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The challenge project presented in this report evaluates commercially available antenna masts for application in a rapidly deployable ground communication system.

The purpose of this report is to document the candidate challenge project and demonstrate that it has the depth to meet requirements for the Gordon Engineering Leadership program and the College of Engineering at Northeastern for a Master of Science in mechanical engineering.

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Design of Rapidly Deployable Antenna Support System for Mission Critical Communications



MITRE

A Challenge Project Final Report presented

by

Jaclyn Hayes

of

The MITRE Corporation

to

The Gordon Institute of Engineering Leadership

in progress towards the requirements

for

the Graduate Certificate in Engineering Leadership

Northeastern University

Boston, Massachusetts

July 2019

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1 ABSTRACT

The purpose of this report is to document the candidate challenge project and demonstrate that it has the depth to meet requirements for the Gordon Engineering Leadership program and the College of Engineering at Northeastern for a Master of Science in mechanical engineering. The candidate evaluated commercially available antenna masts for application in a rapidly deployable ground communication system. A customer need was identified for designs that offer speed, adaptability, and durability. The project required extensive knowledge and application of design and mechanics principles including stress and strain, deflection, fatigue and wind loading. Verification of the closed form solutions took the form of finite element software tools. The candidate needed leadership capabilities to advocate for funding and demonstrate the benefit proposition of the project to teams of multidisciplinary engineers. The successful project resulted in significant time and money savings for the government sponsor once the system is fielded.

The candidate recommended adjustments to the operations and sustainment of the antenna support structure as a result of this project to the sponsor. Challenges from a technical perspective included minimal information available for commercial antenna masts like material properties. The mitigation plans were to reach out directly to manufacturers for data and make conservative assumptions where required. Market challenges included a reduction in funding and public release system delays within MITRE. The mitigation plans were to provide updates to teams to demonstrate value of this project and communicate with security and legal team to budget time for reviewal.

2 AUTHOR'S BIO

Gordon Fellow candidate Jaclyn Hayes is in pursuit of a Master of Science in mechanical engineering with a concentration in mechanics and design at Northeastern University. She began working at MITRE in 2014 as an intern and transitioned to full time work as a mechanical engineer in 2016 after graduating from the University of Massachusetts Amherst.

The candidate technical skills include expertise in Computer Aided Design (CAD) tools, e.g. SolidWorks, and Finite Element Analysis (FEA) software suites, e.g. ANSYS. Her undergraduate thesis work used ANSYS to implement hyperelastic material properties into soft tissues for finite element models, which was published in 2016. She has experience in prototyping designs using 3D printers and the MITRE fabrication facility. Resulting products include a 3D printed enclosure for a demonstration of electronics transported on a drone and a steel plate fixture for vibration testing of an antenna. The candidate also has experience testing prototypes with environmental equipment such as thermal/humidity/altitude chambers and a vibration table. She conducted thermal cycling and vibration tests to qualify components to a space standard prior to launch of equipment integrated on a CubeSat.

The candidate's recent leadership experience at MITRE included development of an externship program for two high school seniors, mentorship for an undergraduate intern, and task leader for an effort to develop a system requirements document (SRD). The candidate worked with the Lowell High School students to design and 3D print a weight

supporting structure and set up job shadowing of other MITRE employees within mechanical engineering, cybersecurity, and human factors disciplines. A mechanical engineering undergraduate intern worked directly for the candidate in the summer of 2018 on tasks involving CAD, 3D printing, and thermal analyses. The SRD that she was an author on was to develop is for a deployable communications ground system, which was the larger system that this challenge project supported.

3 ACKNOWLEDGEMENTS

The candidate would like to thank her employer and sponsor organization, The MITRE Corporation, for its educational assistance program and its continued partnership with the Gordon Institute of Engineering Leadership at Northeastern University. Additional thanks to the faculty and mentors within the program including her Gordon Mentor, Jane Eisenhower, Faculty Advisor, Professor Ibrahim Zeid, and Industry Sponsor Advocate, Justin Ruddock. The candidate would also like to acknowledge her family for their constant support including her parents, Mike and Donna Hayes, her brother Michael and the family's dog, Raven.

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6 INTRODUCTION

6.1 Product Mission Statement

The Rapidly Deployable Antenna Support System mission statement is shown in Table 1. The mission was defined in terms of proposed benefits, key business goals, primary and secondary markets, assumptions, constraints, and stakeholders. The product was the selection of a commercial antenna support structure that met the environmental requirements in a deployed location.

Table 1: Rapidly Deployable Antenna Support System Mission Statement

Product Description	An antenna support structure that meets operational environments in a deployed location.
Benefit Proposition	Contribute to goal for a ground communication platform that is rapidly deployable. Leverage existing antenna mast products.
Key Business Goals	Reduce antenna system setup time by 50% Reduce antenna system costs by 50%
Primary Market	MITRE
Secondary Market	Government Program Management Office (PMO) End users
Assumptions and Constraints	Commercial off the shelf (COTS) antenna masts Accessibility of performance and material data
Stakeholders	MITRE Government PMO End users Requirement Authority

6.2 Project Definitions

Relevant definitions for the challenge project report are shown in Table 2.

Table 2: Definitions for Challenge Project Proposal

Acronym	Definition
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
COTS	Commercial Off the Shelf
DoD	Department of Defense
FA	Faculty Advisor
FBD	Free Body Diagram
FEM	Finite Element Modeling
FEA	Finite Element Analysis
FFRDC	Federally Funded Research and Development Center
GM	Gordon Mentor
ISA	Industry Sponsor Advocate
NSEC	National Security Engineering Center
PMO	Program Management Office
ROI	Return on Investment
SOW	Statement of Work
SRD	System Requirements Document

Acronym	Definition
STE	Staff Years of Technical Effort
UHDL	Ultra-Heavy-Duty Locking
UTS	Ultimate Tensile Strength
WBS	Work Breakdown Structure

6.3 Company/Industry Background

The MITRE Corporation is a private, not-for-profit company that operates seven federally funded research and development centers (FFRDCs). The largest and oldest one is sponsored by the U.S. Department of Defense (DoD) to support its services: Army, Navy, Marine Corps, and Air Force. MITRE is similar to a matrix organization with a hybrid of functional/technical and project organizations [1]. The technical centers are groups with high depth of expertise within a field, such as mechanical engineering. There are also program divisions which focus on certain customers, such as the Air Force. Projects are mainly comprised of members in the relevant program division with support as needed from the technical centers.

MITRE values speed, risk-taking, and adaptability to deliver quality recommendations and products to its sponsors. Another recent goal within MITRE originated in a memo from the Assistant Secretary of the Air Force for Acquisition in 2013: “to own the technical baseline.” This requires the right data, processes, and resources to make informed and timely decisions that improve the performance of the program. Issues with the lack of technical ownership include the inability to perform independent analysis and validate contractor technical decisions as well as control costs.

7 MARKET AND IMPACT ASSESSMENT

7.1 External Market

The external market for the challenge project was the DoD, with a budget of 686 billion dollars for fiscal year 2019 [2]. The government program management office was the most direct external customer for the challenge project. The major product that the PMO managed was a communication system on an aircraft that was remotely controlled from ground stations. The infrastructure for communications is a key focus within the operational environments of the Information Age. Timely and accurate information is needed to support command and control authorities. The PMO develops and delivers products to the end users which meet the operational needs defined by the requirements agency within the DoD.

DoD Instruction 5000.02 developed a “waterfall” structure of systems acquisition phases with decision points or milestones to meet in order to continue to the next step. During the material solution analysis phase, the need for a new product or capability is identified and alternative solutions are analyzed. The next step is Milestone A, which is the investment decision to pursue design concepts and commit resources to reduce risks and mature technology. During the technology development phase, the requirements are finalized in the Capability Development Document and the Request for Proposal is released. This phase ends at Milestone B to commit resources for development activities. The engineering and manufacturing development phase leads to hardware and software prototypes and extensive testing to demonstrate system capability and manufacturing processes. The following step is Milestone C to enter production. The production and deployment phase begins with low-rate initial production systems for operational test articles and continues to full-rate production and deployment. The last phase contains life cycle sustainment and the disposal of the system. Figure 1 shows a visual representation of this waterfall structure used within the DoD [3].

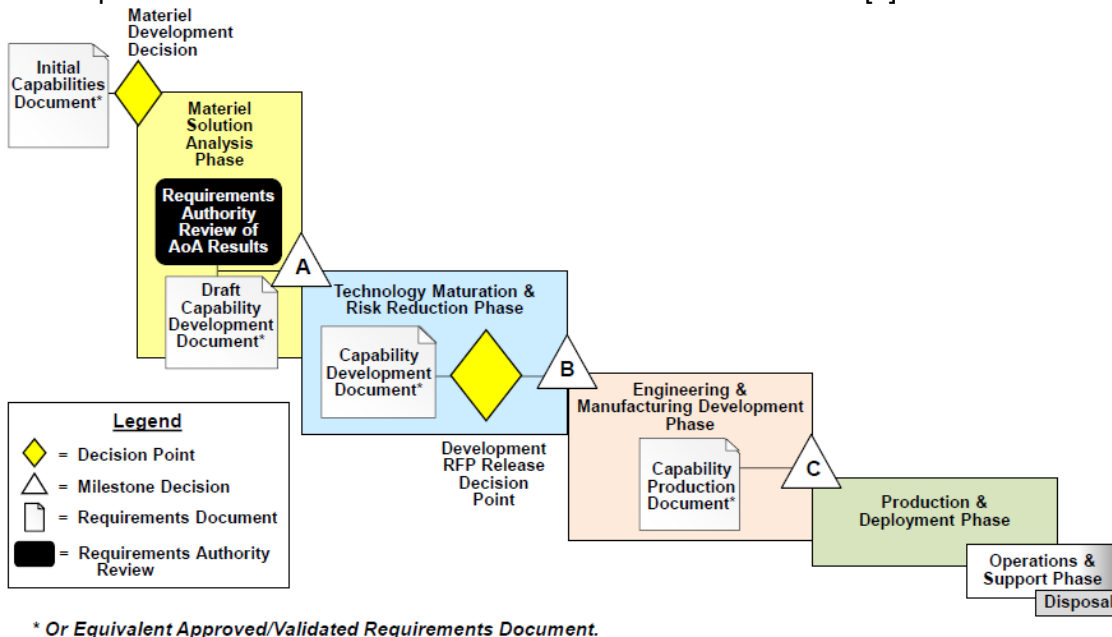


Figure 1 Typical Acquisition Strategy for the DoD [3]

A recent push in the DoD was toward rapid acquisition strategies as documented in the National Defense Authorization Acts. These laws dictate the budget and policies of the DoD as agreed upon in Congress each year. Since 2016, Section 804 allowed for middle tier rapid acquisition with rapid prototyping and rapid fielding. This stated that after a requirement is approved, the system must be fielded in less than 5 years. Benefits to the process are exemption from the Joint Capabilities Integration Development System and DoD Instruction 5000.01 and no funding limit. For rapid prototyping, the deliverable is a fieldable prototype that uses innovative technology to demonstrate new capabilities. For rapid fielding, proven technologies are used with minimal development to begin production within 6 months of the requirement. Using Section 804 will allow rapid prototyping and/or fielding within five years which would save costs associated with retaining personnel for teams, formal documentation and review processes, and sustaining out-of-date systems that are currently fielded [4].

