Description of document: National Science Foundation (NSF) Documents Concerning the Arecibo Radio Observatory Response Plan

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Source of document: National Science Foundation
Attn: FOIA Officer
2415 Eisenhower Avenue
Alexandria, Virginia 22314
Fax: (703) 292-9041
Email: foia@nsf.gov

NATIONAL SCIENCE FOUNDATION
2415 Eisenhower Avenue
Alexandria, Virginia 22314

OFFICE OF THE
GENERAL COUNSEL

February 26, 2021

Via email

Case #2021-45F

This is a partial response to your November 19, 2020 emailed Freedom of Information Act (FOIA) request to the National Science Foundation (NSF) for the following records pertaining to Arecibo Observatory, specifically:

1) The technical/engineering assessment of the Arecibo Observatory Telescope in 2020.

2) a copy of the decisional document(s) or memorandum(s) making the determination to scrap the Arecibo Observatory Telescope.

3) A copy of the Analysis of Alternatives regarding the Arecibo Observatory Telescope.

4) A copy of letter correspondence with the University of Central Florida regarding the decision to scrap the Telescope. You may limit this request to documents between August 1, 2020 and November 19, 2020.

Enclosed is the Response Plan to the Auxiliary Cable Failure at the Arecibo Observatory that I interpreted as being responsive to item #3 of your request. Personal information (signatures) has been withheld wherever it appears under the privacy protection of Exemption (b)(6) of the FOIA. I am also enclosing some links to the public website that may be useful.

http://www.naic.edu/~phil/hardware/telescope/auxmain200810/auxmain4.html

http://www.naic.edu/~phil/hardware/telescope/auxmain200810/auxmain4photos.html

We will continue processing the remainder of your request and update when records are received.

Your right of administrative appeal is set forth in Section 612.9 of the NSF FOIA regulation (copy enclosed). Your appeal must be postmarked or electronically transmitted within 90 days of the date of the response to your request.

If you need any further assistance or would like to discuss any aspect of your request, please do not hesitate to contact our FOIA Public Liaison at 703-292-8060. Additionally, you may contact the Office of Government Information Services (OGIS) which was created to offer mediation services to resolve disputes between FOIA requesters and Federal agencies as a non-exclusive alternative to litigation. Using OGIS services does not affect your right to pursue litigation. If you are requesting access to your own records (which is considered a Privacy Act request), you should know that OGIS does not have the authority to handle requests made under the Privacy Act of 1974. You may contact OGIS in any of the following ways:

National Archives and Records Administration
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College Park, MD 20740-6001
E-mail: ogis@nara.gov
Web: https://archives.gov/ogis
Telephone: 202-741-5770
Facsimile: 202-741-5769
Toll-free: 1-877-684-6448

There is no fee for FOIA services in this instance in accordance with 5 U.S.C. 552(a)(4)(A)(i) et seq.

Sincerely,

/s/

Sandra Evans
FOIA/Privacy Act Officer

Enclosures

WJE

Wiss, Janney, Elstner Associates, Inc.
330 Pfingsten Road
Northbrook, Illinois 60062
847.272.7400 tel
www.wje.com

September 1, 2020

Mr. Ramon Lugo
Principal Investigator
University of Central Florida
Florida Space Institute
12354 Research Parkway
Partnership 1 Building, Suite 214
Orlando, FL 32826-0650

Response Plan for the Arecibo Observatory Cable Failure

Dear Mr. Lugo:

As outlined in our proposal dated August 20, 2020, Wiss, Janney, Elstner Associates, Inc. (WJE) is pleased to provide the attached Response Plan for the Auxiliary Cable Failure at the Arecibo Observatory. This plan was developed using the information provided to WJE to-date including our conference call with the project team on August 31, 2020. We believe we have structured the plan and its associated tasks so that the investigative and repair work can be completed timely and safely. WJE will lead the overall forensic investigation of the failure and the visual condition assessment of the remaining cables. WJE will also be responsible for working with other parties to assess and maintain structure stability at the various stages of the investigative and restorative work. These responsibilities have been clarified in the proposed plan.

We are available to discuss and answer questions as needed.

Sincerely,

(b) (6) [redacted]
Principal

(b) (6) [redacted]
Brian J. Santosuosso
Principal

Attachment

RESPONSE PLAN FOR THE AUXILIARY CABLE FAILURE AT THE ARECIBO OBSERVATORY

Introduction

As requested, Wiss, Janney, Elstner Associates, Inc. (WJE) performed a preliminary review of information provided by your office to-date related to the recent auxiliary suspension cable failure at the Arecibo Observatory. The purpose of this review was to become familiar with current conditions at the Observatory and develop a plan for pursuing a forensic investigation of the failure, performing a condition assessment of remaining cable elements, and implementing measures as needed to maintain stability of the suspended platform during these efforts and while repairs designed by others are implemented to restore normal observatory operations. WJE will lead the overall forensic investigation of the failure and the visual condition assessment of the remaining cables. WJE will also be responsible for working with other parties to assess and maintain structure stability at the various stages of the investigative and restorative work.

