanged. The compressed air end socket box for M4N AUX has condensation on the plexi-glass view port. See recommendation 4.1.1. The paint condition of the auxiliary main cables was rated as good in the 2003 report and there is no change in status.

3.2.4 – P1: Auxiliary cable end socket as viewed from the top of tower T4. The cast zinc has separated from the leading edge of the end socket. This condition was observed at all the upgrading cables and is believed to have occurred during fabrication or proof loading.

Tower 12 – backstay auxiliary – ~2” separation

Image: Tower 12 auxiliary backstay socket separation

Reported after August failure:
Many of the auxiliary cables and auxiliary backstay cables are showing more than ½” separation (cast zinc from leading edge of socket); from ¾” to 2” in the worst case

Immediate Concern: Another cable will pull loose from its socket

Note: Review after August 10th indicated this slippage was not entirely new

Date	Event	NSF Response
2020 Aug 10	**Auxiliary Cable Failure at Tower 4**	• NSF leadership notified • Collaboration with UCF on press release • NSF internal coordination meetings held • NASA Program team notified
2020 Aug 11-14	UCF and Arecibo operations team work to evaluate and stabilize structure • Under direction of WSP: Gregorian dome moved to safest position to reduce load on Tower 4 cables • WSP conducts structural analysis • UCF authorizes emergency procurement of temporary cables and testing equipment • AO developing plans for short-term repairs	• PO provides 2003 structural assessment materials to AO • PO instructed UCF to use O&M funds to proceed with necessary repairs and provided $ 3.325M of supplemental funding • PO consults with external expert to identify engineering firms to support ongoing activity.
2020 Aug 17-21	Additional site evaluation and response continues • Separated socket on Tower 12 backstay reported • Structural modeling continues • UCF engages Thornton Tomasetti and WJE	• NSF requests safety plan prior to approving work at site • NSF insists on sign-off of any work by an engineer of record • NSF communicates to UCF and AO that safety of personnel is the highest priority • NSF approves work to put facility in safe mode for passage of hurricane
2020 Aug 24-28	• Thornton Tomasetti designated Engineer of Record	• NSF engages Sabal Engineering for advice on forensic analysis • NSF engages with USACE as source of additional advice/support
2020 Sep 21-25	• WJE develops criteria for safe work • Emergency repair quote and designs submitted by UCF	• Repair plans evaluated by Sabal Engineering and USACE
2020 Sep 28		• Approval sent to UCF to procure materials needed for emergency repairs

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<u>September 15th</u>: Thornton Tomasetti presented results of structural analysis and modeling

<u>September 23rd</u>: AO staff retrieve failed socket on top of Tower 4

Socket shipped to NASA Kennedy Space Center, arrived October 7th

Thanks to NASA Planetary Defense Office for supporting cost of laboratory analysis Leading to report by NASA Engineering and Safety Center (NESC)

Teams in place - NSF

- **Safety experts (GEO/OPP)**
- **US Army Corp of Engineers (USACE)**
  - Assist NSF in the review of engineering and design plans
- **Forensic Engineer Consultant (Sabal Engineering)**
  - Assist NSF in review of contracts established with the lead AE firm, structural analysis, and forensic evaluation

Teams in place – UCF

- **Wiss, Janney, Elstner Associates, Inc.**
  - lead forensic evaluation through collapse
  - establish safe working conditions, keep-out zones
  - Work with NASA Kennedy lab, NASA Engineering and Safety Center (NESC) for forensic evaluation of failed auxiliary socket

- **Thornton Tomasetti (TT)**

  - Engagement with TT initially to provide additional resources for structural analysis and modeling of tower/cables
  - Transitioned to Engineer of Record for stabilization/repair
  - Single point engineering lead of forensic evaluation after collapse (role also included engineering analysis for cleanup, environmental, etc.)

  Subcontractors: Langan (environmental), LPI (fracture mechanics and fatigue analyses), DH Griffin (cleanup)

