LOCKHEED MARTIN

Low Speed Wind Tunnel

User Manual

1 INTRODUCTION

This manual describes the Lockheed Martin Aeronautics Company Low Speed Wind Tunnel and provides information for customers who wish to conduct tests in the facility. The details presented for the wind tunnel and associated systems are current at the time of publication, but potential customers should contact the Wind Tunnel about facility updates. The Low Speed Wind Tunnel, shown in aerial view in Figure 1, is located in Marietta, Georgia, as shown on the map in Figure 2.

During a scheduled test period, it is company policy to provide complete protection for customer proprietary data and for the security of Government classified information. Personnel access to the wind tunnel can be controlled to conform to the customer's desired degree of protection. LM Contracts will work with its customers to establish a non-disclosure agreement. When a formal RFQ/RFP is received, a contractual service agreement between the customer and Lockheed Martin will be drafted by LM Contracts and signed by both parties.

The wind tunnel is equipped to support testing of vertical/short take-off and landing (V/STOL) or conventional subsonic aerospace models in either of its tandem test sections. Industrial models, such as automobiles, can also be tested in the facility. Variable frequency electrical power and a high-pressure air supply system are available to power simulated propulsion systems in the models or to satisfy other test requirements. Six-component aerodynamic forces and moments on the models are measured, when so mounted, by an external balance located below each test section or, when sting mounted, by an internal strain gauge balance. It should be noted that the V/STOL external balance is not currently functional.

Online data acquisition and monitoring are managed using a dedicated computer system located in the wind tunnel facility. Subroutines written in FORTRAN enable the data system to present raw or reduced data in tabular or plotted form in near real-time. Data reduction to corrected coefficient form is performed on a dedicated server, also located in the wind tunnel facility.

Normally, wind tunnel charges are based on fixed rates per occupancy hour. The total test occupancy hours include time required for installation of the model and support system, model testing, configuration changes, and removal of the model from the test section. This time is accumulated during the scheduled shift working hours and any other time that the wind tunnel staff must be present for tunnel operation. Any normally chargeable time expended on maintenance, wind tunnel equipment breakdowns, or any other unscheduled shutdown caused by Lockheed Martin is not charged as occupancy time. The rental rate for the facility includes all labor for conducting a standard test, processing data, and transmittal of the final data package.

If extra supporting services are required for a particular test, an additional fee will be negotiated with the customer prior to performance of the work. Non-standard services will be clearly outlined in the technical volume accompanying each quote.

Customer data can be presented using any standard units of measurement specified by the customer. For convenience all weights and measures in this manual are in both Imperial and Metric units. The Low Speed Wind Tunnel is AS9100 certified, and all instrumentation calibrations are traceable to national standards.

Figure 2 shows the recommended route to the wind tunnel from Hartsfield Atlanta International Airport. Exit the airport on Camp Creek Parkway and follow I-285 North to the Atlanta Road exit. Customer parking is available next to the Low Speed Wind Tunnel, as shown in Figure 3. There are several conveniently located hotels in Marietta, Smyrna, and Kennesaw. However, it is recommended that test crews have personal transportation since there is no suitable public transportation in this area.

Inquiries concerning the wind tunnel, its capabilities and limitations, scheduling, and current facility occupancy rates should be directed to:

Matthew Bradley
Lead Engineer
Telephone No. 770-494-5619
E-mail Address: matthew.k.bradley@lmco.com

2 DESCRIPTION OF WIND TUNNEL

2.1 General

The Low Speed Wind Tunnel is a horizontal, atmospheric pressure, single return circuit, closed throat system having an overall circuit centerline length of 780.5 ft (238 m). The facility has two large test sections in tandem. The first nozzle (3.4:1 contraction ratio) delivers airflow from the turbulence-settling chamber to the larger upstream test section. This test section, designed for testing airplane models in the V/STOL flight regime, is designated as the V/STOL Test Section. The air then flows through a second nozzle (2.06:1 contraction ratio) into the smaller downstream test section. This latter test section, designed for testing aircraft models in subsonic flight regime, is designated as the Primary Test Section. However, each test section also has wide-ranging application to non-aerospace test subjects. Figure 4 shows the LSWT circuit diagram.

The main building enclosing the test sections is a four-story, steel-frame structure, which is gas heated and mechanically ventilated. Air conditioning is provided for the offices, control and computer areas, instrumentation laboratory, balance rooms, and customer area.

A single-story addition to the building was completed in 1995. This addition includes two separate, securable model build-up rooms, a machine shop, a balance calibration area, and additional office space. The separate model build-up rooms, in conjunction with the main building, permit simultaneous build-up of up to three separate programs of varying levels of security.

The wind tunnel circuit structure outside the main building is steel plate. It is passively cooled by spraying water on the outside surfaces at a rate of approximately 7000 gal/min (26,500 L/min). The water is recovered in a concrete catch basin beneath the tunnel and recirculated. The wind tunnel stagnation temperature is maintained below 120 °F (49 °C) and usually below 90 °F (32 °C) to protect the wooden fan blades and to maintain safe working conditions in the test section.

2.2 Test Sections

The V/STOL Test Section is formed from welded steel framing overlaid with wood planking and a plywood lining. It measures 26 ft (7.93 m) wide, 30 ft (9.14 m) high, and 63 ft (19.20 m) long. The Primary Test Section is 23.25 ft (7.09 m) wide, 16.25 ft (4.95 m) high, and 43 ft (13.11 m) long and is formed from welded steel framing overlaid with acoustic panels on the walls and ceiling. The test section floor comprises wood planking overlaid with Mezz-Tread plywood. Figure 5 shows a view looking downstream through both test sections. The roof and floor of each test section are parallel while the sidewalls diverge slightly to account for boundary layer growth. There are no corner fillets in either test section. The Primary Test Section has full height slots at the downstream ends of the sidewalls to vent the circuit to atmospheric pressure. The empty test section speed range is 15 to 135 ft/s (5 to 41 m/s) in the V/STOL Section and 30 to 270 ft/s (9 to 82 m/s) in the Primary Test Section. Corresponding dynamic pressure ranges are 0.25 to 20 psf (12 to 957 Pa) in the V/STOL Section and 1 to 80 psf (48 to 3830 Pa) in the Primary Test Section.

There are four impact-resistant observation windows, approximately 2 ft (0.61 m) high by 7 ft (2.13 m) long in each sidewall of the V/STOL Test Section. An extra window is located just downstream of the other four on the north wall of the V/STOL Test Section to improve the view of the model test region from the control console. The V/STOL Test Section has six 2-ft (0.61-m) square observation windows in the ceiling.