Background

Accident Description

On August 10, 2020, a structural cable failed at 2:35 am during normal observatory operations. The failed cable was a primary component of the system used to suspend a large, steel-framed platform (Feed Platform) above the telescope reflector dish. The failed cable was one of twelve auxiliary cables installed as part of a 1992-designed modification to the observatory. As a result of the cable failure, the supported Gregorian dome and many reflector panels were damaged. The observatory is no longer operating.

Document Review

We have received many documents related to the facility and the failure, and we anticipate receiving many more. The information received and reviewed to date has enabled us to develop the response plan outlined in this letter.

According to drawings provided for our review, the subject structure includes the following primary components (refer to Figure 1):

- A suspended, steel-framed platform (Feed Platform, in blue)
    - Shaped as an equilateral triangle in plan, with each side measuring 216 feet
    - Suspended from three sets of wire ropes; each set aligned with the bisector of a corner angle
    - One corner angle bisector points north and is given a position designation of 12 (as in 12 o-clock), while the other two bisectors point south east (position 4, as in 4 o-clock), and southwest (position 8, as in 8 o-clock)
    - Substantially modified in 1992 via addition of equipment and additional structural elements
- Wire suspension cables (in red and cyan)

  - One set corresponding to each corner of the Feed Platform, generally aligned with the corner's bisector, so that there is one set of cables at 12 o-clock, one set at 4 o-clock, and one set at 8 o-clock
  - Each set contains 4 original (1960 construction) cables (red), each 3.0-inch diameter with a breaking strength of about 600 tons, extending about 575 feet from a corner of the Feed Platform to a support tower, at a vertical angle of about 12.8 degrees
  - Each set contains 2 auxiliary (1992 construction) cables (cyan), each 3.25-inch diameter with a breaking strength of about 720 tons, extending about 700 feet from a point on the side of the Feed Platform to the same tower that supports the original cables, at a vertical angle of about 10.5 degrees
- Support towers (in purple)
  - One tower for each set of suspension cables (designated T12, T8 and T4 corresponding to the clock positions of each cable set)
  - The tops of the towers are at a common elevation that is about 100 feet above the top chords of the Feed Platform main trusses
  - Reinforced concrete, cruciform cross-section
  - Cross-section varies via setbacks at various elevations
  - Foundation consists of reinforced concrete pad bearing on natural rock
  - Suspension cables are anchored to the top of the tower
  - Inward pull of suspension cables is balanced by a set of backstay cables that are also attached to the top of the tower
- Backstay cables (in orange and yellow)
  - One set for each tower
  - Aligned radially with suspension cables, but on the opposite side of the tower
  - Each set contains 5 original (1960 construction) cables (orange), each 3.25-inch diameter with a breaking strength of about 700 tons; and 2 auxiliary cables (1992 construction in yellow), each 3.625-inch diameter, with a breaking strength of about 880 tons
  - Each set of backstay cables attaches to a single reinforced concrete anchorage set in natural rock; the distance of the anchorage from the base of the corresponding tower and the angle of the backstay set vary as follows: T12: anchorage is 380 feet from tower, and cables are at an angle of 36 degrees from horizontal; T8: anchorage is 390 feet from tower and cables are at an angle of 26 degrees from horizontal; T4: anchorage is 455 feet from tower, and cables are at an angle of 37 degrees from horizontal.
- Hold down cables (in green)
  - Three pairs of cables, each of which is 1.5-inch diameter with a breaking strength of about 150 tons
  - Each pair connects an outrigger aligned with a corner of the Feed Platform to an anchorage located directly below (i.e., the cables are vertical)
  - The as-designed tension in each hold down cable was 24 kips under gravity load only conditions with a maximum "operational" load of 59 kips

On August 10, 2020, the north auxiliary suspension cable in the 4 o-clock set failed. According to documents provided for our review, the mode of failure involved the tower end separating from the zinc-filled spelter socket in the clevis that connected the cable to Tower T4.

An event summary document we were given access to on August 26, 2020 summarized information concerning various operational conditions shortly before and shortly after the failure. According to this document, the total tension in the hold down cables was about 95 kips just before the event and about 110 kips shortly thereafter. This document also noted that, shortly after the incident, the remote-controlled jacks on the hold down cables were moved to their total stroke such that the total tension in the cables was reduced to around 40 to 48 kips, concentrated at the 4 o-clock corner of the Feed Platform.