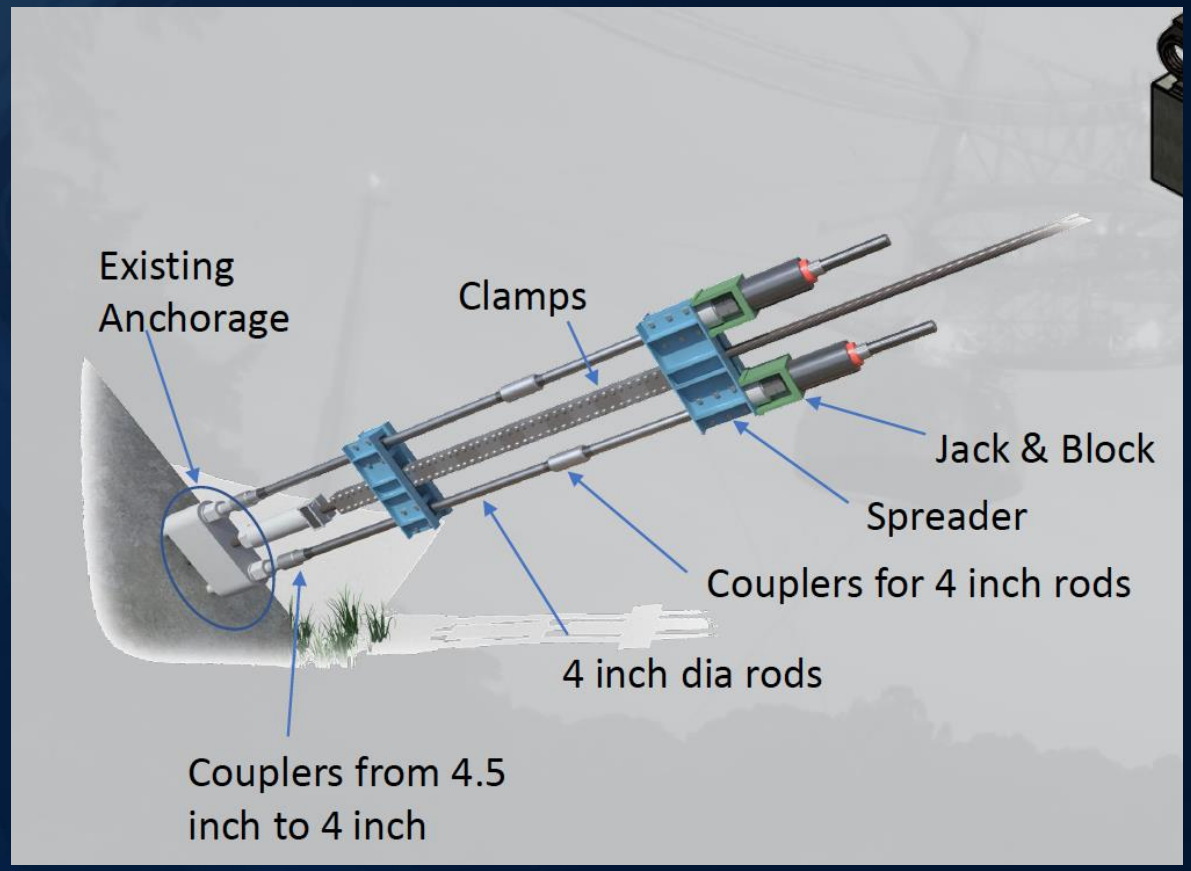
- **WSP (acquired Louis Berger, which had acquired Ammann & Whitney)**
  - Structural engineer for main cable replacement (Tower 8); led initial modeling after August 10th cable/socket failure; transitioned to a different role shortly thereafter:
    - project management; historical perspective

Stabilization timeline

- Structural modeling and safety zones identified; ***September***
- Socket removed (Sept 23) & sent to NASA Kennedy lab for forensics; ***early October***
- Emergency stabilization plans approved; ***end of September***
  - Backstay friction clamps designed and ordered for two backstay cable/sockets that were most concerning; ***installation to begin Nov 9th***
  - Two auxiliary cables and two temporary cables ordered; ***early December installation expected***
- Oct 19 – emergency repair proposal for stabilization submitted
  - NSF asked UCF to include all costs incurred since Aug 10th failure, forensic evaluation, engineering analysis, designs for immediate stabilization, and evaluation leading to the designs for a full repair.
- Oct 19 – 23: Review by NSF, Sabal, USACE

Stabilization plans

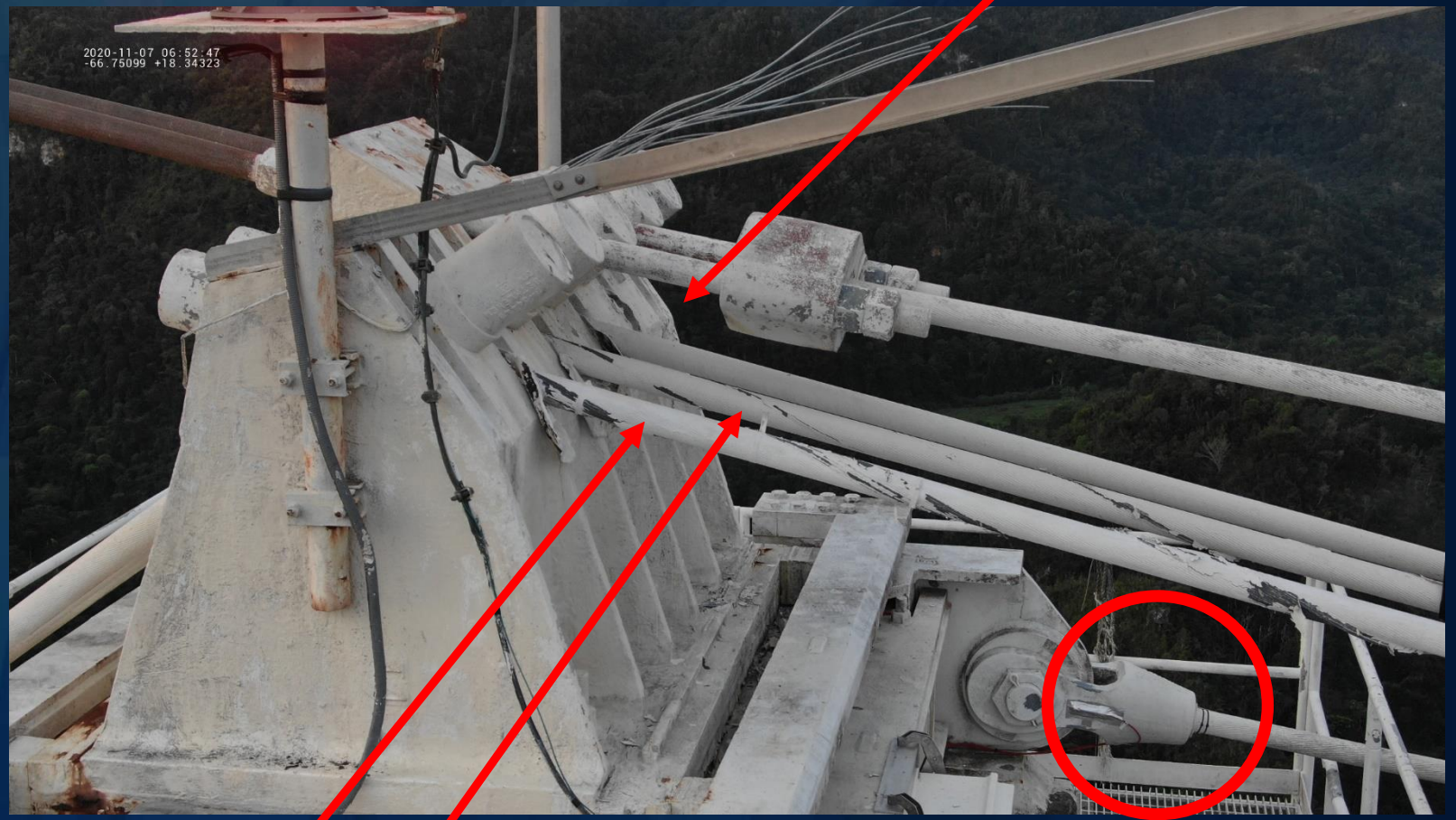
- Backstay friction clamps
- Arrestment clamps (tops of towers)
- Temp + 2 new auxiliary cables
- Monitoring
  - Strain gauges
  - Tilt meters
  - Acoustic monitors