As discussed in further detail in the internal market section, the majority of MITRE's work involves the operation of federally funded research and development centers for the U.S. government. These can be operated, managed, and administered by not-for-profit organizations, universities, or separate operating units of industrial firms. Examples include RAND Corporation, Massachusetts Institute of Technology, and Sandia Corporation, a subsidiary of Lockheed Martin Corporation. Potential competition between these groups can occur as FFRDCs typically run for a renewable term of five years. After this time the center could be terminated or the sponsor could choose to open it to a new managing body, if the need and value from the current manager no longer exist.

7.2 Internal Market

MITRE operates seven federally funded research and development centers. The FFRDC model was developed to provide technical expertise to the government with no commercial conflicts of interest. The Federal Acquisition Regulations set operating constraints and legal criteria for the sponsorship of FFRDCs. Staffing levels are capped at a congressionally mandated limit expressed in staff years, and sponsoring agencies like the DoD prioritize the work for the centers. Staff years of technical effort (STE) are negotiated between MITRE and the government to distribute funds to various MITRE projects that support government programs.

The majority of MITRE work involves cost reimbursable contracts which cover funding for allowable expenses. Advantages to this structure are greater focus on quality, performance, or time to completion instead of fiscal budgets, which are more uncertain in this system. MITRE's revenue consists of these contracts with fees for reasonable and necessary expenses, business risks, and lender obligations in addition to capital costs for equipment and facilities. The total revenue for MITRE in 2016 was 1.542 billion dollars [5, 6].

An organizational chart of MITRE is shown in Figure 2. As a matrix organization, there is a combination of functional/technical and project organizations within the company [1]. Most of the employees reside within one of three groups: portfolio directors, program divisions, and technical centers. Portfolio directors work to maintain relationships and scope work plans directly with the FFRDC sponsors such as the DoD, Department of Homeland Security, and Federal Aviation Administration. The program divisions are focused at a smaller scale on the sponsors, with teams working on projects for the Air

Force for example. The technical centers provide departments with deep technical knowledge in a specific domain such as cybersecurity, human factors, and mechanical engineering. Employees within technical centers are pulled into projects that are focused within a program division, combining the functional and project organizations into one structure.

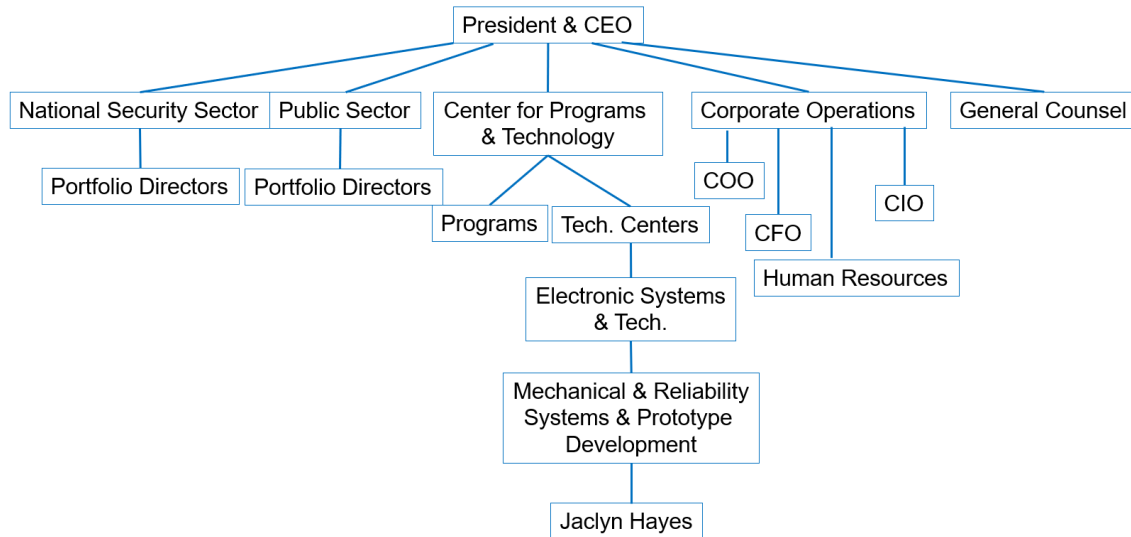


Figure 2 MITRE Organization Chart

The FFRDC that the challenge project falls under is the National Security Engineering Center (NSEC) which is sponsored by the DoD and Intelligence Community. This includes the Services (Army, Navy, etc.), Defense Information Systems Agency, and the offices of the Secretary of Defense and Joint Chiefs of Staff. MITRE defined goals for this FFRDC: “dramatic performance improvements, reduced system costs, and accelerated delivery to the field” [7].

MITRE promotes speed, risk-taking, and adaptability in delivering impact to sponsors. As mentioned earlier in section 6.3, the government wants to gain ownership of the technical baseline and MITRE wants to support with its collective expertise in a variety of domains. A key piece of that is validating contractor technical decisions through independent analyses. MITRE can develop a framework for analytical tasks and document the steps to gain and retain knowledge within the government.

7.3 Customer and Customer Needs Assessment

Within the government PMO, operational needs are provided by the appropriate requirements agency for the program. Specifications are created per those needs and then reviewed by the PMO and requirements agency to confirm that the correct items were addressed. The identified customer needs for this project included rapid fielding and setup/teardown (“speed”), durability, compact design, adaptability, and safety. These features will allow the user to have a ground system that can be rapidly deployed to various locations as the operational environment changes.

Speed and adaptability were assessed as needs for both the external and internal markets. The shift in acquisition strategy from the waterfall system to a more agile approach outlined in section 7.1 demonstrated that the DoD recognized the process can

be more efficient. The government must respond to global conflicts that change rapidly and adapt, which includes transport. A compact design will allow more means of transportation to be leveraged such as ground vehicles, fixed and rotary-wing aircraft, as well as rail. A lightweight product can reduce fuel costs and the number of personnel required for setup. Related to the need for adaptability is durability, since the system must be designed to operate in extreme environments including temperature and wind. In these conditions, the system cannot catastrophically fail and harm the personnel, so safety must be considered as well.

7.4 Economic Impact and Return on Investment

MITRE is a not for profit company that operates the DoD FFRDC under congressional mandated staffing delivery limits or STE. The company then allocates its staff to various projects to achieve the outcomes of the PMOs. The return on investment for this challenge project will be discussed in terms of benefits to the government PMO. These include a cost reduction with pursuing available COTS antenna masts and reduction in time for development, testing, fielding, and sustainment. The goal of the challenge project was to reduce antenna support structure material costs by 50% and time to deploy and setup the antenna by 50%.

The existing process for installing the antenna system at sites began with surveys of the area to see which structures can be leveraged, such as a roof. If no items were available, a platform was built which can be costly and increases time to fielding. After the site was prepared, the equipment was shipped and setup, which can be slowed by approval processes from the site civil engineering or other authorities. Trenches were also dug to place cables between the workstations and antenna. This antenna mast design will allow setup in hours instead of weeks and require less time and labor which reduces costs. The analytical results of the antenna mast design will allow the government to own the technical baseline for the antenna support structure and provide confidence in safely fielding a solution that follows this design.

The return on investment (ROI) was calculated assuming an outside contractor or consultant would perform this task instead of a MITRE employee. The ROI is the ratio of profit to investment, or the cost difference between an external contractor and an internal employee like the candidate.

$$ROI = \frac{Cost_{consultant} - Cost_{candidate}}{Cost_{candidate}} \quad (1)$$

As detailed in section 10.3, the cost for the challenge project performed by a MITRE employee for 460 hours is \$30,000. An engineering consultant can charge \$100 to \$200 per hour. Assuming a rate of \$150 per hour (including overhead) would be a total salary of \$66,000. Travel may also be required for a consultant which could increase costs by roughly \$10,000 for a total consultant cost of \$76,000. The resulting ROI is calculated to be 153%.

7.5 Market Challenges and Risks

The MITRE program received less funding for this task due to shifting priorities within the sponsor organization and MITRE. This led to a reduction in the duration and scope of the effort, but the candidate was able to develop a project that could meet those new goals. To mitigate, the project proposal and status updates were provided to the MITRE team to demonstrate the value proposition. Another challenge was the handling of

sensitive information and the long lead time required to review a published paper for public release, such as the final challenge project report and presentation. To mitigate, the candidate consistently communicated with the project Industry Sponsor Advocate (ISA) and MITRE's legal team to provide drafts in advance and complete the deliverables with sufficient time for review.

8 TECHNOLOGY DESCRIPTION

The challenge project supported a communication program with an airborne payload and ground entry node. The ground node provided a significant data path to more robust terrestrial networks, so it needed to be located near the mission. The previous setup required either sharing space with other platforms or constructing a building from scratch. A new requirement was to integrate the ground node into a rigid wall relocatable shelter to reduce time and costs. By integrating the system into a standard shelter configuration, lengthy processes to certify to security standards and plan logistics would also be streamlined. The program needed to demonstrate operational capability with a prototype. MITRE supported the sponsor with a multidisciplinary team of engineers including systems, networking, communications, reliability, and mechanical subject matter experts. Mechanical engineering expertise was required to verify the antenna support structure can meet the mission requirements. These sites could be in austere locations with extreme environments and the system must survive extreme wind loads.

8.1 Overview of the Technical Challenge

The previous ground communication platform setup was ad hoc at each site location and antennas needed to be attached to large towers. This could require new towers to be erected but at a minimum, extensive cable routing via trenches from the ground station facility. The new, rapidly deployable system must be setup and torn down quickly, so the previous antenna mount process was not viable. The technical challenge was to analyze existing antenna mount solutions and propose a design that will fulfill the new mission requirements. These included providing sufficient height to maximize the range of the antenna system and stabilization of the directional antenna. Too much deflection in the support structure could reduce the communication system quality or even prohibit any transmission from occurring. The parabolic antenna had a reflector or dish with a diameter of four feet that could create a significant drag force. The main concern from the sponsor was wind loading as these may be erected in a location without buildings or other protection surrounding it.