The Primary Test Section has four removable acoustic plugs on the north wall and one on the south wall. Each plug measures 2.25 ft (0.69 m) high by 3 ft (0.91 m) long and they can each be replaced with impact resistant windows. The Primary Test Section ceiling has one or two small observation windows that may be monitored by PTZ camera, depending on which roof hatch is installed. One roof hatch is acoustically treated for maximum ambient noise reduction in the test section, while the second, non-acoustically treated option may serve as an image system for strut-mounted models (see Section 2.5.4).

Access to the wind tunnel circuit is provided by doors at the floor level of each test section. Those from the north side are 2.5 ft (0.76 m) wide by 6.92 ft (2.11 m) high and are primarily for personnel access. The south side of the V/STOL Test Section has two doors; one measuring 5.67 ft (1.73 m) wide by 9.92 ft (3.02 m) high to provide for equipment access and a drive-through door 11.83 ft (3.61 m) wide by 9 ft (2.74 m) high. The Primary Test Section equipment access door is 6.25 ft (1.90 m) wide by 10 ft (3.05 m) high and the drive-through door is 7.48 ft (2.28 m) wide by 8.67 ft (2.64 m) high. Removable 16-ft (4.88-m) diameter roof sections provide overhead access in each test section, and an electrically powered 7.5-ton (6800-kg) crane can be used to move models and equipment in and out of the test sections through these roof openings. The crane access opening from the first floor to the test section area is 19.75 ft by 13.75 ft.

Calibrations of the airflow in each test section have been accomplished over a volume 9 ft (2.74 m) upstream and downstream of the balance center and 7 ft (2.13 m) each side of balance center. Throughout this region, and within a height of 7 ft (2.13 m) above and below the balance center, the dynamic pressure variation is less than or equal to ±0.50% in the Primary Test Section and ±0.75% in the V/STOL Test Section across the entire operational range of dynamic pressure.

	TEST SECTION	
	V/STOL	Primary
Size		
width, ft (m)	26.0 (7.93)	23.25 (7.04)
height, ft (m)	30.0 (9.14)	16.25 (4.95)
length, ft (m)	63.0 (19.20)	43.0 (13.11)
Velocity Range		
ft/s	15 to 135	30 to 270
mph	10 to 92	20 to 185
knots	9 to 80	18 to 160
m/s	5 to 41	9 to 82
Dynamic Pressure		
psf	0.25 to 20	1 to 80
Pa	12 to 957	48 to 3830

Adjustable working platforms and ladders are available to permit access to any height in the test sections for model installation, reconfiguration, or repair work. An area is allocated for model preparation and change on the south side of each test section. These areas, at the level of the respective test section floor, are connected by a stairway and are accessible by the overhead 7.5-ton (6800-kg) crane. Figure 43 shows the Primary and V/STOL rigging areas.

2.3 Acoustic Treatment

The Low Speed Wind Tunnel underwent a major acoustic modification in 2016. The Primary Test Section walls and ceiling were replaced with acoustic panels comprising a stainless-steel mesh cloth over perforated stainless-steel panels and 16-in of mineral wool encapsulated in fiberglass. A felt liner was installed just downstream of the test section. The high-speed diffuser walls and ceiling were treated with perforated stainless acoustic panels and mineral wool of varying depth, as were the vertical walls in the first cross-leg and settling chamber. All four sets of turning vanes were replaced with acoustically treated vanes. Turning vanes in corners 1 and 3 were replaced with a fewer number of long chord vanes. The turning vanes in corners 2 and 4 were replaced with vanes identical in profile and number to the original vanes. The acoustic treatment resulted in an overall decrease of 16 dB of background noise in the Primary Test Section, measured at 70 mph. The pre- and post-modification sound pressure level profiles are shown in Figure 6.

2.4 External Balances

A six-component pyramidal external balance system is installed under each test section. Currently, only the Primary balance is functional. The balance systems are similar and, as shown in Figure 7, consist of a rigid earth frame, coupled lift levers, a forces frame, and a moments frame. The moments frame includes a yaw turntable together with the equipment required to support and pitch the model within the wind tunnel. The coupled lift levers integrate the lift loads transferred through four vertical links that suspend the forces frame and allow it only horizontal motion. The moments frame is suspended from within the forces frame by a virtual center pyramid linkage. Vertical and horizontal forces are transmitted through the model support struts to the top of the moments frame and then to the coupled levers through the inclined links, the forces frame, and the vertical links.

Pitching and rolling moments applied to the model support are reacted in the moments frame, which is free to move (spherically about the virtual center) relative to the forces frame. A yawing moment applied about the vertical axis, to the moments frame, is transferred into the forces frame by transfer links so as not to incur any relative motion. Thus, both frames rotate as a unit about the vertical axis. The yawing moment and the side force are separated through a system of levers enabling these two components to be measured independently.

The described motions are restrained by links connecting the balance to precision weigh beams through a series of flexural linkages and bell crank levers. In 2025, stepper motor-driven leadscrews and jockey weights originally used to respond to load inputs at each weigh beam were removed and replaced by load cells. By eliminating moving components from the weigh beam assemblies, balance maintenance has been greatly simplified, and weigh beam response time improves without compromising load capacity or balance accuracy. Weigh beam locking and damping mechanisms have been retained from the original configuration to protect the load cells during model installation, or when the balance is not in use. Weigh beams are also equipped with mechanical stops that serve as overload protection for each load cell.

The load cells are strain gauged instruments that connect to EtherCAT-based digital signal conditioning (EDSC) units. A PLC controls the system and OEM software through an operator's graphical interface (OGI) is installed in the control room to process data and transmit the outputs to the LSWT data acquisition PC via TCP stream. Full scale output of each load cell is divided into 300,000 (±150,000) increments or "read out counts" (ROC). An ROC represents scaled millivolt output of the load cell, normalized by applied excitation voltage. The rated load for each load cell is the bi-directional balance component range, though a manually adjustable bias weight may be used to increase uni-directional load capacity up to each balance component limit load.

The balances are designed for identical maximum aerodynamic loads and moments about the balance virtual center using either a strut system or one of several test section floor-level mounting systems. Each balance has been calibrated about a fixed point at the nominal virtual center, which is identified as the resolving center. The location of the resolving center of the Primary Test Section balance is shown in Figure 8. Nominal balance limit loads for each component are listed in the table below.