Up until November 6…

- Assessment, structural modeling, observations led to assessment that structure was stable enough for further stabilization work to proceed aided by additional monitoring devices, regular drone inspections, work safety plans, etc.

Failure on November 6, 2020



Failed main cable

Failed main cable wires

New broken wires on M4-1 (4) and M4-2 (2)

Main Cable M4-4 Failure Details

- **Tower 4 is where the auxiliary cable failure occurred** August 10, 2020; 4 of 6 cables remaining between tower and platform
- **Cable failed below its expected capacity** making it impossible for engineers to determine stability of structure (cable that failed was designed for 1044 kips; was expected to hold 1044 kips, but failed at 614 kips)
- **Engineers identify in official report that another cable failure at Tower 4 would likely be catastrophic**; failure at other towers may be absorbed by structure, but would increase loading on the cables at Tower 4
- **WSP and Thornton Tomasetti recommend planning a controlled demolition (November 11th and 12th, respectively)**

November 19th decision to decommission

- Focused plans to get platform to the ground, preserving as much of remaining infrastructure as possible
- Pursue in parallel other opportunities for stabilization (Based on recommendation from WJE; NSF also pursuing interagency agreement with the PR Air National Guard; discussion of work supported by helicopter)
  - Tower tilt, friction clamps at backstay of Tower 12

Engineering assessments from the companies contracted by UCF are available online:

Thornton Tomasetti recommendation for course of action at Arecibo Observatory

WSP recommendation for future efforts at Arecibo Observatory

WJE memorandum on Arecibo Observatory stabilization efforts

https://www.nsf.gov/news/news_summ.jsp?cntn_id=301674

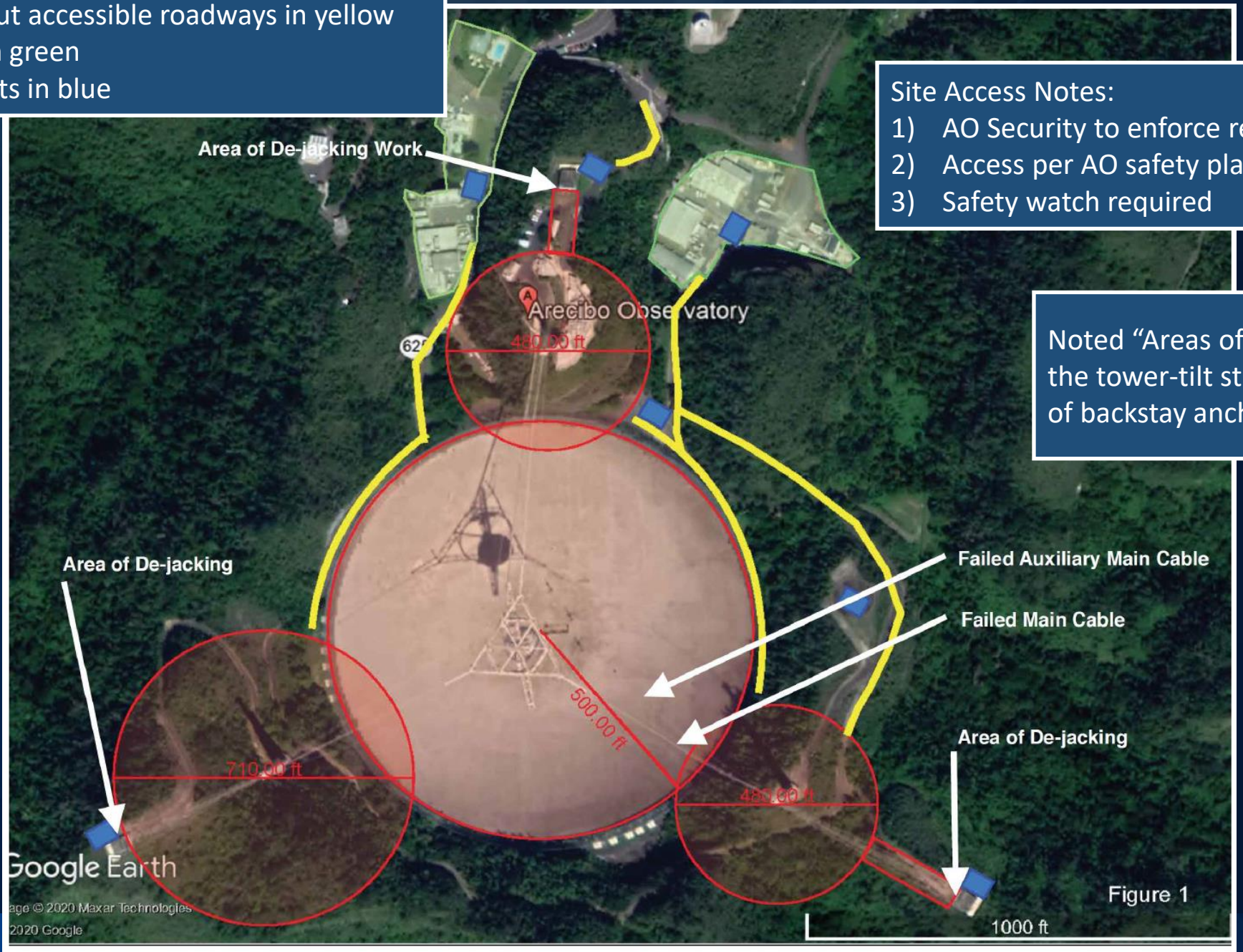
Steps after November failure

- Increase Monitoring
  - Strain gauges
  - Drone inspections
- Materials
  - NSF approved expedited shipment of cables from two suppliers
- Load reduction/transfer strategies (WJE)
- Determine new “keep out” zones
  - Work may proceed in these zones only with adequate work/safety plans

Restricted areas in red
Restricted but accessible roadways in yellow
Safe areas in green
Muster points in blue

Site Access Notes:
1) AO Security to enforce restrictions
2) Access per AO safety plan
3) Safety watch required

Noted “Areas of De-jacking” were proposed for the tower-tilt strategy: these are the locations of backstay anchorages



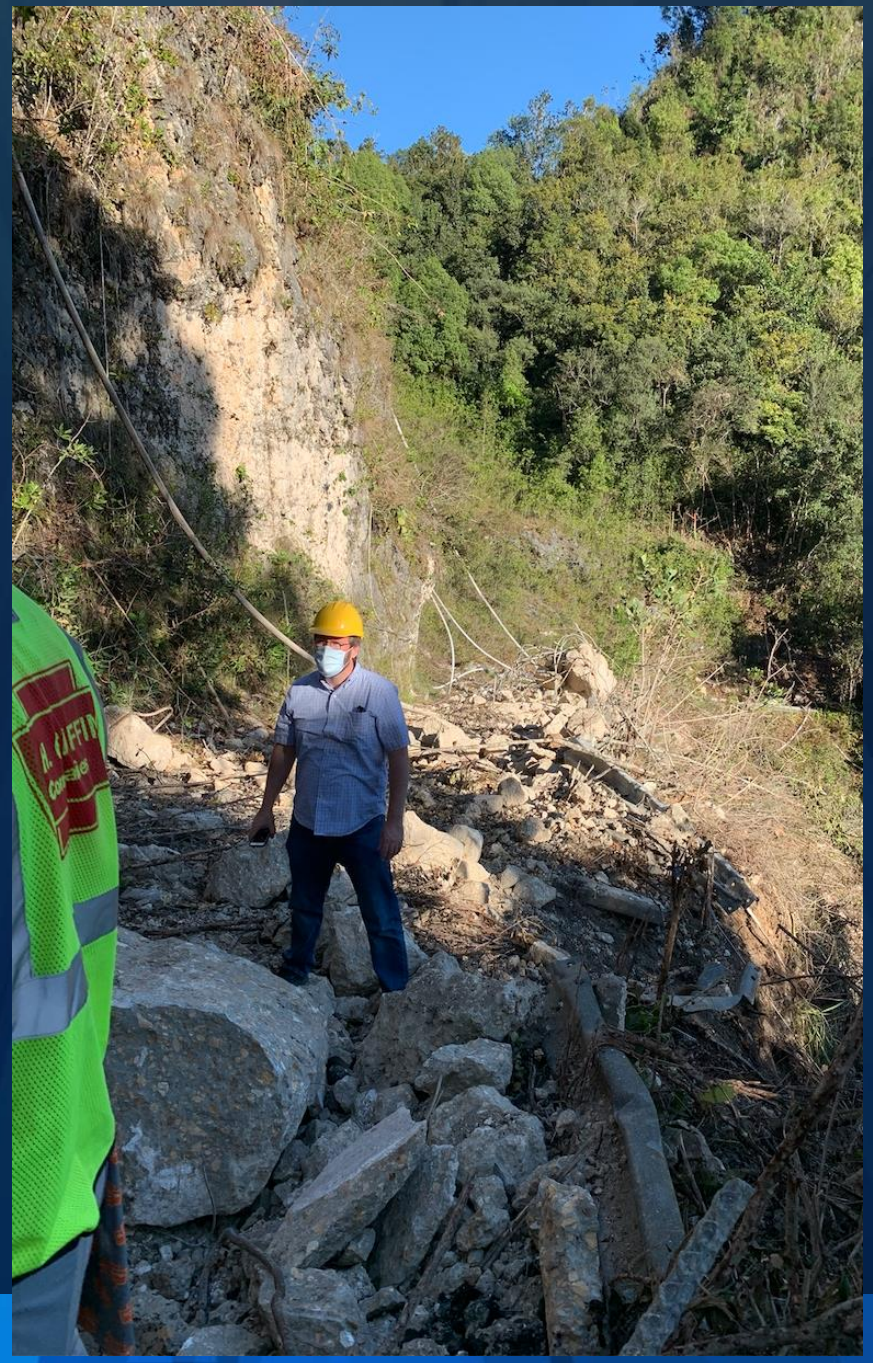
December collapse

- Drone footage of collapse taken by very adept AO staff provides us a precise sequence of events for the final collapse
- Loads were exceeded and it was a cascading failure