The antenna support structure or mast was assumed to be free-standing as a worst-case conservative measure. Installations could be next to the wall of a building or shelter with mounting brackets that offer additional supports, but this was not part of the scope of the current task. The free-standing mast products were analyzed with and without guy wires which support the top of the mast from lateral loads. A structural analysis of the guy wires would add additional complexity and non-linearity so as part of the current effort, only the effects of the wire tension on the mast was considered (i.e. a point load).

The design product was defined to have a more modular architecture. This could allow changes to portions of the design or replacements independent of other functional elements. The specific type of modularity that the mast design leverages is sectional-modular architecture. Interfaces between functional elements are of the same type and each can attach to another instead of a common bus. Examples of other items with sectional-modular architecture are office partitions and sectional sofas [1].

8.2 Product Specifications

The product specifications for the challenge project were:

- The subsystem shall withstand wind speeds up to 80 mph in operational configuration without structural yielding.
- The subsystem shall withstand wind speeds up to 120 mph in non-operational configuration without structural failure.
 - Same requirement for storage configuration, but will be in stowed position
- The subsystem shall withstand exposure to temperature range of -40 to 49 degrees Celsius.
- The subsystem shall meet lift criteria as defined in MIL-STD-1472 [8].
- The subsystem shall support payloads of up to 100 pounds at heights up to 30 feet without structural yielding.
- The subsystem setup and operational requirements shall be met in all coarse-grained and fine-grained soil conditions as defined in FM 5-472/NAVFAC MO 330/AFJMAN 32-1221(1), Materials Test, Appendix B, and Unified Soil Classification System [9].
- The subsystem shall meet motion tolerance of five degrees of translational and zero degrees of rotational deformation to allow optimal antenna performance.

The operational configuration was defined as the antenna reflector facing into the wind and the non-operational was in “bird bath” as shown in Figure 3. The storage configuration was the same as the non-operational one, except the mast is retracted and packaged for transport. Depending on the product, it could be in a transit case or duffel bag for example. The storage configuration was considered benign compared to the extended masts in operational and non-operational configurations, so it was not analyzed for this task.

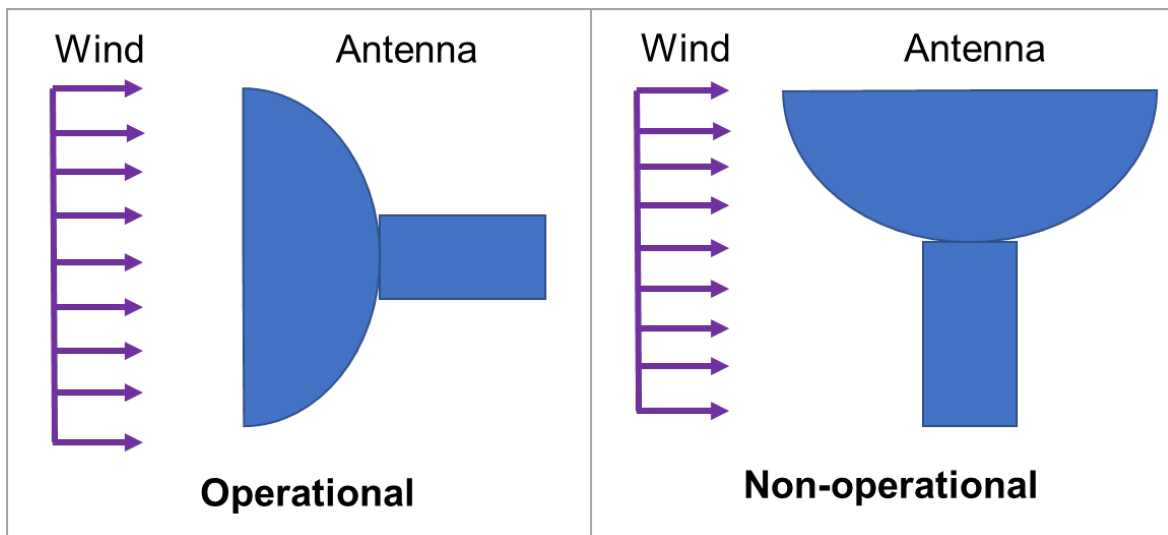


Figure 3 Antenna Operational and Non-operational Configurations

The DoD Design Criteria Standard for Human Engineering is MIL-STD-1472 which specifies weights limits for manual lifting. However, a tradeoff exists between light weight masts that can be carried and heavy weight ones that can support a larger payload at greater heights. The weight specification was considered but not the focus as it was less critical than structural stability. A materials testing standard for the military is FM 5-

472/NAVFAC MO 330/AFJMAN 32-1221(1) which defines the Unified Soil Classification System. "All coarse-grained and fine-grained soil conditions" covers gravel, sand, and silt but does not include peat. The motion tolerances were chosen to restrict the deformation to small translational deflections and no rotational, as the analysis originated in two dimensions. Small deflections were assumed to be less than 1/10 of the mast height (3 feet) or approximately five degrees of translational deformation [8, 9, 10].

8.3 Scientific Principles Applied

The antenna mast analyses required knowledge of mechanical engineering topics including stress and strain, deflection, fatigue, and wind loading. Further detail is provided in the corresponding subsections below.

8.3.1 Stress and Strain

Tensile or compressive (axial) stress is defined as:

$$\sigma = \frac{F}{A} \quad (2)$$

where F is the force applied perpendicular to the specimen cross-section and A is the cross-sectional area. Axial strain is defined as:

$$\epsilon = \frac{\Delta L}{L} \quad (3)$$

where ΔL is the change in length and L is the unstressed length. The relationship between axial stress and strain is shown in:

$$\sigma = E \epsilon \quad (4)$$

where E is the modulus of elasticity. The stress level at which plastic deformation begins is known as the yield strength and for many metals, it is seen as the departure from the linear stress-strain curve. The standard convention is to use a strain offset of 0.002 with the same slope as the elastic portion on the stress-strain curve to find the yield strength. The stress level at the maximum of the stress-strain curve is known as the ultimate tensile strength (UTS) [11, 12, 13].

Another form of normal stress is bending, as defined as:

$$\sigma_b = \frac{M y}{I_x} \quad (5)$$

where M is the moment around the neutral axis, I_x is moment of inertia of cross section with respect to the neutral axis and y is the perpendicular distance from the neutral axis [14].

Direct shear stress is defined as:

$$\tau = \frac{F}{A} \quad (6)$$

where F is the shear force applied parallel to the upper and lower faces and A is the area of each face. The relationship between shear stress and strain is shown in:

$$\tau = G \gamma \quad (7)$$

where G is the shear modulus and γ is the shear strain.

Torsional stress is defined as:

$$\tau = \frac{T r}{J} \quad (8)$$

where T is the applied torque, r is radius, and J is the polar moment of inertia for the cross section [11, 14].

8.3.2 Deflection

Table 3 shows elastic deflection equations that apply for the simple case of a straight bar of length L with uniform cross-section.

Table 3 Elastic Deflection Equations for Uniform, Straight Bar

	Deflection
Tension/Compression	$\delta = \frac{F L}{A E} \quad (9)$
Torsion (solid round bar)	$\theta = \frac{T L}{J G} \quad (10)$
Bending (angular deflection)	$\theta = \frac{M L}{E I} \quad (11)$
Bending (linear deflection)	$\delta = \frac{M L^2}{2 E I} \quad (12)$
Cantilever beam loaded at end	$\delta = \frac{F L^3}{3 E I} \quad (13)$

Further computations can be performed using Castigliano's method, which relates deflection to strain energy and applied load [14].

8.3.3 Fatigue

Fatigue failure occurs in structures subjected to dynamic and fluctuating stresses. Lower levels than static tensile and yield strength can cause fatigue failures when repeated stress or strain cycling occurs over a significant time period. Applied cyclical stresses can be axial (tension-compression), flexural (bending), or torsional (twisting). A reversed stress cycle has a sinusoidal time dependence with a symmetrical amplitude about a mean zero stress level, alternating from maximum tensile stress (σ_{max}) to minimum compressive stress (σ_{min}). A repeated stress cycle has asymmetrical maxima and minima relative to the zero stress level. Mean stress σ_m and stress amplitude σ_a can be calculated using the following equations:

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (14)$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (15)$$

Fatigue properties of materials can be determined from laboratory simulation tests. The specimen is subjected to stress cycling and data are plotted as stress S (σ_a) versus the logarithm of number N of cycles to failure. The higher magnitude of the stress, the

smaller number of cycles. For ferrous metals, the S-N curve reaches the endurance limit at a horizontal plateau [11].

For a component without fatigue test data and completely reversed fatigue loading, the fatigue strength can be estimated with:

$$S_n = S'_n C_L C_G C_S C_T C_R \quad (16)$$

where S'_n is the endurance limit (or stress at 10^8 cycles), C_L is the load factor, C_G is the size factor, C_S is the surface factor, C_T is the temperature factor, and C_R is the reliability factor. The fatigue strength values of 40-50% of the ultimate tensile strength is common practice for a first order approximation of the endurance limit for aluminum and steels, respectively [14, 15].

8.3.4 Wind Loading

The equation for drag force is:

$$F_D = \frac{1}{2} C_D \rho V_{wind}^2 A \quad (17)$$

where F_D is the drag force, C_D is the drag coefficient, ρ is the density of the fluid (such as air), V is the velocity, and A is the cross-sectional area. The air density is inversely proportional to temperature, so the largest drag force would occur at the lowest temperatures. The air density as a function of temperature is described as:

$$\rho = \frac{P}{R*T} \quad (18)$$

where P is the air pressure, R is the universal gas constant, and T is the air temperature. For a conservative analysis, an industry-standard of 1.6 was applied to the wind loads at the antenna and mast sections. Wind loads can also be applied as distributed loads or a force per unit length [16, 17].

8.3.5 Statics

Statics is a category of mechanics where objects are at rest and forces in equilibrium. A Free Body Diagram (FBD) is typically a sketch of an object of interest with notes on the supports, forces and moments. To draw a FBD: remove all external supports, draw relevant dimensions, add all external forces and moments, and apply a coordinate system (i.e. Cartesian with x, y and z). External supports include fixed and pinned. Fixed supports do not allow translation or rotation at that location, while pinned supports allow rotation [18].

An example of a FBD for an antenna and mast is shown in Figure 4 where the applied external forces are in red and the reaction forces at the base of the mast are in blue.