The accuracy of each balance component is based on several factors, including load cell hysteresis, calibration system accuracies, and component cross-coupling (interactions). The accumulation of these factors has been calculated by an uncertainty analysis method and experimentally checked. For the Primary balance in its current condition the component design specification accuracies, and the accuracies achieved during calibration, are also listed in the table below.

Component	Limit Load Ranges		Design Accuracy		Achieved (RMS)	
Lift, lbf (N)	±10,000	(±45,000)	±1.0	(±4.5)	±0.35	(±1.56)
Drag, lbf (N)	±1,500	(±6,500)	±0.4	(±1.8)	±0.28	(±1.26)
Pitching Moment, lbf-ft (N-m)	±10,000	(±13,500)	±2.0	(±2.7)	±1.47	(±1.99)
Side Force, lbf (N)	±10,000	(±45,000)	±1.0	(±4.5)	±0.41	(±1.81)
Yawing Moment, lbf-ft (N-m)	±10,000	(±13,500)	±2.0	(±2.7)	±2.24	(±3.04)
Rolling Moment, lbf-ft (N-m)	±30,000	(±41,000)	±2.0	(±2.7)	±2.10	(±2.84)

The recommended maximum model span ratio for a strut-mounted model at the LSWT is 0.65. Floor-mounted semi-span models can achieve even larger scale for increased sensitivity in characterizing small incremental effects. However, other limitations become important: the balance load range limits, the available electrical power or compressed air, tunnel boundary corrections (unrepresentative impingement of air jets against the boundaries), and the ability of a very large model to negotiate the size restrictions within the wind tunnel building during model delivery and installation.

2.5 External Balance Model Support System

Models can be supported by the external balance using any of several available support systems. The following described support systems bolt to pads of 3 in (76 mm) thickness, which are clamped to the balance ways. Figure 9 presents dimensional details of a typical pad and dimensions of the access through the floor turntable ways.

A conventional three-strut system, shown in Figure 10, uses two main support struts as the primary load-carrying members. These struts also serve as the pivot point for changes in model pitch attitude. The pitch angle is varied by vertical (parallelogram) motion of the third strut, which can be mounted either forward or aft of the main strut supports and is mounted to a motor-actuated tilting beam, or yoke. The third strut transfers model pitching moment and a proportion of the lift into the balance.

There is also a two-strut system, shown in Figure 11, with a tandem arrangement of the supports. With this arrangement one main support provides the pivot function, and the attitude control is provided by the other strut in the same manner as the third strut of the three-support system.

Fork or unistrut bayonets in conjunction with a single strut and fairing, are also available. An example of this system is shown in Figure 12. The fork unit has two fixed blade supports in the form of a “Y” that provide the model attitude pivot. Coaxial with the strut, there is a third support that moves vertically and provides pitch angle variation. The unistrut consists of a single blade with a wide roll-reacting trunnion bearing, together with the same coaxial pitch strut as above.

Panel or semispan models can be tang mounted on the external balance with a small test section floor clearance or with a raised reflection plane. Figure 13 shows an example of a semispan model installed in the Primary Test Section.

Other special mountings can be custom-made to support aerospace or non-aerospace models. An example of a special aerospace mounting is the parachute model shown in Figure 14. Some of the many non-aerospace tests that can be conducted are architectural, antenna, automotive, motorcycle, and scaled semi tractor-trailers, as shown in Figure 15 through Figure 21.

2.5.1 Struts

Connecting the balance to the model is a two-section unit with the lower structural segment (strut) and the upper mechanical interface (bayonet). The bayonets will be discussed in Section 2.5.2. The strut transfers the model loads into the balance below the test section floor. As discussed above, the struts can be positioned for three-support (Figure 10), two-support (Figure 11), or unistrut (similar to Figure 12).

The main struts, which carry most of the load, can be positioned in the three-support configuration 22.5 to 88.5 in (572 to 2248 mm) apart. Incidence variations are affected by using a pitch strut which can be located either forward or aft at distances between 22 and 48 in (559 and 1219 mm) from the balance centerline. With the struts spaced more than 56 in (1422 mm) apart, the nominal angular ranges for the balance are ±60° in pitch and ±180° in yaw. As the struts are moved closer together, physical interferences between the windshields limit the angle ranges. For example, at a main strut spacing of 45 in (1143 mm) and with 35 in (889 mm) on the pitch strut, the pitch angle range is ±51°, and the yaw angle range is ±78°. General pitch angle limits are shown in the upper half of Figure 22, and the yaw angle limits with 35 in (889 mm) pitch strut spacing are shown in the lower half of Figure 22. Specific pitch angle limits are dependent upon windshield selection, angle ranges, strut spacing, etc. Therefore, customers are encouraged to contact the tunnel staff during model design for assistance with hardware selection. Model attitude can be commanded within 0.01° either manually from the control room or by computer control.

The strut used for the fork and unistrut mount system is a separate unit that contains an internal push-pull rod for pitch actuation of the model. The lower end of the rod is attached to the standard pitch angle drive system of the balance.

There are two available pitch struts used in conjunction with the full-length main struts. While the struts are equal in length, they differ in inner diameter, as well as the type of mechanical connection made with bayonets and the balance pitch yoke. One allows the passage of only a few instrumentation wires or tubes; the other allows the passage of a large bundle of wires or compressed air, etc., for model auxiliary power.

Short structural members (e.g., a tang) connect panel models and special test models directly to the balance turntable at floor level. Such mounting hardware usually must be tailored to the model. Customers should coordinate model installation requirements with the LSWT as early as possible during test planning.

2.5.2 Bayonets

Aerospace models are usually mounted in the center of the test section and attach to bayonets that, in turn, attach to the struts. Numerous bayonets exist to support different types and sizes of models.

Main strut bayonets used with the three-support system are shown in Figure 23. With the three-support system, all loads except that part of lift reacting to pitching moment are carried through the two main bayonets. The two-support system uses only one main support. The support strength and stiffness must be considered carefully since the system transfers all model loads except pitch. Figure 24 shows existing configurations of the two-support main bayonet.