Documentation post-collapse

- Photos and videos after collapse
- 3D model prepared by Thornton Tomasetti
  - Chain-of-command established, hardware gathered


Thornton
Tomasetti



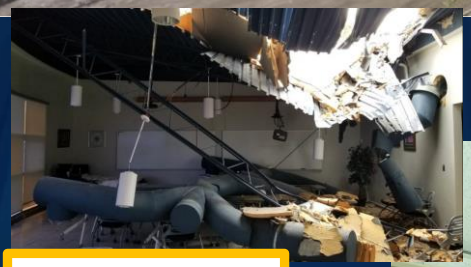
December 2020 – December 2021

- ***Safety consistently prioritized***
  - *Damage assessment*
  - *Debris cleanup*
  - *Environmental* - Hazardous materials identified, EPA and DNER notified, firm on site the day of the collapse to begin assessment and cleanup
  - *Historic preservation*
  - *Forensic Evaluation*
  - *Current and Short-term Science*
  - *Future Science*

Visit by PR State Historic Preservation Office (SHPO)

Damage Assessment

Area with primary damage



Learning Center roof

Minimal damage to Visitor's Center

- Platform, azimuth arm, Gregorian with instrumentation, reflector panels, cables
- Tops of towers
- EPO trailer
- Learning Center
- Cable car shed
- Minimal damage to:
  - Visitor's Center
  - Bldg #1
- 3/6 HF dipoles

Regular Maintenance

Preventative Maintenance Records: Tower 4

Preventive Maintenance Report

Work Order			
Description:	B083 TOWER T-4 - TOWER CLIMB INSPECTION - MONTHLY		
		Date Created:	20 jul. 2018 0:00
		Desired Date:	20 jul. 2018 0:00
		Customer Request:	
Type:	ASSET MGMT	**Category:**	PREVENTIVE
Organization			
Organization:	PLATFORM		
Phase			
Location:		**Priority:**	4
Shop:	REFLECTOR (REFLECTOR SHOP)	**Funding Source:**	Shop
Work Code:	SUPERVISOR	**Work Code Group:**	ASSET MGMT
Equipment			
Equipment:		**Equipment Group:**	
Asset Tag:	00001478 (B083 - TOWER 4)	**Asset Type:**	BUILDING
PM Standard:	SYS CLB TWR-M	**Description:**	ARECIBO SUSPENSION SYSTEM CLIMB - MONTHLY
Active:	Yes	**Reference:**	**RS Means**

Checkpoint	Description	Measurement	Notes
001	CLIMB THE TOWER USING THE STANDARD SAFETY CLIMBING EQUIPMENT.	OK	
002	INSPECT SAFETY CART, IF THERE IS ANY DAMAGE, REPORT TO PLATFORM SUPERVISOR.	OK	
003	INSPECT THE LADDER AND LANDING FOR SAFETY HAZARDS AND FOR GENERAL CONDITIONS. NOTE PARTICULARLY THE CONDITION OF THE WELDS, BOLTED JOINTS AND FASTENING OF METAL TO CONCRETE.	OK	
004	CHECK LADDER PAINT AND IF REQUIRES REPAIR, REQUEST A WORK ORDER.	OK	
005	AT THE TOP, MAKE A SIMILAR INSPECTION OF THE BALCONY AND RAILINGS.	OK	
006	NOTE CONDITION OF CABLES SOCKET AND SADDLES. VERIFY THAT SADDLE DOES NOT SHOW CRACKS, ARE COMPLETELY PAINTED AND ARE NOT RUSTED. IF YOU FIND SOMETHING OF THE ABOVE LISTED ITEMS, REPORT TO THE MAINTENANCE OFFICE THROUGH YOUR SUPERVISOR.	OK	
007	OBSERVE THE CABLES ALL THE WAY ALONGSIDE AS YOU CAN WITH BINOCULARS TO SEE IF THERE IS DEFORMATION, REPORT IT ON A PIECE OF PAPER TO THE PLANT ENGINEER THROUGH YOUR SUPERVISOR.	OK	
008	EXAMINE EACH CABLE CAREFULLY, LOOKING FOR EVIDENCE OF BROKEN WIRES. IF ANY APPARENTLY BROKEN WIRE IS FOUND, WHICH HAS NEVER BEEN REPORTED.	OK	No broken Wires
009	VERIFY ALL TOOLS, EQUIPMENT AND MATERIALS HAVE BEEN REMOVED AND THE SERVICED AREA IS CLEANED AND RETURNED TO NORMAL OPERATION.	OK	
010	VERIFY ALL STEPS OF THE INSPECTION HAVE BEEN COMPLETED PER THE PROCEDURE.	OK	
Extra Description			

- Task 006: Note condition of cables socket and saddles. Verify that saddle does not show cracks, are completely painted and are not rusted. If you find something of the above listed items, report to the maintenance office through your supervisor.