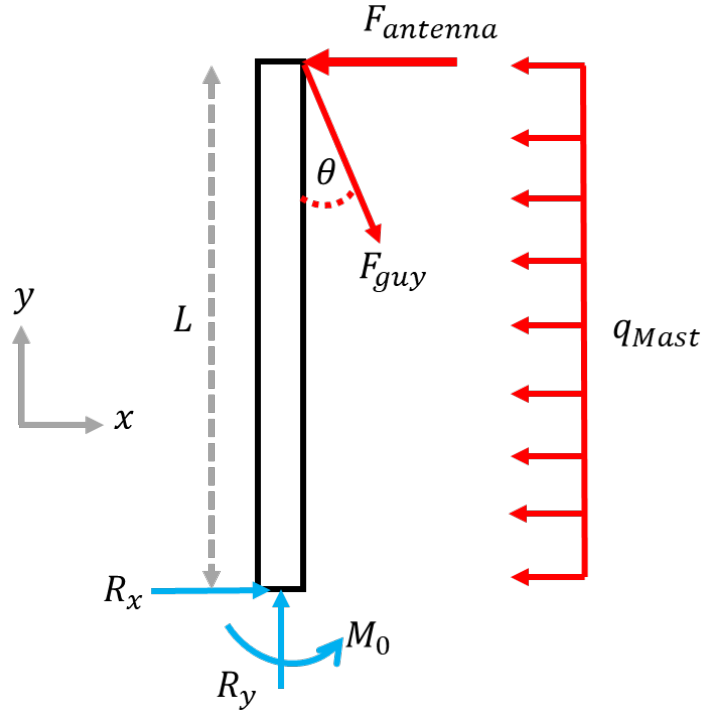


Figure 4 Free Body Diagram (FBD) of Antenna on Mast

Equations of static equilibrium in 3D are:

$$\sum F_x = \sum F_y = \sum F_z = 0 \quad (19)$$

$$\sum M_x = \sum M_y = \sum M_z = 0 \quad (20)$$

where the first states that the sum of the forces in any direction equals zero. The second equation states that the sum of the moments around at point in any direction equals zero. These series of equations can be solved for the unknown forces or moments in a FBD.

For the example shown in Figure 4, the following equations resulted:

$$\sum F_x = R_x + F_{guy} * \sin(\theta) - F_{antenna} - \int_0^L q_{Mast} dy = 0 \quad (21)$$

$$\sum F_y = R_y - F_{guy} * \cos(\theta) = 0 \quad (22)$$

$$\sum M_z = M_0 + L * (-F_{guy} * \sin(\theta) + F_{antenna}) + \int_0^L q_{Mast} y dy = 0 \quad (23)$$

where R_x , R_y , and M_0 have unknown values but can be solved with algebra and calculus.

$$R_x = -F_{guy} * \sin(\theta) + F_{antenna} + q_{Mast} * L \quad (24)$$

$$R_y = F_{guy} * \cos(\theta) \quad (25)$$

$$M_0 = L * (F_{guy} * \sin(\theta) - F_{antenna}) - \frac{q_{Mast} * L^2}{2} \quad (26)$$

Shear and bending moment diagrams are used to determine values for shear force and bending moment at a given point on an object like a beam. The process of generating these diagrams begins with a FBD and finding reaction forces and/or moments at the supports.

The FBD from Figure 4 is shown in a new orientation to find the internal forces and moments between in Figure 5.

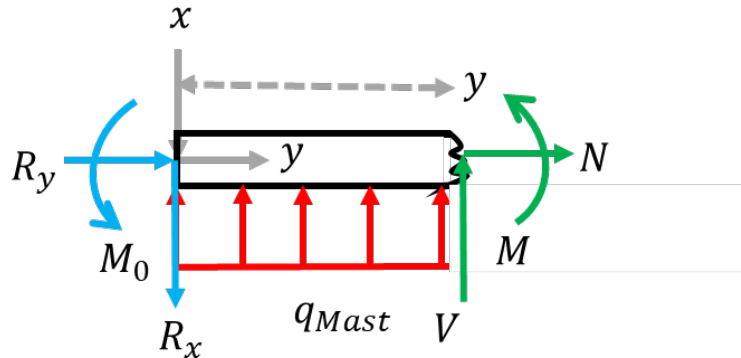


Figure 5 FBD with Internal Forces and Moments of Antenna on Mast

Using the equations of static equilibrium results in:

$$\sum F_x = R_x - \int_0^y q_{Mast} dy - V = 0 \quad (27)$$

$$\sum F_y = R_y + N = 0 \quad (28)$$

$$\sum M_z = M_0 + \int_0^y q_{Mast} y dy + V * y + M = 0 \quad (29)$$

where V , N , and M had unknown values in terms of y distance from the base of the mast [18].

Using algebra results in:

$$V = R_x - q_{Mast} * y \quad (30)$$

$$N = -R_y \quad (31)$$

$$M = -M_0 - \frac{q_{Mast} * y^2}{2} - V * y \quad (32)$$

2D diagrams can then be generated for the normal force, shear force, and bending moment in terms of the distance “ y ”.

The angular deflection θ and translational deflection δ can be calculated from the moment M with the following equations:

$$\theta = \frac{1}{EI} \int M dy \quad (33)$$

$$\delta = \int \theta dy \quad (34)$$

which utilize the modulus of elasticity E and the moment of inertia I for the material.

9 TECHNOLOGY APPROACH AND RESULTS

9.1 Development Approach and Methods

The direction for the project was to use COTS antenna mast products. These models are cheaper than custom contractor designs, and quick to acquire and replace. However, COTS products are often not rugged enough for military applications so substantial analytical and/or test methods must be used to mitigate risk of failure in the field. The focus of the technical part of this challenge project was on the analytical methods to verify the antenna support subsystem design and structural integrity of candidate masts in various environmental conditions including wind. The following scientific principles were considered via closed form solutions and finite element analyses: drag force, bending stress, deflection, and fatigue. These are further detailed in section 8.3.

The leading hypothesis was that a design utilizing a COTS antenna mast existed that could meet the system requirements. The project identified structural risks of the antenna mast and proposed methods to secure the structure further, such as guy lines. These wires attach to the mast and secure to the ground via anchors. The risk of pull-out from the soil was not included in the scope of this effort [19, 20].

A technology review was performed to research antenna mast manufacturers. Information was gathered on the screened list of products including material properties, dimensions, weight, and cost. Potential vendors of antenna masts that could be leveraged in the designs included The Will-Burt Company, Clark Masts, BlueSky Mast, and South Midlands Communications Limited. A list was generated of masts that could support the antenna payload weight at heights of at least thirty feet, totaling 250 potential options within the four vendors. The options were refined to products that specified the number of mast sections, mast weight, section tube diameter at the base and top of the mast. Based on the availability of sufficient data to support a structural analysis, this resulting list of 55 masts was limited to the Will-Burt pneumatic Ultra Heavy-Duty Locking (UHDL) family of telescopic mast models [21].

The mast itself was made of aluminum but further details on the specific type was not available so the assumption was 6061-T6. Will-Burt specified guys for heavy-duty masts made with a Kevlar core and polyester outer braid with a diameter of ¼ inch. The Krypton-K double braid with Kevlar core sold by Pelican Rope listed a tensile strength of 3500 pounds. An industry recommended tension in guy wires is 10% of the ultimate tensile strength or 350 pounds for this case. Other relevant material properties for the analyses are shown in Table 4 [21, 22, 23, 24].

Table 4 Material Properties for Aluminum 6061-T6 Mast [24]

	Aluminum 6061-T6
Density	0.0975 lb/in ³
Young's Modulus	100,000 ksi
Poisson's Ratio	0.33
Yield Strength	40,000 psi
Ultimate Tensile Strength	45,000 psi

As discussed in section 8.3.3, an approximation of the endurance limit for aluminum is 40% of the UTS which would result in 18,000 psi. Using the equation for fatigue strength and the values in Table 4 resulted in:

$$S_n = S'_n C_L C_G C_S C_T C_R = 18,000 \text{ psi} * 1.0 * 0.9 * 1.0 * 1.0 * 0.753 = 12,200 \text{ psi (35)}$$

Calculations were performed using the scientific methods described in section 8.3 for the selected masts. Matlab was chosen to implement the closed form solutions due to its availability at MITRE and the candidate's existing knowledge of the program. Initial efforts for the project began with one mast section and point loads applied to it before adding distributed loads, additional sections, and guy wire. A free-body diagram of the final layout on a multi-sectioned mast with guy wires is shown in Figure 6. The normal force was ignored as it was negligible compared to the impact of the other loads on the mast.

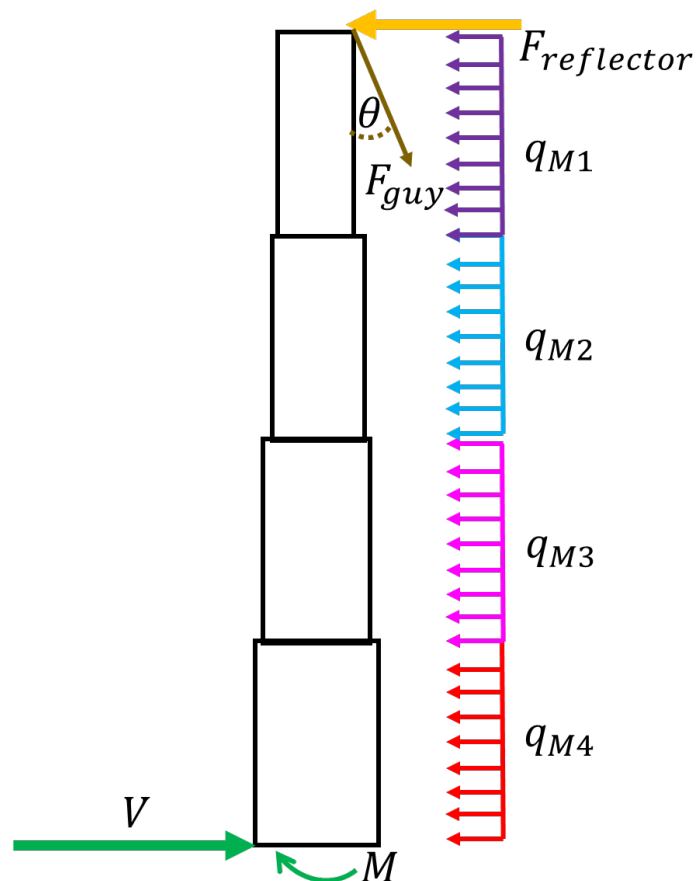


Figure 6 Free-Body Diagram of Antenna and Mast Subsystem

The cantilever beam model was written into a Matlab script by the candidate to allow quick parameter adjustments and the creation of graphical plots such as the shear and bending moment diagrams. Parameters are initialized with inputs for the mast including extended height, number of sections, material properties, drag coefficients, section diameters, air density, and wind speed. Setup calculations were performed to get the wind force from the antenna for either the operational or non-operational configuration, the wind distributed loads on the mast itself, and the moments of inertia. Each mast section had a different diameter, so the distributed load and moment of inertia varied

depending on the location. The guy wire was implemented as a point load at the top of the antenna mast, opposing the direction of the wind.