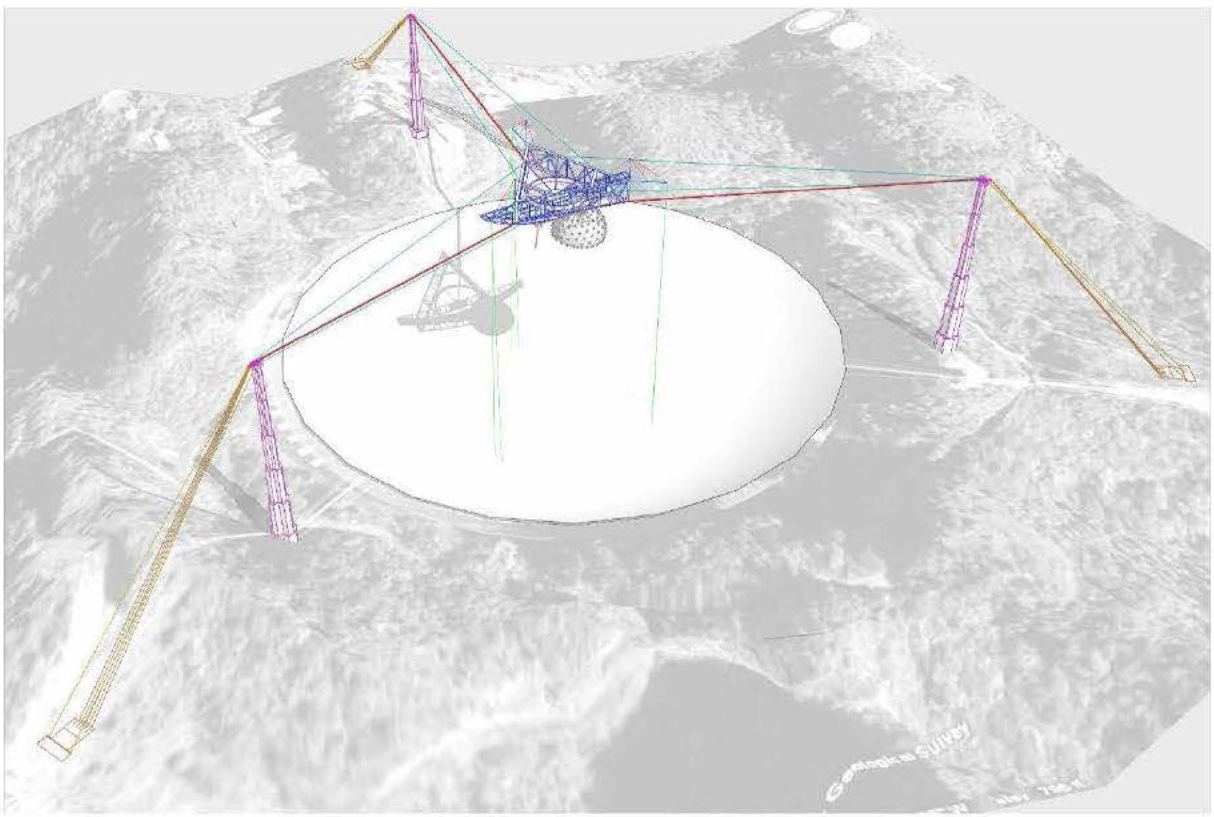

Figure 1. Arecibo Observatory with components color-coded.

RESPONSE PLAN

Based on our review of available documentation and an August 31, 2020 conference call with parties involved with this indicent, we developed a plan for investigating the failure and restoring the affected Feed Platform suspension system to a serviceable state. We have identified three, somewhat concurrent tasks under which the work will be completed. The various steps in this plan and the supporting rationale are summarized below. Given the fact that we are receiving additional information almost daily and that we have yet to visit the site, this plan is necessarily general in scope and will be supplemented with greater detail as work progresses.

Task 1 – Initial Measures

Step 1.1 – Initial Assessment

The load in the failed cable was likely much less than its original capacity. This suggests that the cables have been subjected to mechanisms (e.g., corrosion, fatigue) that have significantly reduced their strengths. Until the effects of such mechanisms can be reliably quantified, reliable analytical determinations of current cable capacities are not possible. In contrast, reasonably accurate capacities of platform framing members and connections can be established using analytical methods. We understand that others will be responsible for developing an analytical model that will be used to quantify demands in cable and platform elements at any particular stage in the investigation/restoration process, and that they will also provide capacities for platform members and connections.

When considering possible courses of action, it is helpful to have some understanding concerning the stability associated with existing conditions. In this context, the following facts are relevant:

1. The design capacities of the remaining 4 o-clock suspension cables (and all other suspension and backstay cables) are much greater than the current demands. In fact, the as-new capacity of the original set of 4 suspension cables is about 150 percent of the current tension in each suspension group. This means that even with both auxiliary cables lost, the original cable set would have to be substantially compromised in order for a cable group to fail under gravity loading.
2. During the loss of the failed cable, the structure was able to sustain the associated dynamic loading without becoming unstable.
3. After the dynamic effects of the failure subsided, the demands in many elements were (and remain) less than the peak demands sustained during the dynamic response phase.
4. The yet-to-be-determined mechanisms that led to the failure of the subject cable almost certainly created substantially varying capacities in all auxiliary cables, which means the relative capacities of the remaining cables are likely significantly higher than the capacity of the weakest cable (i.e., the one that failed).
5. After the cable failed, loading on the remaining Feed Platform suspension cables was significantly reduced by relieving tension on the hold-down cables.