Preventative Maintenance Records: Tower 4

- Noted No broken wires and all systems OK for following inspections:
  - July 20, 2018 (Monthly)
  - September 19 – 20, 2018 (Monthly)
  - October 24, 2018 (Monthly)
  - November 21, 2018 (Monthly) – *Noted Towers 4 and 12 inspected for the possibility of a robot to clean and paint the cables; robot could not pass past the dampers on the cables*
  - January 9, 2019 (Monthly) – *Noted all normal conditions*
  - February 25, 2019 (Monthly) – *Noted all in normal conditions (subsequently more information available; see NESC/WJE report)*
  - *March 12, 2019 (Monthly) – 4.8 mag Earthquake in Salinas PR at 9:08 AM. Noted inspection of tower, stairs, saddle, cable sockets and cables. Noted all in normal conditions.*
  - *April 22, 2019 (Monthly) – Tower inspected and safety lines measured for replacement. No other notes.*
  - *May 16 – May 21, 2019 (Monthly) - New safety line installation project*
  - July 31, 2019 (Monthly) – Notes of maintenance activity unrelated to socket.

Preventative Maintenance Records: Tower 4

- Noted No broken wires and all systems OK for following inspections:
  - August 29, 2019 (Monthly) – Routine inspection to all three towers due to Hurricane Dorian. No impact from Hurricane, no findings.
  - September 23 – 25, 2019 (Earthquake inspection) – Two strong earthquakes noted at 6.0 and 5.1 mag at 11:35 am on 23 Sept 2019 were felt. Inspections to all three towers took place on 25 Sept 2019, no damages. On 24 Sep 2019, AO was in lockdown due to storm Karen. No damages from Karen.
  - September 27, 2019 (Monthly) - Notes: Two strong earthquakes 6.0 and 5.1 @11:35am 9/23/2019 were felt. Inspections to all three towers took place on 9/25/19, no damages. A measurement scale was installed to the socket/cable Auxiliary 4 to monitor any movements. Inspected tower and noted that all the cables and the saddle were painted.
  - November 14, 2019 (Monthly)
  - Dec 28, 2019 (Monthly) – Two strong earthquakes took place in Guanica (mag 4.8 at 6:00 pm and mag 5.1 at 9 pm). No damages noted.
  - January 6 – January 27, 2020 – Pictures noted to have been taken of the cable socket and saddles. No damage to the structure noted.
  - February 4 – 5, 2020 – Another mag 5.0 earthquake in Guanica noted at 10:30 am. Inspections to all towers noted (This was the week structural engineer on site)
  - May 1 – 3, 2020 – Inspections by drone due to COVID after 4.8 and 4.5 mag earthquakes were felt at AO.
  - June 4 – 5, 2020 – Earthquakes noted (mag 4.4 and 4.6 mag); inspections were performed by drone.
  - July 3 – 6, 2020 – Noted strong Earthquakes of mag 5.1; all observations were stopped. Inspections by platform personnel was performed. No damages were found.

Many items were being watched….

- Rim wall structure
- Tower 12 (shifting over time? Stability of ground underneath)
- Cracks in platform?
- Spliced Main cable on Tower 8
- Cracks in buildings
- We knew the weight of the platform was close to limit (no new instruments could be added)

COVID added complication with only drone inspections for a few months

Forensic Evaluation

NASA NESC report (June 15, 2021)

- Focused evaluation on failed socket/cable from August 10th failure
- Found failure was “primarily due to cumulative damage caused by initially low structural design margins and a high percentage of sustained load, resulting in zinc creep deformation, progressive internal socket wire damage, and eventual loss of joint capacity”
- No further hardware provided as after collapse, mission shifted from forensic evaluation to implement a stabilization and repair to a full forensic evaluation (to be led by Engineer of Record, TT)

NASA NESC findings

- The resulting core-pullout failure mode that preceded observatory collapse was found to be (1) unique compared with other industry applications, (2) insufficiently addressed within existing standards, and (3) a potential risk for similar designs, and should be characterized and mitigated.
- The effective design factor of safety was significantly less than the minimum necessary to ensure structural redundancy in the event of a cable failure.