As discussed in 8.3.5, the reaction forces and moments were then found at the base, shown in green in Figure 6. Afterwards the internal forces and moments were calculated, starting at the base tube and working up towards the top one. From the shear and moment, the angular and translational deformations were also calculated. Using the proceeding calculations, the bending stress was found which was compared to the yield stress and fatigue stress to get factors of safety. The last part of the Matlab script plots the shear and moment diagrams as well as the deflection of the mast in terms of the mast length. Figure 7 shows the shear force, bending moment, and deflection diagrams for the operational configuration with winds at 80 MPH. Iterations were run at various wind speeds with both antenna configurations and with or without the use of guy wires.

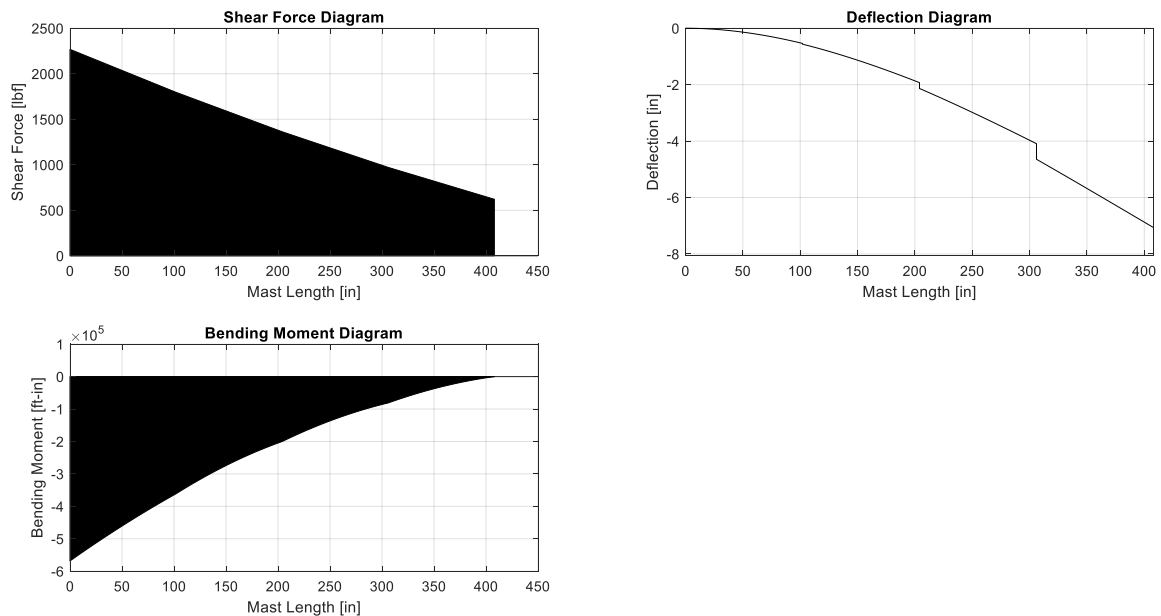


Figure 7 Shear Force, Bending Moment, and Deflection Diagrams for Operational Configuration at 80 MPH

9.2 Testing, Verification and Validation Implementation

To verify the results of the efforts detailed in section 9.1, finite element analyses were performed using ANSYS tools. The validation strategy was to obtain experimental data from the mast manufacturer and compare to the analytical results.

9.2.1 Finite Element Analysis

Finite element analysis is a numerical approximation technique that divides a structure into discrete regions (finite elements). The response is a set of functions that represent the displacements or stresses in that region.

Typical steps for linear static finite element method of stress analysis are:

1. Divide (discretize) the part (continuum) into discrete elements (mesh)
2. Define the properties of each element (material properties)
3. Assemble the element stiffness matrices
 - a. Stiffness coefficient relates nodal force to displacement
 - b. Structural stiffness matrix equation: $[K]\{\delta\} = \{F\}$, where $\{\delta\}$ is the displacement vector and $\{F\}$ is the force vector
4. Apply known external loads at joints (or “nodes”)
5. Specify part support conditions (boundary conditions)
6. Solve the system of simultaneous linear algebraic equations for $\{\delta\}$
7. Calculate the strain, $\varepsilon = \frac{\delta}{L}$
8. Calculate stresses in each element, $\sigma = E * \varepsilon$

Steps 1, 2, 4, 5, 7 and 8 usually require input from the user to the program [14, 25, 26].

9.2.2 Antenna Subsystem FEA

Finite element analyses were performed for the antenna support subsystem to evaluate static stresses and deformations, and fatigue. During the execution of the project, airflow, dynamic stresses and deformations, and buckling were not investigated. Due to schedule and budget constraints, the candidate thought best to focus on statics at this time. ANSYS simulation software was available for this project and included tools that perform these analyses. SolidWorks was used to create the Computer Aided Design (CAD) and import them into ANSYS. This process was efficient as the candidate had access and experience using both tools.

Initially one mast section was modeled and compared to Matlab results with the same parameters to refine the ANSYS simulation. The single hollow aluminum tube CAD was expanded to four sections with four aluminum collars that sit at the interface between tube sections. The collars allow the sections to twist and lock when extended and additionally are the location where the guy wires attach to the mast. The final CAD that represents the Will-Burt UHDL 11.3-59 mast model extended for the antenna to reach 30 feet is shown in Figure 8.

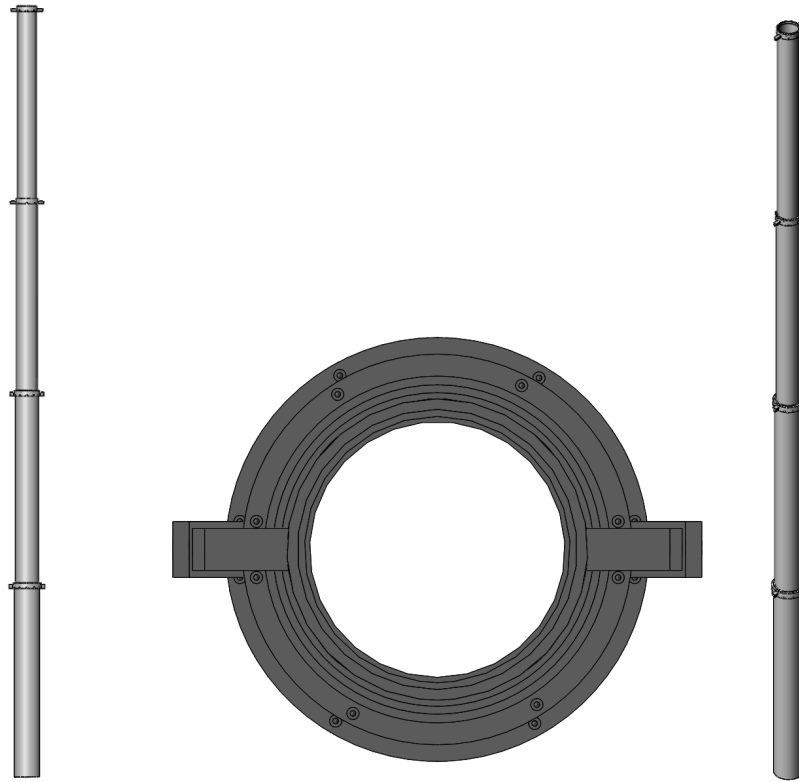
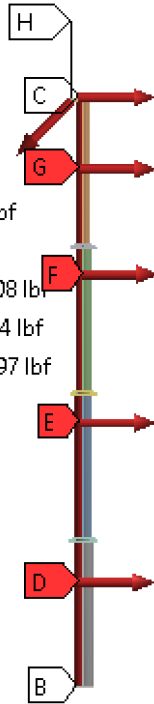


Figure 8 Side, Top and Isometric Views of Will-Burt UHDL 11.3-59 Mast CAD

Material properties discussed in section 9.1 were also applied to the ANSYS model. The boundary conditions and forces resulting from the Matlab model were applied within static structural models of the antenna subsystem to look at stresses and deflections of the antenna mast. The CAD in Figure 8 was modified to split the mast faces for application of the loads as wind would be coming from one direction and only affecting that side. Simulations were run for operational and non-operational configurations with and without guy wires at wind speeds from 80 to 120 MPH. To keep the problem linear and efficient to solve, only bonded or rigid connections were utilized between the mast sections. The setup in ANSYS with the fixed support at the mast base and wind loads for both configurations at 80 MPH is shown in Figure 9.

Operational Configuration with Guy Wire at 80 MPH

- B** Fixed Support
- C** Antenna Wind Load: 620.87 lbf
- D** Base Wind Load: 472.45 lbf
- E** 2nd Section Wind Load: 433.08 lbf
- F** 3rd Section Wind Load: 391.54 lbf
- G** Top Section Wind Load: 349.97 lbf
- H** Top Section Guy: 350.02 lbf



Non-Operational Configuration with Guy Wire at 80 MPH

- A** Fixed Support
- B** Antenna Wind Load: 185.28 lbf
- C** Base Wind Load: 472.45 lbf
- D** 2nd Section Wind Load: 433.08 lbf
- E** 3rd Section Wind Load: 391.54 lbf
- F** Top Section Wind Load: 349.97 lbf
- G** Top Section Guy: 350.02 lbf

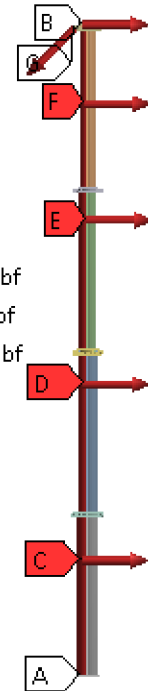


Figure 9 ANSYS Models for Operational and Non-Operational Antenna Configurations with Guy Wires at 80 MPH

The mesh was refined to show convergence and no dependence on the size of the finite elements, which provided confidence in the fidelity of the models. The coarse mesh size of 4 inches was reduced to 1 inch and the deformation was plotted for all four scenarios at 120 MPH as shown in Figure 10 in addition to the 3D mesh on one mast section.