Special bayonets serve a variety of configurations. In Figure 25, Bayonets 21 or 25 are used when there are few or no onboard instrumentation wires. When a large bundle of wires or tubing is to be attached to the model, they can be routed through Bayonet 22 or 24, shown in Figure 25. When compressed air is required on the model, Bayonet No. 23, shown in Figure 26, is used in conjunction with a swivel fitting at the bottom of the pitch strut. Due to considerations at the strut to pitch yoke joint, this unit can be used only with an attachment point in the range 46 to 48 in (1168 to 1219 mm) forward or aft of the main support center. The fork mount bayonet support is shown in Figure 27, and the unistrut bayonet support is shown in Figure 28. Different pitch control members are used with these supports to obtain various model pitch ranges. A right-angle mount, useful as a light duty sting, is shown in Figure 29. Bayonet No. 7 in Figure 30 is used to adapt the light duty sting mount to a standard or short main strut. Insertion of an angle spacer, such as those in the same figure, permits some pitch-yaw combinations. The bayonets in Figure 30 have various model support uses.

The yaw range for all systems is nominally ±180°, but the actual range available may be affected by test-required hardware in use beneath the floor.

2.5.3 Windshields

In the floor of each test section there is a turntable that is synchronized to rotate concentrically with the balance. Windshields, which mount on the turntable, are available to streamline the flow around the struts and to minimize the influence of the metric supports on the net balance output. There is, in addition, a general-purpose tail strut windshield. Figure 31 shows the main strut and fork strut windshields in end view and elevation. The windshields can be seen in Figure 10, Figure 11, and Figure 12. When the balance is yawed, the windshields counterrotate with the turntable to remain aligned with the streamwise airflow. These relative movements can create physical interferences that limit balance motion, as previously shown in Figure 22. During pitch changes, the pitch strut windshield telescopes to maintain a constant length exposed to the airstream.

Electrical circuits are attached to the windshields to indicate fouling between the balance supports and windshields. Console controls provide windshield yaw adjustment to clear most fouling.

2.5.4 Image System

A support image system, with dummy bayonets, strut windshields, and turntable, is available for installation on the roof of the Primary Test Section. The image system is electrically actuated as a synchronized drive system that enables its turntable to yaw with the balance turntable. The image pitch strut and windshield follow the movement of the model-supporting pitch strut and maintain preset spacing between the model and the windshield.

The image system can be configured to match either the two- or three- strut system windshields used in the Primary Test Section. The dummy bayonets are identical in contour to the model-supporting bayonets and are also mounted on the model. The dummy bayonets extend into, but maintain clearance within, the image windshields.

2.5.5 Four-Wheel Mount System for Automobiles

By means of extension arms bolted to two balance strut pads on the balance strut ways, four flat wheel pads are available for supporting automobiles. Each standard wheel pad measures 23.25 inches (591 mm) in the streamwise direction by 14.875 inches (378 mm) across the stream. Figure 32 shows the layout of the pads within the floor turntable. The pads are discernible in the photograph in Figure 18. There is no provision for measuring each individual wheel load, but reduction procedures for the balance data assign measured net aerodynamic lift to individual wheels by using the measured pitching and rolling moment data.

Each pad is instrumented with surface pressure-measuring orifices in the top, front, and rear faces. The orifices are manifolded to pressure transducers, thus allowing pressure-created tare loads on the pads to be calculated and then removed from the balance-measured loads. Several different sizes of extension and reduction plates (Figure 32) are available to match the range of wheelbase and track requirements of both large (trucks, vans) and small (mini) vehicles.

2.5.6 Under-Floor Beam Support

Figure 33 shows details of a beam support that is used for mounting long models to the main balance. The primary use is the mounting of 0.3-scale tractor/trailer models, as shown in Figure 21. The mounting post configuration and cover plate hole locations shown in Figure 33 are typical for this type of model. An existing cover plate can be adapted, or a new cover plate made, to accommodate changes in support post configuration. Cross bars with custom model attachment posts can be bolted or clamped to the machined upper surface of the beam. The beam is designed for high bending and torsional stiffness. The high stiffness construction is continued into the 2-inch (49 mm) steel foot for attachment to a centrally positioned balance strut pad, a detail of which appears in Figure 9. When installed, the beam surface is 1.88 inches (48 mm) below the tunnel floor level.

2.6 Sting Model Support System

A sting support system was added to the inventory of equipment in 1987, and it has wide-ranging applications. It supports models of moderate weight and vertical lift, can deliver to the model the full output of the facility's air compressor, and can position the model over a very wide matrix of pitch, yaw, and roll angles.

Figure 34 shows an aircraft model mounted on the sting system. The system consists of a vertical beam, extending from the floor to the ceiling of the downstream end of the Primary Test Section, a carriage that can be raised and lowered on the beam, and an articulated arm and model sting, mounted on the front of the carriage. The carriage travels on linear bearings and is actuated by a motor driven ball-screw. The arm is articulated at two joints, with actuation effected by hydraulic jacks. Feedback for carriage height and jack extensions is provided by linear displacement transducers. An optional hydraulic-powered roll pod with magnetic incremental encoder feedback may be added to the assembly upon request. Figure 35 is a general arrangement drawing of the articulated sting arm. Shown on the drawing are interchangeable forward sections to provide 0°, 30°, and 45° offsets to a model attached to the nose of the arm. The nose is a conically shaped boss with a stepped parallel-bored hole of 5.4-inch (137 mm) nominal diameter. Figure 36 and Figure 37 are detailed drawings of the two available bosses. Customer model stings should be made to fit either of the bosses directly or to adapt to it by means of a sleeve. Various model stings are available for use; customers should contact the LSWT for sizing, application, and availability.

Compressed air can be supplied to the model at 16 pps and 100 psi (689 kPa) output of the compressor. Details of the compressed air system are given in Section 3.1. This is achieved by a minimum of 4-inch (102 mm) internal diameter piping to the sting carriage, at which point a computer-controlled stepper-motor-actuated 4-inch Vee-Ball valve provides control of the air flow. The air is then ducted to the model through a stainless-steel flexible hose contained within the arm. A 4-inch hose is used in conjunction with the 0° and 30° offsets, and a 3-inch (76 mm) hose with the 45° offset. Alternately, a 6-port manifold can be installed directly below the 4-inch Vee-Ball valve. This manifold has outlets of various diameters that allow high pressure air to be routed externally to the model via individual valves and hoses. The air supplied to the sting is dried and filtered, and it can be heated, as described in Section 3.1.

A valuable feature of the sting system is the capability of setting combined pitch and sideslip angles in the usual yawed wind axes system. The two angle joints can be partially dismantled and rolled 90°, plus or minus as appropriate, to place a yawing axis at the aft joint while retaining the pitching axis at the forward joint. Figure 34 is a photograph of the sting configured in this manner.