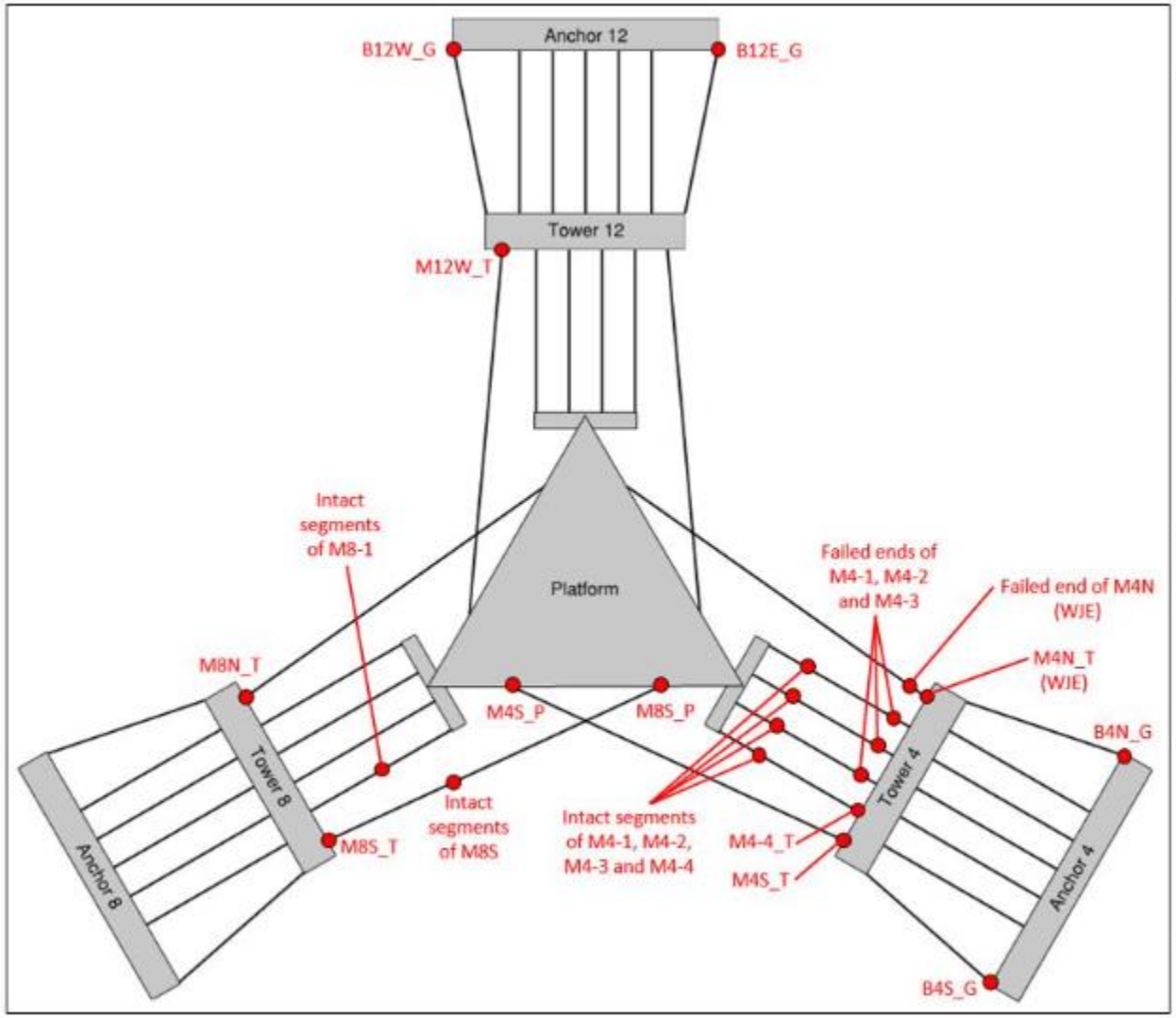
WJE Analysis

- Detailed report includes NASA NESC analysis as an appendix
- Includes historical information, results of their forensic investigation of the failed auxiliary cable socket

Thornton Tomasetti

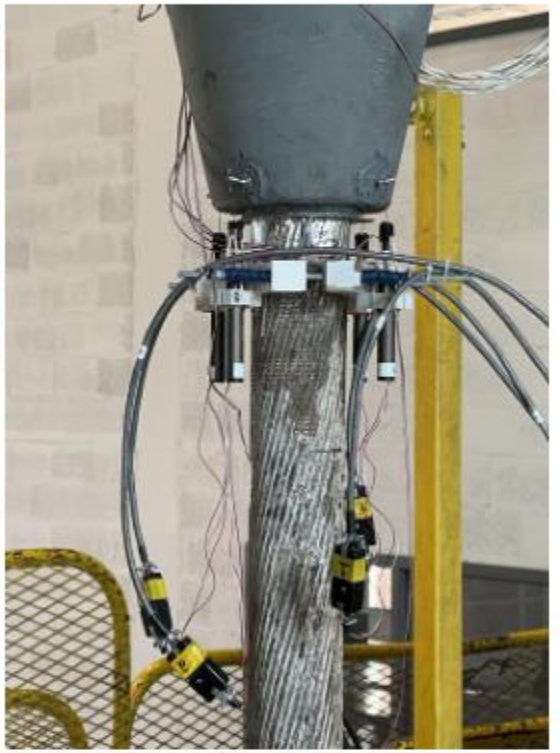
- Forensic evaluation includes:
  - Design Review (Design adequacy, structural behavior from the original design and repairs over time)
  - Document Review (Historical data on telescope structure during its operation; findings to be used to assist in analysis of environmental effects on cable systems)
  - Site investigation (preserve evidence and collect critical field evidence samples for lab testing)
  - Environmental Effects on Cable System (assess environmental effects such as hurricanes and earthquakes on cables performance by evaluating load history)
    - 3D socket connection models, computational fluid dynamics analysis, utilization of large-deformation nonlinear models (Abaqus, Flex) for wind and seismic analysis
  - Laboratory testing and crack analysis (lab tests on samples from concrete tower, main and aux cables and sockets to verify material properties, identify deficiencies of materials and progression of defects over time)
    - Led by LPI, include other sockets with and without separation, stereomicroscopy of fractured wires, pull tests, neutron imaging
  - Forensic Information Model (to visualize technical data)
  - Summary Report – expected March 2022