Items 1 through 4 provide subjective reasons for believing the current capacity/demand (C/D) ratios for the primary structural elements and the suspension system as a whole are significantly greater than one rather than just barely greater than one. The actions related in Item 5 provided a quantitative reduction in the load carried by the suspension system of about 4 percent. Consequently, when there are no significant loads other than gravity acting on the system, failure of additional cables in the near future is unlikely. With this in mind, we believe that it would be appropriate to carefully remove the clevis of the failed cable, and lower it to the ground, provided the work can be done during a period of calm weather (i.e., wind gusts remaining below 20 mph). However, as discussed below, we believe additional measures should be implemented before permitting access within the perimeter defined by the towers (i.e., within about 700 feet of the center of the reflector dish) and before allowing extensive work to be performed at the tops of the towers.

A detailed model of the Feed Platform and suspension cable system is being prepared by others for the purpose of performing the following tasks:

1. Analytically evaluate the existing condition of the Feed Platform framing to identify members and connections that are highly loaded.
2. Establish a benchmark estimate of element demands (truss members, cables, connections) as a basis for comparisons with changing conditions.
3. Evaluate the effects of substantial temperature changes on key elements.

As part of the initial assessment, WJE will rely upon the model results to prioritize stabilization efforts and establish safe procedures for beginning repair and investigation work.

Step 1.2 - System Load Management

Immediately after the cable failure, the suspended platform system was stable, which means the elements comprising the system clearly had C/D ratios greater than one. Equally clear is the fact that the C/D ratios for critical system elements need to remain greater than one if people are going to be working on the towers and within the tower perimeter. Maintaining C/D ratios greater than one also mitigates risk to the facility. WJE will oversee the efforts to manage the system loads in coordination with others.

Although the system is currently stable, time-dependent mechanisms (e.g., corrosion, fatigue) are at work, at least some of which are reducing element capacities. The key to maintaining system stability is to keep demands below the corresponding capacities as those capacities decrease. The previously noted reduction in hold-down cable tension was a productive, quantifiable action in this regard.

Although much more time-consuming than relieving hold-down cables, lengthening the backstays on the towers would provide additional, quantifiable reduction in key element demands, and it could be done without personnel working within the tower perimeter. Lengthening backstays will allow the tops of the towers to move inward. This will, in turn, cause the Feed Platform to drop, which will relieve the remaining tension in the hold down cables and increase the slopes of the suspension cables. Both of these actions will reduce suspension cable tensions. We performed some rough preliminary analyses using as-designed dimensions and material properties which indicated that allowing the top of each tower to move inward one foot (a very small and very tolerable amount of movement) would have the following beneficial effects:

1. The remaining hold down tension would be relieved, reducing the load on the Feed Platform by about 2 percent.
2. The tension in the original main suspension cables would be reduced by about another 1 percent due to geometric effects.
3. The tension in the auxiliary main suspension cables would be reduced by about another 5 percent due to geometric effects.

This modification is illustrated in Figure 2. The impact of adjusting the tower lean in this manner should be verified using a detailed model of the suspension cables and the Feeder Platform. Details of the backstay anchorage points where the lengthening would occur are shown in Figure 3 and Figure 4.

The combination of the initial post-event hold down cable release and allowing the tower tops to move inward as indicated above would add a significant, quantifiable margin of safety to the already stable conditions.

Relieving system loads is not the only way to provide a quantified estimate of C/D ratios in the cable elements whose capacities cannot be determined analytically. The hold-down cables can be used to "proof test" the platform and suspension system by applying significant vertical loads near the platform corners. For example, if we want to prove that the suspension cables have C/D ratios of at least 1.10 under current conditions, we can load the platform using the hold-down cables such that the demands in the suspension cables are increased by 10 percent and then remove the added load. Such proof-load testing is relatively easy to implement. However, unlike the tower lean adjustments previously discussed, it increases the risk of causing additional damage to the facility, such as failing another deteriorated auxiliary cable connection. However, given the amount of reserve capacity included in the design, global failure of the suspension system seems very unlikely. Also, proof testing does not reduce the demands in any elements. Hold-down cable proof testing can also be used as a rapid, point-in-time check before certain activities are undertaken. For example, before allowing workers to occupy the Feed Platform to remove the failed cable, the hold-down cables can apply a load greater than the loading caused by the workers and their equipment as a test of the system's ability to accommodate the work.