The 9 ft (2.74 m) range of vertical travel of the carriage can be used to keep the model centered in the test section for all but the most extreme angles of attack. The model deviates from the centerline during yaw excursions. Maximum vertical travel speed is limited to 4 inches (102 mm) per second, which is adequate for pitch-and-pause testing but too slow for rate-derivative testing.

The forward joint can be actuated -52° through +45°, while the aft joint can be actuated -30° through +30°. With both joints configured for pitching, a model can be pitched through a 157° range. The model angle-of-attack range can then be located within that range by using one of the three offset sections as follows:

Offset (degrees)	Boss Pitch Range (degrees)	
Joint Configuration:	Pitch/Pitch	Pitch/Yaw
0	-82 to +75	-52 to +45
30	-52 to +105	-22 to +75
45	-37 to +120	-7 to +90
	(No yaw)	(±30 yaw)

The vertical travel also permits ground effect testing using the tunnel floor or a small ground board (described in Section 3.3). The height traverse serves a dual purpose: maintaining a particular height for a specified point on the model (e.g., main landing gear axle or aircraft center of gravity) while testing through a pitch excursion or setting a designated schedule of ground clearance heights at fixed or varying angle. Note that, unless the model is attached by a blade of sufficient drop or a bent sting, ground effect testing with pitch incidence typically requires use of the ground board.

The load capacity of the sting system is defined by the ability of the vertical beam linear bearings to react moments at the sting root and by the moment capacities of the two joints. For example, the maximum allowable gross model loads (combined aerodynamic, propulsive, and weight) applied at a (typical) model point 5 ft (1.5 m) ahead of the sting boss reference point (see Figure 35, Figure 36, and Figure 37) are as follows:

(a) Sting arm configured with front and rear joints in pitching mode:

Gross normal force from the model is limited to the range -2200 to +2900 lbf (-9800 to 12900 N). Negative model pitching moment will reduce the negative normal force limit by 13 lbf per 100 lbf-ft (43 N per 100 N-m), and positive pitching moment will reduce the positive normal force limit by 8 lbf per 100 lbf-ft (26 N per 100 N-m).

(b) Sting arm configured with front joint in pitching mode and rear joint in yawing mode:

Gross normal force from the model is limited to -900 to +1800 lbf (-4000 to +8000 N). Side force, positive or negative, reduces both normal force limits by 50 lbf per 100 lbf (50 N per 100 N) of side force; an allowance for yawing moment likely to accompany such side force has been added to this rate. Pitching moment, positive or negative, will reduce both normal force limits by 8 lbf per 100 lbf-ft (26 N per 100 N-m).

For configuration (a) a very heavy model and sting can be used, as the positive normal force range for aero and propulsive loads is extended. Configuration (b) is more restrictive in load capacity. Sting-use customers should therefore, early in the test planning cycle, provide the Wind Tunnel personnel with enough geometric data (model sting/blade basic dimensions), model and sting/blade weight, center of gravity location, and anticipated test ranges of pitch and yaw angle, to enable allowable load envelopes to be computed.

When requested, the roll pod is installed between the pitch knuckle and the sting boss and enables 360° (±180°) of model roll positioning. The roll pod is designed to sustain up to 180,000 lbf-in of bending moment and 12,000 lbf-in of rolling moment. Note that the weight of the roll pod itself contributes to the total gross loads applied to the sting support system linear bearings and may contribute to a reduction in normal force capacity if included in the installation. Also note that it extends the overall length of the sting support system by approximately 24 inches, meaning that the clearance between the test section walls and the model is reduced when positioned to high angles of attack or sideslip.

2.7 Main Drive System

The primary components of the main drive system are the motor, the fan, and the counter-rotation vanes. An upstream facing view of the drive system is shown in Figure 38. The motor is electrically powered, air cooled, and rated at 9000 hp (6700 kW). It is installed within the center section of the faired nacelle, allowing direct coupling of the fan to the motor with no exposed drive shaft in the airstream. Additionally, the nacelle houses a viscous torsion damper connected in tandem to the main drive shaft.

The primary main drive speed control station is located on the power section of the console in the control room. Starting and stopping the drive motor and adjusting the speed throughout the desired range are accomplished from this console. In addition, there are emergency stop buttons positioned on the console and strategic locations around the wind tunnel circuit. Interlock switches on circuit doors prevent inadvertent start-up of the main drive system if a door is left open.

The main drive motor is directly coupled to a fixed pitch, six-bladed fan fabricated from laminated Sitka Spruce wood. The fan hub and motor nacelle diameter is 15.6 ft (4.75 m), and the fan tip diameter is 39 ft (11.9 m). These dimensions at the maximum rotational speed of 250 rpm correspond to a blade tip speed of 530 ft (161 m) per second. The outer four inches (100 mm) of the blade tips are made of balsa wood, which can break away without affecting the remainder of the blade in case a foreign object is ingested. A 1-inch (25-mm) mesh stainless steel debris screen is located at the trailing edges of the turning vanes in the second corner to minimize foreign object damage to the fan. The blade leading edges are covered from hub to tip with thin polyurethane film to protect the blades against abrasion from particles traveling in the airstream.

Five fixed counter-rotation vanes are installed downstream of the fan to remove the rotation imparted to the airstream by the fan. Additionally, these vanes serve as fairings around the support structure for the motor and nacelle and as ducts into the nacelle. These ducts are used for cooling air for the totally enclosed drive system and for passing the electrical power and control wiring, brake cooling water, and fire suppression carbon dioxide lines to the drive system components.

2.8 Speed Measurement and Control

The rotational speed of the fan is controlled by an Innomotics system between 5 and 260 rpm.

Tests may be computer-controlled at constant rpm, dynamic pressure, or velocity. Static pressures related to the tunnel flow rate are sensed using piezometers, which are rings of static pressure orifices situated around the settling chamber and around the entrance to each test section. Each ring is designed to pneumatically average the orifice pressures. The rings are connected to precision transducers that sense the settling chamber static pressure and the pressure difference between the settling chamber and the test section in use. The transducer signals, which have an accuracy of 0.08% of the reading or 0.01 psf (0.5 Pa), whichever is larger, are calibrated against pitot-static surveys in the respective test sections. The resulting indicated test section dynamic pressure is controlled by adjusting the main drive fan motor rpm. The time-dependent variation in dynamic pressure in the low range is negligible, and at the higher end of the range the variation is within ±0.06 psf (±5 Pa) as shown in Figure 39.

The dynamic pressure transducer reading, and all other data required for reduction are read by the acquisition computer continuously. The computer reduces the airflow data and displays the corrected wind speed and dynamic pressure on the operator's console. These values are updated approximately once per second and are also input to the speed control program.