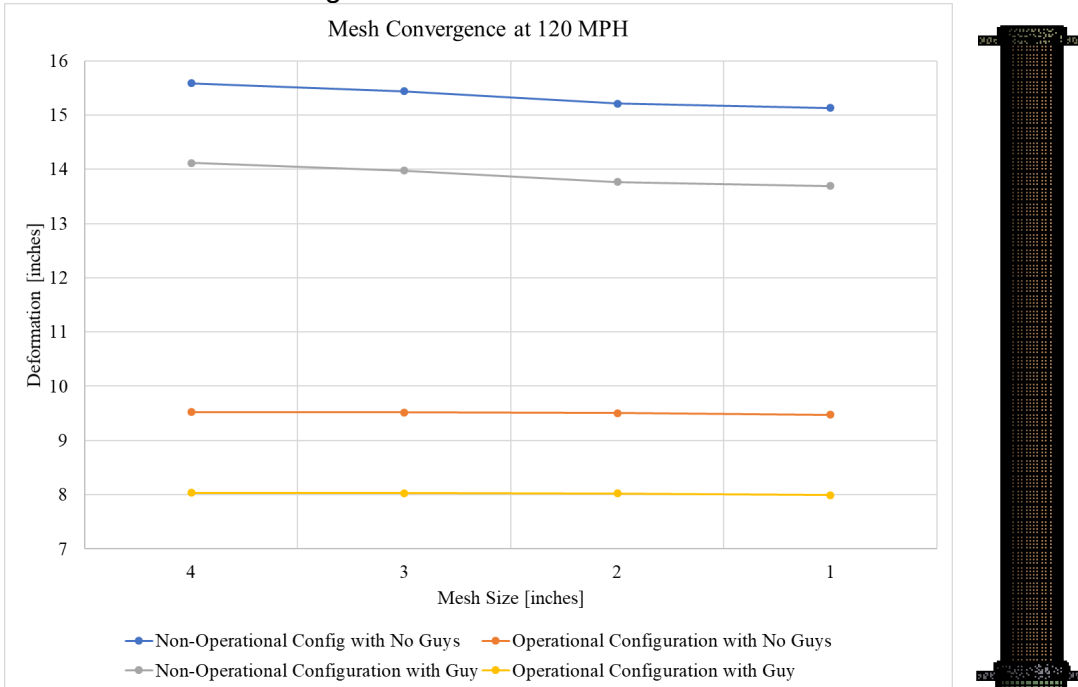


Figure 10 Convergence of ANSYS Model Mesh in 2D Plot and 3D Rendering

9.2.3 Verification Implementation

The procedure for verifying the results of the analytical effort met the system requirements is shown in Table 5.

Table 5 Verification Plan for Antenna Subsystem Requirements

Requirement	Verification
Withstand wind speeds up to 80 mph without structural yielding.	Compare results to yield strength of materials.
Withstand wind speeds up to 120 mph without structural failure.	Compare results to fatigue strength of materials.
Withstand exposure to temperature from -40 to 49 degrees Celsius.	Analyze models at ambient temperature and both temperature extremes.
Meet lift criteria defined in MIL-STD-1472 or provide method for assisting movement.	Compare weights to limits within standard.
Support payloads up to 100 pounds at heights up to 30 feet without structural yielding.	Analyze models in these conditions and compare results to yield strength of materials.
Meet setup and operational requirements all in soil conditions defined in standard.	Analyze subsystem for soil conditions defined in standard, including anchors for guy wires.
Meet motion tolerance of five degrees of translational and zero degrees of rotational deformation.	Compare results to deformation limits.

During execution of the project, the focus was refined to the requirements on wind speed, support of 100-pound payload, and the motion tolerances. The requirements on manual lifting and soil conditions were considered but not extensively investigated within the project.

9.2.4 Validation Implementation

The validation strategy was to contact the antenna mast vendors to request experimental data from previous tests. The wind loading requirements originated from a commonly used military standard for environmental qualification, MIL-STD-810 [27]. Although the payload size and weight may differ, there could be data documenting the results of testing to those environmental requirements or requirements in a similar test standard. The FEA results and closed form solutions could then be performed for the applicable scenarios to validate the model with the goal to demonstrate agreement within 5% margin. The shelter prototype effort schedule shifted so that any new prototype and test activities of the antenna system were out of scope for the challenge project validation.

Unfortunately, the candidate was unable to receive sufficient information from vendors to perform the validation strategy at this time.

9.3 Results and Technical Conclusion

Results were obtained from the Matlab and ANSYS models of the Will-Burt UHDL 11.3-59 mast at speeds from 80 to 120 MPH. The four scenarios modeled were the antenna configuration as operational or non-operational and the application or removal of guy

wires. To compare results from both software tools, the yield factor of safety, fatigue factor of safety, and deflection for the operational configuration with no guys at 80 MPH are compared in Table 6.

Table 6 Analytical Results for Operational Configuration with No Guys at 80 MPH

	<i>Operational Configuration No Guys at 80 MPH</i>		
	Matlab	ANSYS	% Diff
Yield Stress Factor of Safety	5.00	4.77	4.5
Fatigue Stress Factor of Safety	1.52	1.41	7.5
Deflection [inches]	7.07	6.87	2.7

The percent difference between the Matlab and ANSYS results is less than ten percent which was deemed acceptable for the project to progress and focus on the ANSYS results with confidence. The FEA results for the operational and non-operational antenna configurations from 80 to 120 MPH are shown in Table 7 with no guy wires and Table 8 with guy wires. The cells with red text exceeded the specification.

Table 7 ANSYS Results for Both Antenna Configurations with No Guys

Wind Speed [MPH]	<i>Operational Configuration No Guys</i>			<i>Non-Operational Configuration No Guys</i>		
	Yield Stress Factor of Safety	Fatigue Stress Factor of Safety	Deflection [inches]	Yield Stress Factor of Safety	Fatigue Stress Factor of Safety	Deflection [inches]
80	3.52	1.04	6.87	5.45	1.61	4.23
90	2.80	0.83	8.70	4.34	1.28	5.36
100	2.28	0.67	10.7	3.54	1.04	6.61
110	1.87	0.55	13.0	2.94	0.87	8.00
120	1.34	0.40	15.1	2.15	0.63	9.48

Table 8 ANSYS Results for Both Antenna Configurations with Guys

Wind Speed [MPH]	<i>Operational Configuration with Guys</i>			<i>Non-Operational Configuration with Guys</i>		
	Yield Stress Factor of Safety	Fatigue Stress Factor of Safety	Deflection [inches]	Yield Stress Factor of Safety	Fatigue Stress Factor of Safety	Deflection [inches]
80	4.42	1.31	5.37	8.11	2.40	2.72
90	3.34	0.99	7.20	5.85	1.73	3.85
100	2.62	0.77	9.25	4.47	1.32	5.11
110	2.11	0.62	11.5	3.55	1.05	6.51
120	1.47	0.43	13.7	2.50	0.74	8.00

Yielding and excessive deformation were evaluated to be a low risk for all four scenarios, but fatigue could cause issues potentially. For the operational configuration, any wind speed above 80 MPH has a risk of fatigue failure. For the non-operational configuration, with no guys above 100 MPH could be an issue and with guys above 110 MPH for fatigue failure. These conclusions led to the following recommendations to the PMO in regard to operations and sustainment:

- If the wind speed is greater than 80 MPH
 - Utilize guy wires. To be conservative, any speed over this threshold should use guys.
- If the wind speed is between 80 and 110 MPH
 - Use the non-operational configuration.
 - This should not affect the current concept of operations by restricting to one antenna configuration at these speeds.
- If the wind speed is greater than 110 MPH
 - Lower the mast as there could be a potential risk of fatigue failure.
 - These speeds should not be seen often, and this procedure could be added to technical orders for future deployments.

All results were compiled in a formal MITRE document for delivery to the MITRE team and the government PMO in May 2019.

9.4 Scientific and Technical Challenges

One technical challenge or risk was insufficient information provided for the current antenna system, including performance specifications and material properties. The project assumed that the antenna mast was designed to support the current antenna in operations but the level of data available was minimal. The candidate pursued this task and investigated the need for discussions with the antenna manufacturers to gather the information for analyses. In order to continue the project and meet major expectations, assumptions were made for the material properties and antenna payload. Unfortunately, this issue with insufficient communication with vendors led to a lack of experimental data in order to validate the models. A future recommendation is to get better contacts with vendors and perform testing to allow the validation to be implemented. Another risk assessed early on was the availability of ANSYS FEA licenses. These tools are shared among 30 mechanical engineers and can be occupied depending on projects needs at the time. Due to the time of year there were not issues with software licenses, as the summer can be busier with interns.

A major challenge was achieving everything set out in the challenge project proposal after the funding and timeline was shortened for this task. Specifications were loosened including the manual lifting, temperature, and soil conditions. The scope of the subsystem was refined to be just the mast instead of the guy wires themselves, the anchors, and additional lateral support from a shelter wall. The original analytical plan was to perform FEA with Computational Fluid Dynamics (CFD), dynamics, and buckling as well as statics. All of these tasks would be beneficial and are recommended for future work but the work delivered with the project still delivered impact to the sponsor.

10 PROJECT PLAN

10.1 Statement of Work

The purpose of this project was to evaluate candidate antenna masts for application in a rapidly deployable military communication system. To minimize costs and lead time to procure the antenna support system, only COTS antenna masts were considered for the project. A goal of the project was to reduce antenna system setup time by at least 50% as the current system requires site surveys, construction, equipment shipment, and installation before operation. Another goal was system adaptability to allow successful application at range of environmental conditions worldwide. The project used closed-form solutions and finite element analytical methods to assess antenna masts and recommended a design that will meet the system requirements.

10.2 Schedule

10.2.1 Work Breakdown Structure

The Work Breakdown Structure (WBS) for the challenge project is shown in Table 9.