In our opinion, before people are allowed to go inside the tower perimeter or do extended work (i.e., more than a few hours) on the tops of the towers, either of the following measures should be implemented:

- Make the tower lean adjustments as outlined above
- Proof load the suspension cables to at least 110 percent of the current load
  - The system must stabilize under the increased load (i.e., the platform elevation must remain constant under constant hold-down tension) as the peak load is held for 30 minutes

Once either of these measures have been completed, we believe it would be appropriate to retrieve the end of the failed cable from its location in the reflector dish, install monitoring instrumentation on towers and tower-supported hardware (e.g., tower end socket), and install hardware on the tower end of the intact Tower 4 auxiliary main cable that allows cable load to bypass the existing clevis (i.e., clevis bypass hardware). After these measures are done, we believe it would then be appropriate to install socket bypass hardware on the Feed Platform end of the remaining 4 o-clock auxiliary cable, recover the rest of the failed cable, and carefully inspect the entire cable suspension system, in that order. As the strengths of the questionable cables are likely deteriorating over time, conditions must be reassessed periodically, including immediately before any activities on the towers or within the tower perimeter are to be performed. This reassessment could include performing additional proof load tests using the hold-down cables.

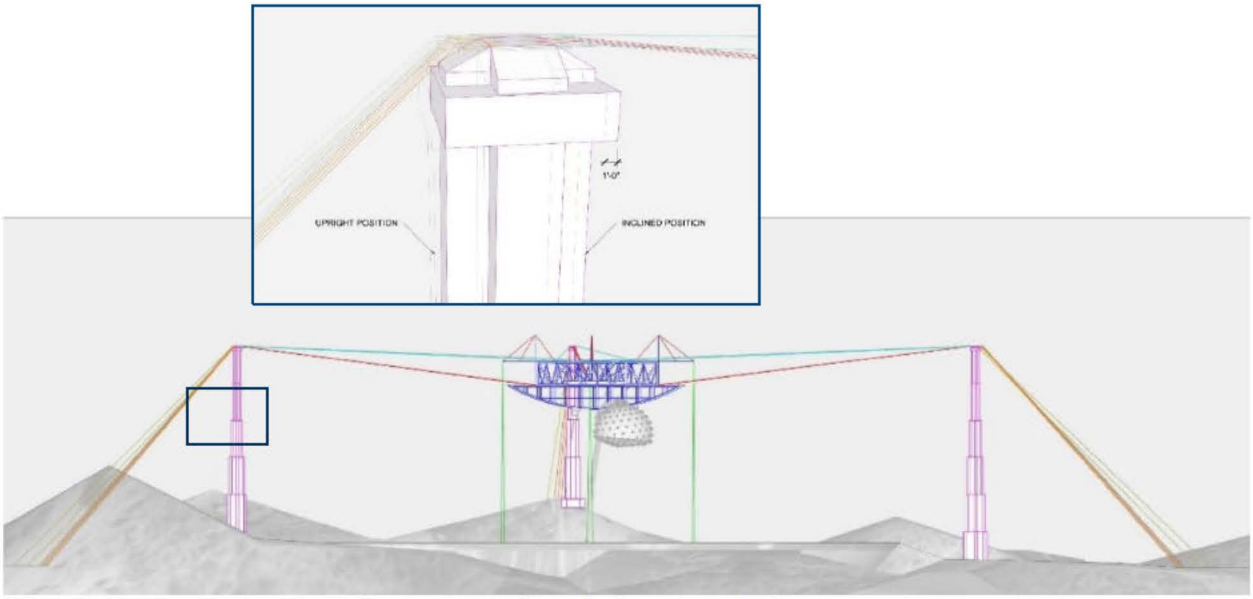

Figure 2. One-foot horizonal translation of tower from backstay lengthening.