Computer control of the tunnel speed consists of dynamic pressure or velocity data being input into a software proportional integral differential control system. This system drives a digital-to-analog converter that completes the control loop between the tunnel airstream and the main drive.

2.9 Steady State Data System

The wind tunnel primary (steady state) data system consists of several computer systems located on the operating floor of the wind tunnel building adjacent to the control room. The data system provides the means of recording data from wind tunnel and model instrumentation, reducing the recorded data to engineering units, monitoring test parameters in near real-time, controlling test parameters, and performing run-to-run analysis of gathered test data. Some of the computers in the data system are also used to provide office automation and word processing functions.

The data acquisition system at the Low Speed Wind Tunnel is an evolving system. It is updated to stay as current as possible with computer technology, instrumentation sensors, and data acquisition methods. The computer systems currently in use consist of PC-based workstations and Hewlett-Packard ProLiant servers. All computer programs are written in FORTRAN on the servers and in LabVIEW on the PCs. The ProLiant systems utilize VMS Software Inc’s OpenVMS operating system and the PC's utilize Windows.

Data from the wind tunnel instrumentation are filtered using Precision Filters 28000 signal conditioning systems and sampled using a National Instruments PXIe A/D acquisition system. The PXIe is equipped with input/output modules to read voltages, strain gauge bridges, thermocouples, and frequency data from rotating test equipment. It is also equipped to read IRIG time codes, which is useful when synchronizing the PXIe to other auxiliary data systems. The LSWT utilizes a Masterclock GMR5000 GPS-connected server to produce IRIG time codes.

The PXIe is connected to a PC running custom LabVIEW applications to acquire, average, and display selected data. A separate LabVIEW application then transfers the data to the ProLiant servers for reduction and storage. Some reduced data is transferred back to the PC from the servers for process controls and customer/control room displays.

Eleven data channels are used to measure basic wind tunnel airflow parameters and reference pressures. Any of the remaining analog data channels may be used for reading pressure transducers, thermocouples, strain gauges, or other voltage-signal sources.

Large numbers of pressures are measured using solid-state scanning units. The solid-state units are continually scanned and sampled with no settling time required as each pressure measurement has a dedicated sensor. A running average of the readings from each solid-state transducer is maintained thus providing an immediately available measurement of the steady state pressure over a selected period.

The wind tunnel data system can display either point-by-point (recorded) or near-real-time data on both control room and customer area monitors. Each display's contents can be set individually and are typically utilized to monitor freestream test conditions and balance output. Any data quantity, both raw and reduced, can be displayed. The LSWT also has a customizable live data plotting tool available to display any reduced data parameter on an X/Y plot as it is recorded.

The data system is controlled from a PC at the tunnel operator's station (Figure 40). The data reduction programs write customized output files to the ProLiant server SSDs and backup flash arrays. Additional data backups are written to LTO-9 tape drives overnight, prior to each day's start of shift. There are several different custom applications for displaying any pre-selected parameters of raw or reduced data on-line on any of the PCs and large flat-screen monitors.

Recorded raw data can be reprocessed upon request to correct any programming errors, data reduction constants input errors, or post-test customer input changes. Selected raw and reduced data can be packaged for delivery to LSWT customers in a format of their choosing to ensure compatibility with wind tunnel data analytical tools.

2.10 Dynamic Data System

An optional high speed data acquisition system (HIDAS) is available at the LSWT upon request. HIDAS uses a Precision Filters 28000 signal conditioning system with a Pacific Instruments 6700U A/D data acquisition system. It is currently equipped with five amplifier-filter-digitizer modules, totaling 40 data channels. The system permits AC or DC coupled inputs and sampling rates up to 200k per second, with an aggregate data rate limit of 16 MS/s. The signal conditioning cards are programmable 4-pole flat/pulse low pass filters with cutoff options of 10 kHz, 20 kHz, 40 kHz, 80 kHz, and 100 kHz.

The most common use for HIDAS at the LSWT is to record data from dynamic pressure transducers installed in strategic locations on or within wind tunnel models where dynamic loads characterization is of particular interest. Kulite pressure transducer products are a popular choice for these types of measurements.

In most applications, the LSWT will program HIDAS to receive a signal that can be sent by the primary data system to trigger dynamic instrumentation recording. The Pacific Instruments 6700U enclosure can also accept IRIG time codes, so the LSWT Masterclock can be used to synchronize time stamps on each data system.

Data acquisition is controlled and displayed from either Pacific Instruments' PI660 software, or using custom LabVIEW applications run by a PC dedicated to HIDAS. Wind tunnel data recorded at dynamic sampling rates produces raw data files that are too large to efficiently reduce online. Therefore, the LSWT typically performs dynamic data reduction offline only. Alternatively, customers may elect to receive raw instrumentation signals without any additional data reduction.

2.11 Control Room

The control room is on the third floor on the north side of the wind tunnel circuit, about midway between the V/STOL and Primary Test Sections so that models can be observed while being tested in either test section. When the acoustic upgrade was completed, lines of sight between the Primary Test Section and control room were considerably reduced. This was addressed by installing pan/tilt/zoom (PTZ) cameras to stream live video feeds of the test section to the control room. There are two PCs controlling the camera system using Blue Iris video security and webcam software. Camera feeds are split between the monitors connected to each PC and can be independently configured.

The wind tunnel operates from the main control console located in this room. This console contains the equipment and displays for setting test section conditions, observing main balance loads, changing model attitudes, and controlling auxiliary compressed air and variable-frequency electric motor model power systems. These positions are shown in Figure 40 that also shows the tunnel operator station. Figure 41 shows the layout of the tunnel's main operational areas, in which the control and computer rooms are located.

2.12 Wind Tunnel Building

A four-story building encloses the two test sections and the second contraction section. The foundations of the wind tunnel structure, the building, and the two balances are mutually independent to minimize the transmission of vibrations.

The first floor (ground level) of the building contains the model delivery entrance area, model build-up and preparation rooms, compressor and balance rooms, instrumentation laboratory, workshop, customer on-site staff offices, and a conference room. Delivery and other services entry is through one of two roll-up doorways, each measuring 10 ft (3.05 m) high and 10 ft (3.05 m) wide. One is located on ground level in the northwest corner of the building while the second one is located at the loading dock on the north side of the building.