Table 9 Challenge Project Work Breakdown Structure (WBS)

WBS	Task			WBS Predecessor	Predicted Completion	Actual Completion
1	Concept					
1.1		Leadership				
1.1.1			Spider Chart		9/11	9/11
1.2		Project Plan			9/14	9/15
1.3		Mission Statement		1.2	10/19	10/19
2	Market					
2.1		Customer Needs				
2.1.1			Analyze External Market		10/5	10/4
2.1.2			Analyze Internal Market	2.1.1	11/2	11/2
3	Design					
3.1		Product Specifications				
3.1.1			Metrics		10/26	10/25
3.1.2			Competitive Benchmarking	3.1.1	11/9	11/9
3.1.3			Ideal/Target Values	3.1.2	11/16	11/16
3.2		Concept Generation		3.1		
3.2.1			Research Vendors		11/23	11/30

3.2.2			Gather Product Data	3.2.1	12/7	12/21
3.3		Concept Selection		3.2		
3.3.1			Screening		12/11	1/4
3.3.2			Scoring	3.3.1	12/14	1/11
4	Analysis			3		
4.1		Closed Form				
4.1.1			Static Calculations		12/28	2/15
4.1.2			Buckling Calcs	4.1.1	1/11	N/A
4.1.3			Dynamic Calcs	4.1.2	1/25	3/1
4.2		FEA		4.1		
4.2.1			CFD Analyses		2/10	N/A
4.2.2			Static Analyses	4.2.1	2/24	3/29
4.2.3			Dynamic Analyses	4.2.2	3/10	N/A
5	Document					
5.1		Phase Approvals				
5.1.1			Phase 1		10/12	10/12
5.1.2			Phase 2	5.1.1	2/1	1/23
5.1.3			Phase 3	5.1.2	4/15	4/5
5.1.4			Phase 4	5.1.3	6/7	6/7
5.1.5			Phase 5	5.1.4	8/7	8/7
5.2		Proposal				
5.2.1			Memo to FA		11/19	11/18
5.2.2			Complete and Send to ISA		11/19	11/19
5.2.3			Submit for MITRE Review	5.2.2	11/26	11/28
5.2.4			Submit Final	5.2.3	12/10	12/11
5.3		Statement of Impact				
5.3.1			First Draft		3/15	3/29
5.3.2			Second Draft	5.3.1	4/19	5/09
5.3.3			Submit Final	5.3.2	6/13	6/13
5.4		Project Report				
5.4.1			Section 8 Draft		3/20	3/20
5.4.2			Complete and Send Draft to ISA	5.4.1	4/5	N/A
5.4.3			Submit Draft for MITRE Review	5.4.2	4/19	5/20
5.4.4			Submit Draft to GEL	5.4.3	5/23	5/24

5.4.5			Submit Final for MITRE Review	5.4.4	5/31	6/3
5.4.6			Submit Final to GEL	5.4.5	7/2	7/1
5.5		Project Presentation				
5.5.1			Presentation 1		10/23	10/23
5.5.2			Presentation 2		11/27	11/27
5.5.3			Presentation 3		3/15	3/26
5.5.4			Midterm Deep Dive		4/1	3/16
5.5.5			Presentation 4		N/A	5/14
5.5.6			Presentation 5		N/A	6/11
5.5.7			CP Defense		7/8	7/10

The concept task involved a leadership self-assessment using the spider chart shown in section 11.1, the project plan, and mission statement. These sub-tasks were all delivered successfully as part of Phase 1 in October. Customer needs were assessed during the market task for both external and internal markets. This was accomplished through research and discussions with the MITRE and PMO teams. Metrics, competitive benchmarking, and the selection of ideal and target values occurred as part of product specifications within the design task. Design concepts were then generated by researching vendors and gathering product data, which took more time than originally anticipated. The final part of the design task was to select a concept through screening and scoring techniques [1].

After the submittal of the challenge project proposal, the analysis task was refined to remove the buckling closed form calculations, CFD and dynamic finite element analyses. The telescoping mast design was evaluated to be low risk for buckling and higher risk of failure due to structural yielding or fatigue. Due to minimal details available to the candidate on the antenna design itself, the CFD analyses were skipped. The dynamic analyses were not achievable within the necessary timeframe and the team assessed that the static FEA was sufficient with the closed form calculations to give a conservative design recommendation.

10.2.2 Gantt Chart

The Gantt chart for the challenge project is shown in Figure 11. The blue bars represent the actual progress and the grey bars for the predicted process.

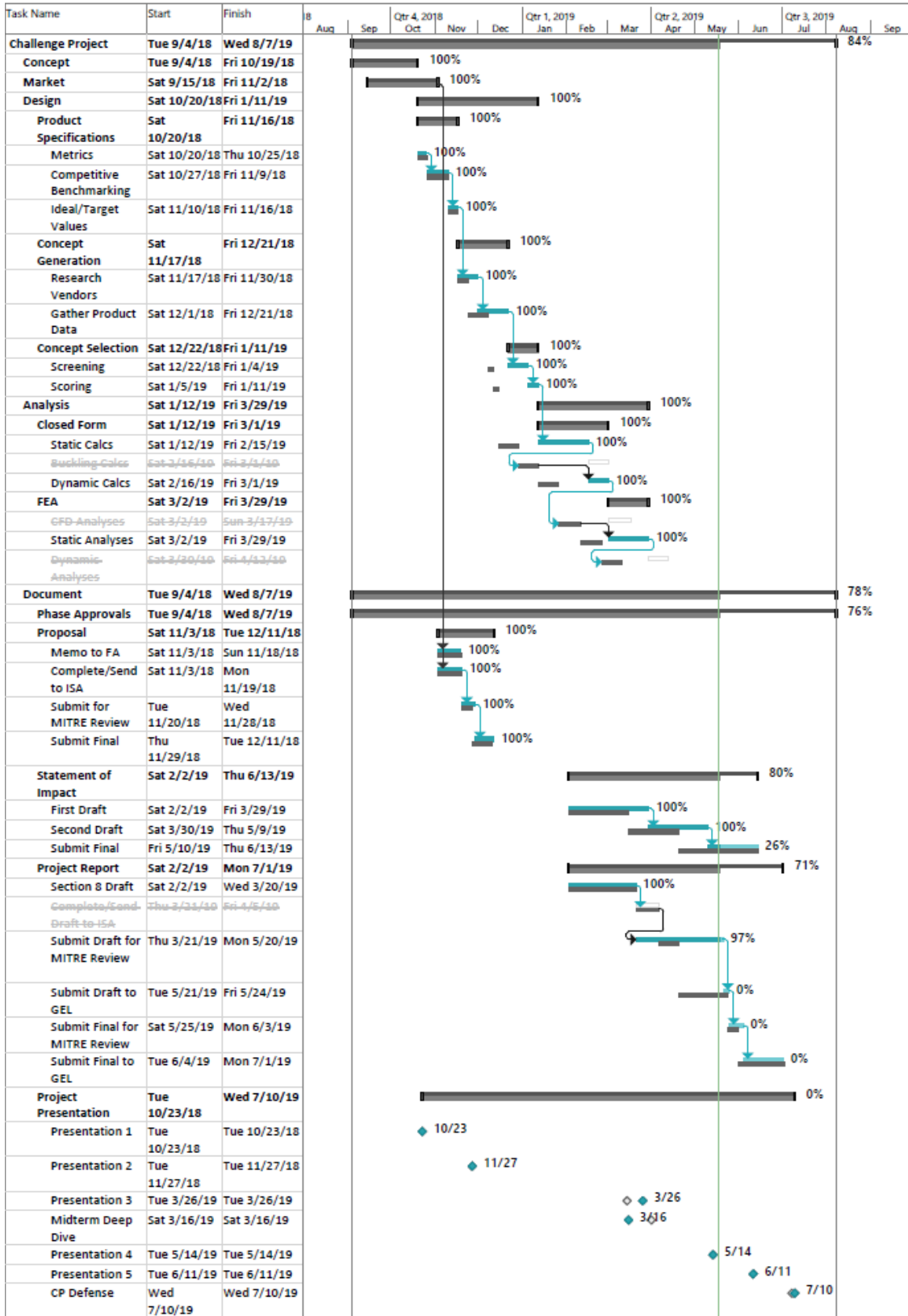


Figure 11 Challenge Project Gantt Chart

10.2.3 Project Planning Assessment

Items that changed from the planning through execution of the challenge project included the scope of the analyses and the availability of data. During closed form calculations and especially for modeling tasks, issues can occur that push the schedule to the right such as syntax problems within Matlab and meshing within ANSYS. An important lesson learned was that modeling and simulation take longer than expected and a larger time buffer should be added to those activities. The lack of data availability was identified as a potential risk during the planning process, and it was encountered within the antenna details as well as from the mast vendors. In order to progress the project, the scope was adjusted to skip the CFD finite element analyses. Without realistic data on the structure, results could not be generated with confidence. Through discussions with her team, the candidate assessed the removal of this task as low risk with conservative static and dynamic models as sufficient. At the conclusion of the challenge project, the candidate achieved most of her original scope with reasonable tailoring and she successfully stayed within budget and schedule restraints.

10.3 Budget and Costs Assessment

The materials cost was limited to software licenses, but these were included in capital costs for the mechanical engineering department at MITRE, otherwise costs would have been an additional \$50,000. The cost of the antenna mast was a factor in mast design selection for the project but was covered by separate funding. The funding allotted for the candidate's technical work in the project was 0.5 STE from November 2018 through March 2019. Loaded salary rates (including benefits and overhead) were estimated as be two to three times the actual salary of the team member. For product development projects, average personnel costs range from \$2000 to \$5000 per week [1]. Personnel cost was estimated using the candidate's staffing plan for 22 weeks and the assumed loaded salary rate of \$2500 per week to get \$27,500. To allow margin for uncertainties like software issues or lack of data, the plan was increased by 9% to result in a final budget of \$30,000. As the project concluded the analyses in March 2019, the schedule was maintained, and the final costs were \$27,500.

10.4 Risk Plan and Mitigation Assessment

The risk plan for the challenge project is shown in Table 10. No additional areas of risk were added during the execution of the project. As originally assessed, insufficient data was encountered so the candidate contacted manufacturers directly as a mitigation technique. Due to the schedule restraints, the project needed to utilize the available data but an area for future work would be to contact additional vendors and leverage the government contacts within the team.

Table 10 Challenge Project Risk Plan

Risk	Risk Level	Actions to Minimize Risk
Insufficient data provided for antenna system	Moderate	Reach out directly to manufacturers and work with government contacts.
Project funding is cut and/or delayed	Low	Provide plan and status updates to MITRE and PMO teams to demonstrate value proposition.

Risk	Risk Level	Actions to Minimize Risk
Delays with MITRE public release system	Low	Communicate with ISA and MITRE legal and budget time in WBS to account for reviews.
Task is given to private contractor	Low	Provide plan and status updates to MITRE and PMO teams to demonstrate sufficient expertise exists without contractor assistance.
Low availability of software licenses	Low	Negotiate with engineers and schedule time

11 LEADERSHIP

11.1 Leadership Capabilities Assessment

The leadership capabilities for the Gordon Institute of Engineering Leadership are shown in Figure 12 [28]. A self-assessment of the candidate was performed using the leadership spider chart at the initiation of the fall semester to identify skills that need improvement. Three were selected to focus on within the challenge project including initiative, communication and advocacy, and decision-making.