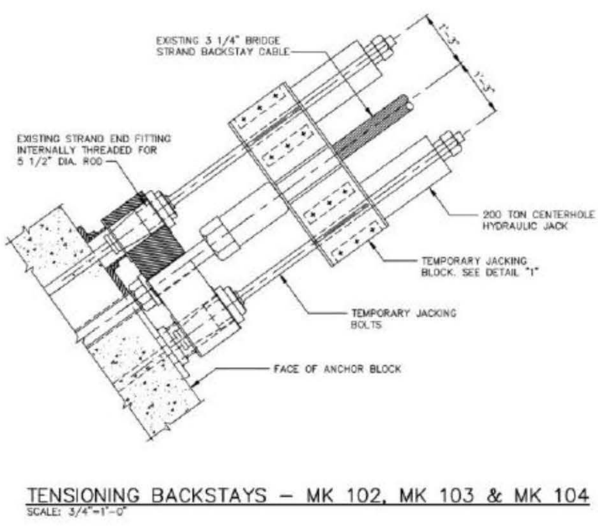

Figure 3. Original cable backstay anchorage

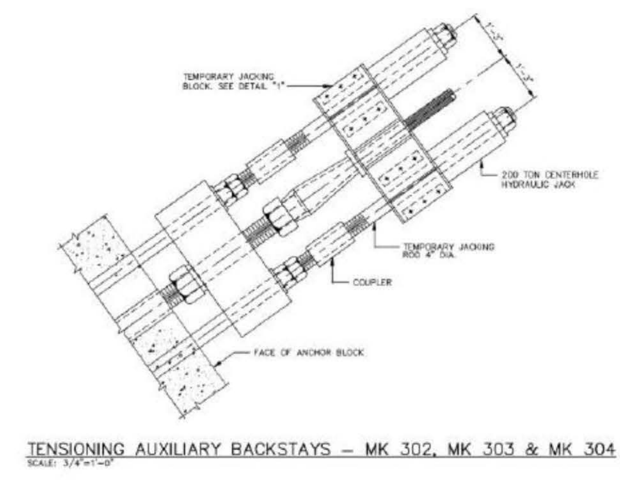

Figure 4. Auxiliary cable backstay anchorage

Step 1.3 - Monitoring

WJE will install a monitoring system to provide feedback on key structural stability parameters. As the cause of the cable failure has yet to be determined, the monitoring system is not expected to provide advanced warning of an impending sudden failure. In other words, the system may not be able to provide sufficient advanced warning to permit safe evacuation from the site. Instead, the system will be designed to detect structural changes whether gradual or rapid and provide notification of these changes so that informed decisions on site entry and task execution can be made.

To begin collecting monitoring data as quickly as possible, a solar-powered, wireless system is proposed. Each tower will be independently powered and use its own cellular modem to provide communications. We understand that in the long term, use of cellular and solar power systems will interfere with the telescope's operation; therefore, the wireless system will eventually be replaced with a hard-wired system where power and communications lines are installed at each tower. Each tower has an aircraft beacon mounted at its top. These beacons are typically high voltage which would require transforming the power to 110 VAC before using with the monitoring system.

The monitoring system is intended for use during the investigative phase as well as during later anticipated repair and rehabilitation work. As currently envisioned, the system will contain the following instrumentation:

- Vibrating wire strain gages on each fork of each auxiliary cable clevis for both suspension and backstay cables. The strain gages will directly measure changes in cable tension as well as bending-induced strain associated with lateral loads on the connection. Total 22 gages.
- Bi-axial tiltmeters to measure tower tilt radially and laterally with respect to the suspended structure. Total 3 tiltmeters.
- Acoustic emissions sensors will be installed on the auxiliary suspension and backstay cables to record evidence of future wire breaks at the cable ends. This system could be expanded to include all of the original suspension and backstay cables as well. Acoustic emission monitoring is a proven technology for detection of wire breaks in steel strands. This technology provides higher sensitivity to the stress waves emitted from sudden release of energy associated with wire breaks, as compared to vibration monitoring technologies. The high frequency of acoustic emission sensors (in the kHz range), along with the high scanning rate of the data acquisition system (1 million samples per second) makes acoustic emission monitoring suitable for this application. For this project, the system will consist of Sensor Highway III data acquisition hardware and highly sensitive acoustic emission sensors from Mistras Group, Inc.
- Linear Variable Displacement Transducers (LVDTs) to monitor additional movements of spelter sockets which exhibit evidence of post-installation slip of the zinc core. These locations are at the backstay anchorages of Towers T-12 and T-4. Total 2 LVDTs.

The instrumentation located at the top of each tower will be connected to a Campbell CR6X data acquisition system also located at the top of the tower in a weather-proof enclosure. A similar system will be installed at the selected backstay anchorages. The collected data will be transmitted via cellular service to a web-based server where it will be readily accessible via a webpage. Alarm thresholds will be established that could trigger an audible alarm on site as well as electronic and cellular notifications.

The monitoring system will also incorporate cable tension measurements determined via cable sag and vibration calculations. The cable sag and vibration techniques will serve as independent checks of the cable tensions. These measurements will be made as part of the initial assessment of the structure in Step 1.1 and thereafter whenever the monitoring system indicates a change in the structure or when the structure has been exposed to conditions that may have affected the structure's performance, e.g. high winds or an earthquake. Currently, Arecibo Observatory staff are performing daily visual observations of the structure. These will continue until the bypass work is complete.

The cable sag measurements performed by others will utilize a theodolite currently being used at the site. From the survey data, using know cable sag equations, a tension will be calculated. The vibration measurements involve using multi-axis accelerometers attached to the cable with tape and couplant wax or a magnet to capture the fundamental frequencies of the cable. The accelerometer is positioned within arm's reach of the cable end. No special supplemental excitation is needed during these measurements. A time-history waveform is generated from the data which is then analyzed using a Fast-Fourier Transform (FFT) analysis to map the frequency spectrum and extract the fundamental frequencies of the first several modes. Based on the cable length between connections and weight per unit length of the cables, the tension in the cable can then be calculated using the relationship between natural frequency, geometry, and material properties of the cable.