The LSWT staff office is on the second floor along with a small and medium-sized conference room. The air-conditioned third floor (Figure 41) comprises the control and computer rooms, and an area between these and the tunnel circuit that is available for customer use. On the opposite side of the tunnel from the control room are model preparation areas which are on the same levels as the two test sections. The fourth floor is used as storage space for wind tunnel support equipment.

In the northeast corner of the building is a small elevator for transportation of equipment. The usable floor area is 5.75 by 7.75 ft (1.75 by 2.35 m), the door opening measures 5.75 ft by 6.83 ft (1.75 by 2.08 m), and its load capacity is 6000 lb (2700 kg). There is access to this elevator from each of the four floors on the north side of the wind tunnel circuit.

An open hatchway in the center of the second floor permits equipment to be lifted from the ground floor to the set-up areas, into the tunnel test sections via the ceiling hatches, or to the fourth-floor storage area. The hatchway measures 19.75 by 13.75 ft (6.02 by 4.19 m). Access to the hatchway on the ground floor has an 8.0 ft (2.44 m) height limitation due to overhead cable trays. A lifting cradle is available to facilitate hoisting of automobiles, awkward loads, or loads consisting of many small items. The cradle’s interior dimensions are 16.0 ft (4.88 m) long, 9.0 ft (2.74 m) wide, and 9.0 ft (2.74 m) high. The load capacity is 10,000 lb (4500 kg).

3 AUXILIARY SYSTEMS

3.1 Compressed Air System

High pressure air is supplied by a multistage centrifugal compressor driven by a 4500 hp (3357 kW) synchronous motor. The compressed air is then routed through a silica gel desiccant dryer system and an air heater. The air can be routed to various subsystems and is regulated at each with valves remotely controlled from a panel located on the main wind tunnel control console.

The compressor is rated at 20 pps at a pressure of 100 psi (689 kPa) gauge; however, actual output has been estimated to be 16 pps. Note that the facility's pneumatic piping is rated for 300 psi, however the 300-psi compressor system has been decommissioned. Higher pressure air compressors may be rented and integrated temporarily if desired for a particular test. The compressed air is filtered through 2-micron (0.002 mm) filters and delivered free of oil and other contaminants to the balance rooms and to the sting support system. Flow rates may be measured using ASME sharp-edged orifice meters, critical flow nozzles, or sub-critical venturis.

The silica gel desiccant dryers are rated at 20 pps at 300 psi (2068 kPa) gauge. They dry the air to -60°F (-51°C) dew point. The dryer system consists of two units so that one is being electrically heated for regeneration while the other unit is on-line. The regeneration cycle is four hours.

The compressed air heater is a solid-state controlled 440-volt, 600 kW electric heater designed to raise the temperature of 10 pps of dry air by 200°F (111°C). Approximately half of this temperature rise can be expected at 20 pps flow, with proportionately greater rises from lesser flow rates. The heater and the steel piping of the compressed air system have an upper limit of 600°F (315°C), but temperatures are usually limited to 200°F (93°C) by the balance room trapeze, or to 300°F (149°C) by the sting flexible hoses.

The compressed air is delivered to the external balance through a flexible hose trapeze arrangement. The upper connections, one on the balance and one attached to ground, are aligned so that only small repeatable tares remain in the balance readings due to pressure or flow. The compressed air is delivered to the sting system via a flexible traveling loop to permit vertical travel motion for the model and sting.

The means of transferring air from the balance or sting to the model depends on the model configuration, but it is advisable to use the existing equipment and systems shown in this manual. If this is not feasible, the Wind Tunnel should be contacted early in model design.

3.2 Model Electrical Power

The LSWT has several electrical panels located around the facility, rated at either 110 or 440 VAC. A portable transformer is also available to supply 220 VAC upon request. Contact LSWT engineering for available breakers and receptacles.

Two electric motor-generator (M-G) sets supply variable frequency electric power to receptacles in the Primary and V/STOL balance rooms. A variety of model motors can be connected to these receptacles depending on size and type of model and test configuration. Control and monitoring of the model power systems are performed from the wind tunnel control room console.

Each M-G power system consists of a generator driven by a 600 hp squirrel cage induction motor through an eddy-current coupling. Output frequency of the generator is controllable from 60 to 400 Hz by adjusting coupling excitation and, thus, generator speed. With the generator in the "delta" configuration, the volts per cycle can be regulated from 0.4 to 1.25; in the "star" configuration, the volts per cycle can be regulated from 1.0 to 2.16. The system is designed for a maximum output of 240 hp per M-G set. Protection is provided to ensure that voltages greater than 15% above any set value are not applied.

Both M-G sets can be used simultaneously to power models provided that identically designed motors are used on any one set. For safety the M-G set controls are locked during model changes, and the key is kept by the designated test operator to prevent an inadvertent model motor start. When a bus is energized, all motors connected are started. They accelerate to a speed corresponding to the minimum bus frequency of 60 Hz. Motor winding temperatures and current are monitored, and in the event of motor overheating or some other emergency, the motors can be stopped immediately.

The specified accuracy of steady state generator speed is ±0.25% of set point between 200 and 400 Hz. At frequencies below 200 Hz, the accuracy is ±0.5%. Steady state volts per cycle are regulated within ±0.01 below 1.0 volt per cycle and within ±1% above 1.0 volt per cycle.

For motor speed-thrust calibrations, high read-out accuracy is available. Motor rotational rates are sensed by tachometers on the shaft of each motor and can be displayed on the control console. The read-out counter indicates to the nearest 0.01 revolution per second up to 1000 revolutions per second, and above that speed to the nearest 0.1. The speed of each motor is continuously displayed and updated. The counter system can sense up to 24,000 pulses per second from each motor tachometer. If a tachometer outputs more than 16 pulses per revolution, conversion to revolutions per second is provided by computer software.

For DC motor applications, an EA-PS 10060-1000 power supply is available upon request. It carries a voltage range of 0-60VDC, a current range of 0-1000A, and a power range of 0-30kW. For all other model power supply solutions, please contact the LSWT staff.

3.3 Ground Board

To obtain ground effects on model test parameters, a small fixed-height ground board is available for use in the Primary Test Section. This board, shown in Figure 42, stands 37.5 inches (0.953 m) above the floor, measures 12 ft (3.66 m) long, and spans the complete width of the test section. The ground board may be optionally configured for 16 ft (4.88 m) length. Note that the assembly contains no turntable and is comprised entirely of 4×8 ft sheets of plywood.