Hardware samples sent by Thornton Tomasetti to their subcontractor, LPI



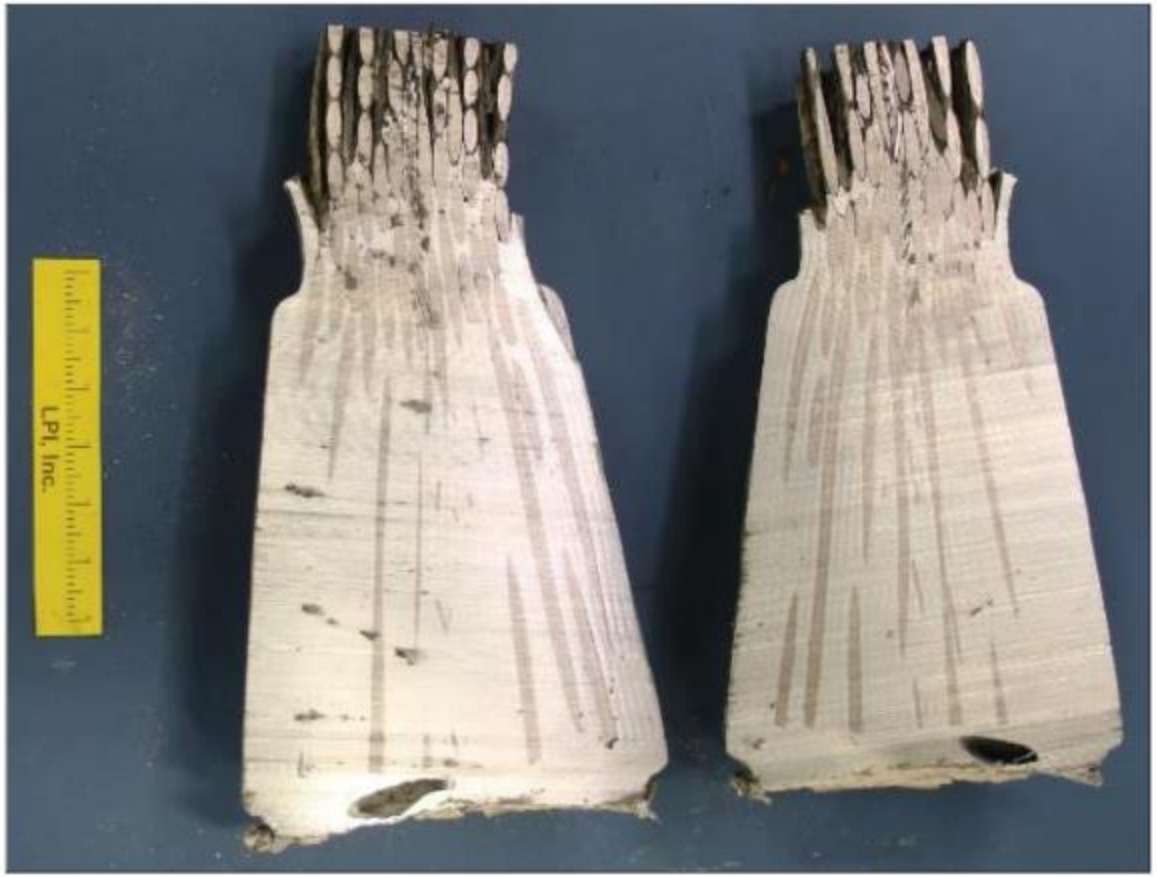
Sample Type	Cable or Socket ID
Original main tower-end socket	M4-4_T
Auxiliary main tower-end socket	M4S_T
	M8N_T
	M8S_T
	M12W_T
Auxiliary main platform-end socket	M4S_P
	M8S_P
Auxiliary backstay ground-end socket	B4N_G
	B4S_G
	B12E_G
	B12W_G
Failed ends of Tower 4 original mains	M4-1
	M4-2
	M4-3
Intact segments of original mains	M4-1
	M4-2
	M4-3
	M4-4
	M8-1
Intact segments of auxiliary mains	M8S

Socket Testing at Lehigh University



Laboratory Update (LPI)

Socket M8N_T exhibited 3/4" cable slip.



Zinc casting was cut open and macroetched to reveal zinc grain and/or flow structure.

Final Conclusions Pending

We expect the Thornton Tomasetti final report to be submitted in March 2022.

Samples are being retained for evaluation by NASEM if it is deemed more study needs to be done in an area that has not yet been explored.

- UCF has also stored other remaining cable sections and hardware, available for NASEM if needed

Encourage further discussions with engineers of the reports themselves including:

- Thornton Tomasetti (TT)
  - LPI
  - Langan
- Wiss, Janney, Elstner Associates, Inc. (WJE)
- NASA Engineering and Safety Center (NESC)

Also: WSP, USACE, Sabal Engineering, NASA Planetary Defense Office

Related Information

- Trusted structural engineering reports (especially analysis post-Hurricanes Maria/Irma and post 2019-2020 earthquakes); after August 2020 failure, NSF added oversight of expert review of these reports (e.g., USACE and Forensic Engineering Firm, Sabal)
  - Did include several structural engineer experts on review of the hurricane proposal (especially due to the main cable replacement activity); led to more oversight requirements (e.g., a PEP)
- Declining funding profile did put a lot of pressure on awardee to save money where they could; in reality, NSF funded at a flat level, so the proposed decline in funding (see Gaume presentation) did not occur; funds available for critical items

Related Information, Continued

- Lots of oversight; UCF had a Business Systems Review, Hurricane Award oversight
- On average, most well-built bridges last ~80 years; note Arecibo had infrastructure that was approaching 60 years old
  - Some cable-stay bridges have shorter lifetime
  - Failed auxiliary cable was approximately 25 years old
- Original design did not include means for easy replacement of key components

Summary

- Rigorous modeling/analysis for structure/safety zones (TT, WJE)
  - During collapse, no injuries to personnel or contractors
- By early September, excellent engineering team assembled by UCF: quality of analysis and rigor is evident in structural models (TT), response plan, safety plan, and forensic evaluation of failed socket (WJE/NESC) and platform collapse (TT)
  - Engineering firms hired by UCF supported by NSF based on their experience analyzing/working with similar structures (e.g,. cable-stay bridges)