Step 1.4 - Strengthening Measures

Once the tower leaning adjustments are made or the proof loading using the hold-down cables is completed, the monitoring systems described above are active, current cable tensions have been calculated based on survey data, and others have completed their assessment of the platform components, we believe it would be appropriate to install certain supplemental items. We understand that socket bypass hardware is being designed to supplement the strengths of certain backstay cable socket connections that have exhibited excessive zinc slippage, and these should be installed at this time. Without knowing more about the existing conditions and the extent of repairs and cable replacements being designed by others, we cannot list specific additional items that would need to be installed at this point. If the analyses show that certain platform elements would be excessively loaded at any time during the investigation/restoration process, this would likely be a good time to install at least some of the corresponding strengthening measures.

Since we cannot reliably determine the strengths of cables using analysis, maintaining the integrity of the remaining cables will require a combination of efforts including surveys, instrumentation monitoring, load testing and, possibly, supplementation. For example, if the repairs being designed by others can be installed in a manner that precludes loading cables beyond their recently demonstrated capacities (i.e., loads currently sustained, loads sustained just before the failure, and loads sustained during a load test using the hold-down cables), there may be no need to supplement them. However, if implementing the desired modifications will involve loading cables beyond demonstrated capacities, supplementing suspect socketed connections might be necessary.

In our opinion, the remaining auxiliary suspender cable at Tower T4 is especially critical because it is a more critical component of its cable group than any of the other auxiliary cables. Given the suspect nature of the auxiliary cable socket connections, it is especially important to prevent loading this cable's clevis socket beyond it recently demonstrated capacity.

Task 2 – Forensic Investigation

It is important to determine the cause of the cable socket failure and evaluate conditions at the remaining 30-year old auxiliary cable connections and original main cable connections that have been in-place over 50 years. Time is of the essence as it relates to securing and protecting important evidence associated with the failure. Metallic failure surfaces begin to immediately corrode which can hinder and complicate later evaluations of the surfaces. In the hot, humid environment of Arecibo, corrosion is accelerated. Therefore, every effort should be made to safely retrieve the failed spelter socket, a portion of the failed end of the auxiliary cable, and the other socket end with a segment of cable from the site. These components should be carefully removed from the structure, prepared for shipment, and sent to a laboratory with appropriate forensic investigation experience and the tools to carry out the required work.

The following outlines the steps to complete the failure investigation of the cable socket by WJE:

Step 2.1 – Failed Clevis Recovery

Once Step 1.1 is complete, recovery of the failed clevis can commence. Removal of the clevis will require personnel to climb Tower T4, secure the clevis to the tower, remove the pin, and then lower the clevis to the ground. This work will be done during low wind conditions and in accordance with a task-specific safety plan. All personnel will have appropriate PPE and will be tied off to proper anchorages during their ladder accent/decent and while working on the top platform. Personnel working on the top platform should remain next to the failed socket and avoid positioning themselves in front of or below any other live cable socket. Figure 5 is a long-distance view of the failed clevis.

Risks associated with failure of another cable and any ensuing collateral damage during this activity will be low. As previously indicated, demands on the intact cables are less than the demands sustained during and shortly after the failure. In addition, in the unlikely event of a future cable failure, the failed unit will not be able to contact personnel positioned on or at the base of the tower. The tower will remain stable should a backstay cable failure occur. The recovered clevis, once lowered to the ground, should be stored indoors in an environmentally controlled space.

Figure 5. Failed clevis (circled). Photo from AO.

Step 2.2 – Cable Recovery

Recovery of the failed cable end can occur as described in Step 1.2 when suspension cable demands have either been reduced or proof testing has shown the cables to have significant reserve capacity.

Approximately 10 feet of the failed cable including the failed end should be recovered (see Figure 6). This will require accessing the lower portion of the primary reflector, securing the individual wires using steel clamps (hose clamps or similar), holding the segment of cable with a material handler, cutting the cable with an electric saw, and lowering the material to the ground. This work will be done during low wind conditions for the site and in accordance with a task-specific safety plan. All personnel will have appropriate PPE. The recovered cable end should be stored indoors in an environmentally controlled space.

Figure 6. Cable end to be recovered. Photo from AO.

Figure 7. Failed cable draped over T12 auxiliary cable. Photo from AO.