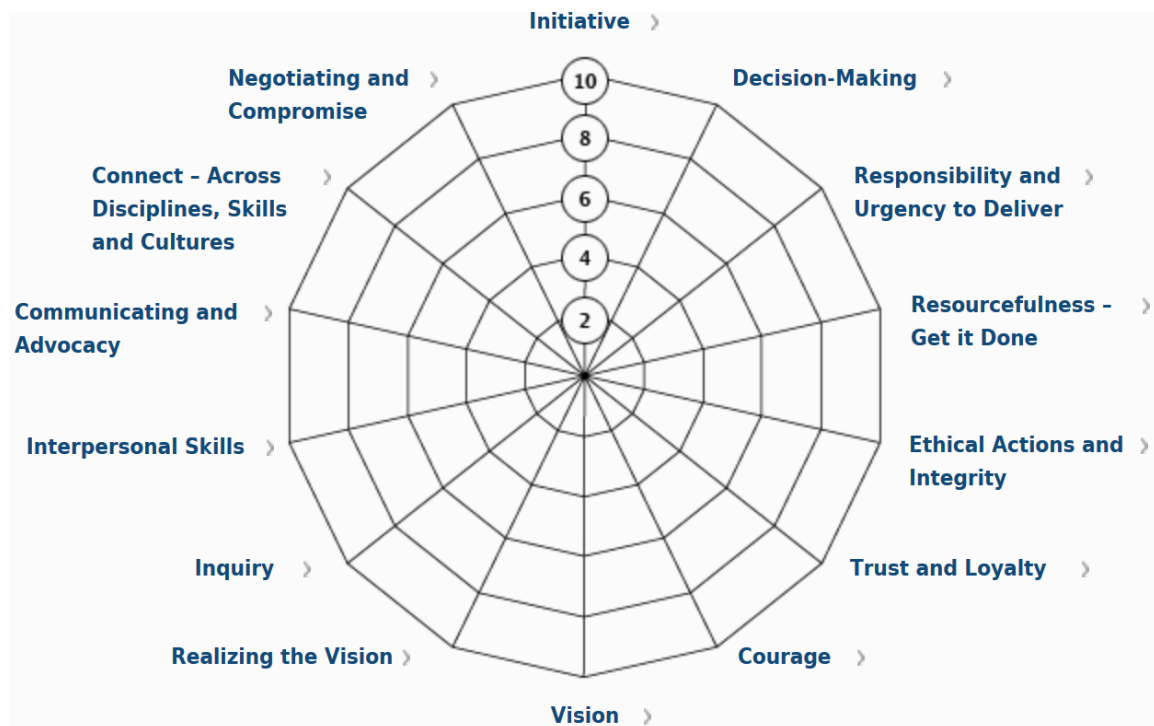


Figure 12 Gordon Institute Leadership Capabilities [28]

Initiative involves risk assessment and the ambition to create a vision. The candidate needed to evaluate antenna masts to various extreme environmental conditions and understand the tradeoffs between the customer needs and system requirements. The candidate needed to develop a path forward after investigation into the available products and recommend design modifications that may be out of scope for this effort but could be pursued later.

During the execution of the challenge project, the candidate was told that she had the opportunity to mentor an undergraduate intern from June to August 2019. She utilized initiative to scope a project for the intern that will leverage the student's skills in CAD to deliver a design product that will demonstrate the viability of another transportation option for the program. The intern will also be contributing to another effort, so the candidate met with members from that team to lay out expectations for the summer together.

Communicating and advocacy involves clear explanation of the approach to those with differing backgrounds and assessment of the extent to which you are understood.

The candidate needed to explain the value of her analytical results and assess how well it is understood by the stakeholders. Many of the team members on the project in MITRE and the PMO do not have a mechanical engineering background and the information may need to be tailored depending on the audience. The candidate also needed to advocate for more time on the task as the scope changed.

In February 2019, the candidate participated in a day-long meeting at MITRE where she presented information on environmental and transportation challenges for a different program. The room consisted of approximately fifty attendees, almost all with no mechanical engineering background. She needed to tailor the content to the audience so that the important information was accessible to all.

Decision-making involves choosing the path forward with the information at hand. The candidate needed to consider risks and uncertainties in her decisions and provide alternative courses of action. The candidate ultimately chose a product to recommend to the PMO for future procurement and fielding, but many decisions were made prior to that one.

The candidate volunteered to lead a program at MITRE where local high school seniors pursuing engineering in college come to the Bedford campus once a week. She worked with another mechanical engineer to develop a schedule of different engineers the students could shadow and design a project through which they can demonstrate what they learned. One important lesson learned from the program was the Socratic method where questions are asked to think more critically. Feedback from the students at the end of the program was positive especially given freedom to make decisions and create their own designs.

11.2 Team Staffing and Organization

The team organization for the challenge project is shown in Figure 13. It consisted of members from MITRE, the Gordon Engineering Leadership program, Northeastern faculty, and the government. The candidate worked directly with the ISA, Gordon Mentor (GM), and Faculty Advisor (FA) to verify that the project met curriculum requirements for market value, technical depth, and leadership. The ISA, Justin Ruddock, has extensive experience in mechanical engineering and contacts to the PMO. The GM, Jane Eisenhower, is a Gordon Fellow and a Raytheon employee with knowledge of the government market. The FA, Professor Ibrahim Zeid, is an expert in CAD and mechanics and has experience working as an advisor for previous Gordon candidates. The candidate reported to mechanical engineering management and the communication platform team within MITRE to provide progress updates and leverage software tools. Through the MITRE project team, the candidate had contact with the PMO to demonstrate the benefits proposition of this analytical effort.

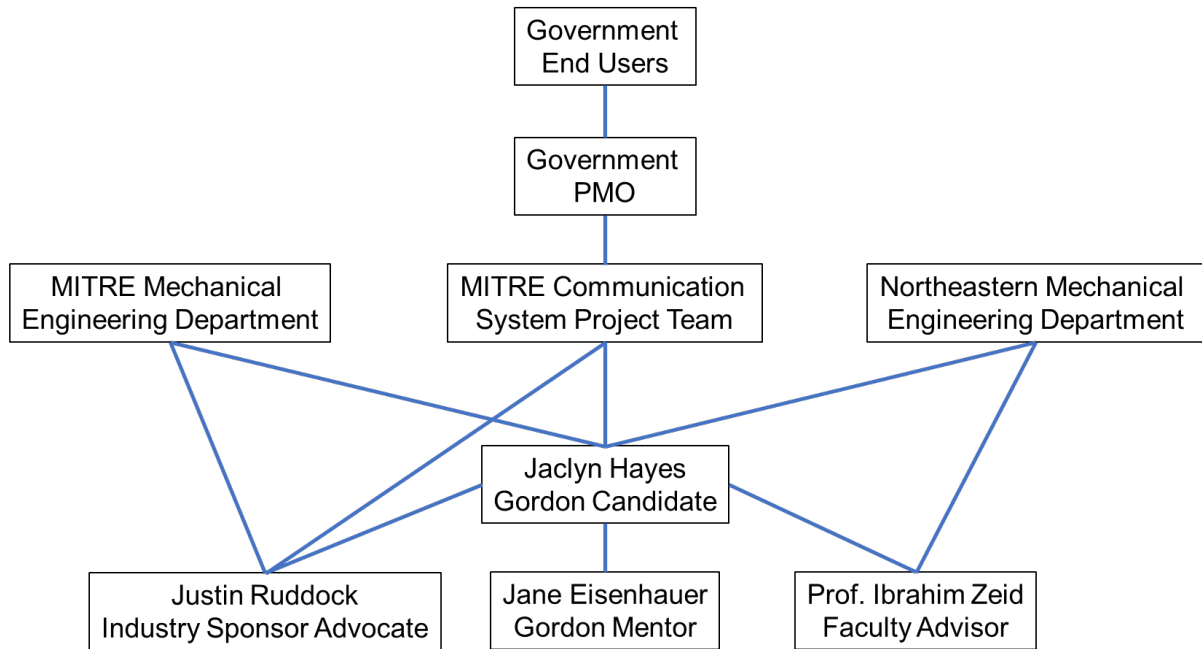


Figure 13 Challenge Project Team Organization Chart

11.2.1 Project Team

Gordon Candidate: Jaclyn Hayes
 ISA: Justin Ruddock
 Gordon Mentor: Jane Eisenhauer
 Faculty Advisor: Ibrahim Zeid
 Others:

12 SUMMARY

The challenge project presented in this report resulted in recommendations to the government sponsor to reduce costs and time to procure an antenna support structure. The ground communication platform must be rapidly deployable, but the existing design required extensive work to install the antenna that is not sustainable for the new method of employment.

The internal market for the project was MITRE and the external market was the government sponsor or PMO. The customer needs were assessed to find that design goals were speed, adaptability, and durability. Timely and accurate information is needed to support command and control while acquisition strategies have shifted more from sequential “waterfall” approaches to rapid agile prototyping. The need for speed was also seen through the NSEC FFRDC goals to reduce system costs and accelerate delivery to field while maintaining or improving performance. Global conflicts require not only speed but also adaptability and durability to withstand worldwide environmental conditions. Market challenges included risks of project funding cuts and delays with the MITRE public release system, but these were mitigated through communication and accountability techniques.

The antenna support system must provide sufficient height to maximize the range of the antenna and enough stability for performance specifications. To reduce costs and lead times, existing COTS antenna masts were evaluated in harsh environment requirements. This task required knowledge and application of design and mechanics principles with support from finite element software modeling tools. These principles included wind loading, stresses, deflection, and fatigue. The closed-form solutions were compared to FEA. Technical challenges included a lack of data on the antenna system to develop the models, which were mitigated through contact with manufacturers.

Leadership capabilities for the candidate to grow within the challenge project included initiative, communicating and advocacy, and decision-making. The candidate needed to make risk assessments and demonstrate the benefit proposition to multidisciplinary teams of engineers. Another role was as an advocate for funding when the scope changed or increased the time for development. The candidate was supported by a team with extensive expertise in the market and technical domains as well as the Gordon Engineering Leadership program.

In conclusion, the information provided in this proposal demonstrated that there is sufficient market value, technical depth, and leadership opportunities within the challenge project.

12.1 Recommendations for Future Work

Due to schedule and budget constraints, aspects of the original challenge project plan were removed that may still hold value for future work opportunities. Adding additional parts to the analysis such as the guy wires themselves with their anchors could uncover potential safety concerns. If the guys are loosened at certain wind speeds, they could become a hazard for nearby personnel. Looking at the impact of the shelter system next to the antenna system could offer benefits with additional lateral support against the wind loads. Developing more FEM for fluids, dynamics and buckling could provide more insight into the antenna support structure. The wind loading could be better

characterized than distributed loads against the mast and another failure mode besides yielding and fatigue could be addressed.

The major task that was not sufficiently covered in this challenge project was the validation of the analytical models. The theoretical and numerical results may be in agreement but could be far removed from the experimental and field results. Pursuing additional mast vendor contacts and potential testing of the system that will be procured in the future would provide data to validate the models.

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