Step 2.3 – Removal of Remaining Cable and Socket

Removal of the remaining attached socket and draped length of cable can proceed after the monitoring and socket bypass retrofits of Steps 1.3 and 1.4 have been installed. These steps will provide further assurance that work on and below the platform will be reasonably safe. Removal of the still-connected socket and cable must avoid damaging the auxiliary cable from Tower T12 over which the failed cable is draped (see Figure 7 above). Because it is advantageous to save the socket and cable for testing, the retrieval effort will need to secure the socket and adjustment rod connection, detach the connection assembly, lift and rotate the assembly away from the supporting cable, and lower it to the ground.

This work will be done during low wind conditions for the site and in accordance with engineered and task-specific safety plans. All personnel will have appropriate PPE.

Step 2.4 – Visual Examination and Materials Testing

The root cause failure investigation will include metallographic and fractographic examinations of the cable wires on both sides of the fracture. Preparation of wire end surfaces will be in accordance with ASTM E3 – *Standard Guide for Preparation of Metallographic Specimens*. The evaluation process will include the following steps: 1) Visually examine by stereomicroscope the failed wire ends, in their as-received condition; 2) Photodocument as appropriate; 3) Perform any dimensional measurements considered relevant to the investigation; 4) Further examine relevant fracture surfaces in their as-received condition by scanning electron microscopy (SEM); 5) Analyze the composition of relevant fracture surface deposits and any other features by energy dispersive x-ray spectroscopy (EDS); 6) If necessary, clean the fracture surfaces to enable further examination and fractography, both visual/optical and by SEM; and 7) Perform microhardness testing of any relevant microstructural regions or features.

Wire segments will be removed from the recovered specimen for mechanical and chemical testing. The mechanical testing in accordance with ASTM A586 –*Standard Specifications for Metallic-Coated Parallel and Helical Steel Wire Structural Strand* will confirm the tensile strength and stress at 0.7 percent elongation, total elongation, ductility, weight of metallic coating, adherence of metallic coating, and finish. Elemental chemical analyses will be obtained using optical emission spectrometry for compositional analysis using ASTM E415 – *Standard Test Method for Analysis of Carbon and Low-Alloy Steel by Spark Atomic Emission Spectrometry*. Hardness testing (ASTM E18 – *Standard Test Methods for Rockwell Hardness of Metallic Materials* and ASTM E92 – *Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials*) will also be performed on the wire samples.

The failed socket will be cut longitudinally to expose the interior for examination. An attempt will be made to match up the failed wire fractures surfaces. In addition, the composition, location and thickness of the zinc corrosion by-product will be documented for evidence of long-term separation of the core.

Environmental testing for hydrogen embrittlement will also be considered if there is evidence of hydrogen assisted failure at the wire fracture surfaces. This test, in accordance with ASTM A1032 – *Standard test Method for Hydrogen Embrittlement Resistance for Steel Wire Hard-Drawn Used for Prestressed Concrete Pipe*, will provide an indication of the wire's resistance to hydrogen embrittlement when exposed to a hydrogen-rich environment. In this case, the environmental hydrogen would be from water.

Step 2.5 – Load Testing of Spelter Socket

The removed spelter socket and connected wire rope from the Feed Platform end of the failed cable will be carefully examined. That cable-socket assembly will then be tested to failure which if undeteriorated and properly constructed will be in the cable. After testing, the spelter socket wedge will be sectioned and examined for evidence of deterioration and proper wire brooming. The formerly attached segment of cable will be sectioned in several locations to examine internal conditions and estimate remaining service life.

Step 2.6 – Analytical Evaluations

An analytical evaluation to determine the estimated loads on the socket at the time of the failure will be performed. If there is evidence of fatigue damage to cable components, a model capable of identifying key dynamic characteristics may be useful.

Task 3 – Assessment and Repair

Using the findings of the laboratory and analytical studies, a determination as to the root cause of the failure will be prepared. With the root cause determined, a plan to assess the remaining cables can then be developed and executed. If an accurate assessment is not possible, then a plan to provide supplemental connections at the socketed ends will be needed.

Step 3.1 – Remaining Cable Condition Assessment

A detailed condition survey of the cables will be completed by WJE. The hands-on visual inspection will include all cable ends at the anchorages, towers, and Feed Platform. A drone will be used to visually survey the cable lengths where they are otherwise inaccessible. Should the drone images reveal a critical finding, industrial rope access methods will be used to provide close-up inspection. This should only begin after the failure investigation has, at a minimum, developed its preliminary findings.

Step 3.2 – Cable Replacement

We understand that various degrees of cable replacement are being considered. Given the demonstrated variability in the capacities of the auxiliary cables and the fact that the original cables are much older, it is important to keep tensions in existing cables below recently demonstrated capacities when working on the system. This can be done by either load testing the system using hold-down cables before critical steps, relieving load on the system, installing supplemental cables, or any combination of these measures. WJE will be responsible for establishing the procedures required to maintain stability of the structure during the replacement work. Our assessment will rely upon the analyses of others to determine member and component forces and platform capacities at each step of the process.