Although the ground board is available, ground effects testing for strut mounted models should, if possible, use the tunnel floor as a reflection plane. Note that LSWT struts are fixed in length, so ground effects testing of strut mounted models may require custom model support hardware. Reduction of the floor boundary layer is sometimes required. This can be accomplished in the Primary Test Section by the Boundary Layer Control System (described below) located near the entrance to the test section.

3.4 Boundary Layer Control System

The Boundary Layer Control System comprises four identical, 66-inch wide, three-chamber boxes with elliptical tangentially blown 0.060-inch exit slots. The boxes are positioned with the slot exits at Tunnel Station –161.5. The system was calibrated using boundary layer rakes to characterize the boundary layers at several locations downstream of the slot over a range of tunnel dynamic pressures and slot plenum pressures. A complete set of boundary layer profile plots are on file at the Low Speed Wind Tunnel.

The criterion for proper boundary layer treatment is defined as zero momentum thickness at the model location (nominal front bumper location for automobile models, moment reference center for aircraft models). A relationship between tunnel dynamic pressure and slot plenum pressure was derived by plotting momentum thickness against slot pressure for a range of tunnel dynamic pressures and model locations. The velocity ratio variation for the front bumper location was determined to be 4% (±2%) of local freestream velocity.

4 DATA REDUCTION AND REPORT

All data are collected by the acquisition portion of the data system and transmitted to the appropriate computers for data reduction. The external balance raw data are reduced to aerodynamic coefficients online, and output to the control room displays and customizable digital output files as desired. The external balance six-component data, as recorded, are in the tunnel axis system. If desired, the data can be transferred to any other appropriate axis system. Data from strain gauges or from other analog sources can be collected and reduced as required.

Several data corrections are applied depending upon the type of model and test. The following corrections are standard for LSWT test data.

Model incidence corrected for:

- Support system deflections
- Test section flow angularity
- Streamline curvature due to tunnel wall constraint

Freestream test conditions corrected for:

- Solid and wake blockage due to the presence of the model (References 4-8)

Drag corrected for:

- Model and wake buoyancy due to the test section streamwise pressure gradient
- Tunnel wall constraint

Lift and pitching moment corrected for:

- Streamline curvature due to tunnel wall constraint (References 1-3)

Corrections to six-component weigh beam balance data resulting from model support system tare and interference effects can be determined from additional runs where the model is inverted, with and without the support image system installed.

Customers may elect to derive flow angularity corrections from analysis of upright and inverted pitch/yaw sweeps in identical model configurations. Note that for strut-mounted models, the support image system must be installed for the model both upright and inverted to determine flow angularity. Sting mounted models may be inverted either manually, or by use of the roll pod. If upright/inverted analyses are omitted from the run plan, then flow angularity values can be obtained from the most current empty tunnel airstream calibration.

The Pressure Signature Method of boundary corrections (developed by Lockheed Martin, see references 6 through 8) uses pressure distributions acquired from one or more of the test section boundary surfaces (walls, ceiling, floor). Such distributions are acquired concurrently with model test data upon request. The signature provides input to equations describing the general condition of a body and its wake confined by solid boundaries, and the solution to the equations permits the calculation of corrections to the data due to the presence of the boundaries. Reference 6 describes the fundamental approach, and References 7 and 8 provide overviews of the developed blockage procedure together with the extension of the method to lift constraint.

Customers may request a test report to be written and included as a part of the final deliverable data package. The report can give pertinent model details as furnished by the customer and present a detailed description of test techniques, test conditions, key findings, and any failure investigations performed during occupancy.

A separate document detailing the LSWT’s data reduction procedure may also be requested. The DR memo outlines a step-by-step procedure for converting raw instrumentation signals into useable engineering units, including the previously described wind tunnel data correction methodology, and any applicable model geometry or calibration constants. A preliminary version of the DR memo may be delivered during test planning, and a final copy capturing any change requests applied mid-test is included with the final data package.

Some tests require data reduction procedures, data listing, and plotting formats that are peculiar to that test and/or to the customer's special needs. The wind tunnel staff is experienced in responding to such needs and new programming or the incorporation of customer-supplied programs can be accommodated within the LSWT standard services occupancy rate.

5 DATA QUALITY ASSURANCE

Key components of the comprehensive quality assurance program continuously conducted by the Lockheed Martin Low Speed Wind Tunnel are:

1) Statistical Quality Control: Establish and maintain statistical quality control by documenting and monitoring the performance of the standard set of instrumentation.
2) Data Reduction Verification: Verify both the standardized and customer-supplied data reduction software by performing a "data reduction check-case" for each test.
3) Uncertainty Quantification: Provide an estimate of the data uncertainty to ensure that the customer's data quality requirements are achieved.

Much work has been done to document the methodology and importance of statistical quality control (see References 9, 10, and 11) and uncertainty analysis (References 12 and 13). A more detailed description of the method employed at the LSWT appears in Reference 14.

5.1 Statistical Quality Control

The first step in quality assurance is to establish and maintain statistical quality control over the measurement process. The purpose of statistical quality control, as stated in Reference 9, is to "guarantee the 'goodness' of measurement results within predictable limits and to validate the statement of uncertainty of the measurement result". This can involve 1) constructing control charts (Shewhart or exponentially weighted moving average) that track individual instrumentation calibrations and ensuring that current calibrations fall within the bounds of the historical values, 2) periodic measurements on a check-standard test article, and 3) repeat runs on a single test article within a given test.

The Shewhart control chart is the simpler of the two methods. It tracks the measurement or calibration baseline value and its symmetric upper and lower limits (UCL and LCL). The baseline is the average of historical data. The upper and lower control limits are typically based on one or two standard deviations of the historical data (68 or 95% confidence level, respectively). This chart is most useful in detecting large changes (greater than one standard deviation) such as an instrument that has been damaged or incorrectly calibrated. It is not particularly useful for detecting small changes.

The EWMA control chart also has upper and lower control limits but is much better suited to detecting small changes (less than one standard deviation). It uses the standard deviation as well as a “depth of memory” constant used to control weight given to recent calibrations. For a process to be under statistical control using the EWMA control chart, all data must fall between the upper and lower control limits. Furthermore, it is important to examine the chart for trends that would indicate the calibration was performed improperly, the calibration is changing over time, the instrument has been damaged, etc.

Control charts have been constructed for all data channels that are normally used for automotive and aircraft tests. It should be noted that internal strain gage balance calibrations are not included in this analysis, as there are far too many balances in existence and their calibrations are normally tailored for a specific test. Customer-supplied balances and their care are beyond the control of the personnel at the Low Speed Wind Tunnel.

5.2 Data Reduction Verification

Microsoft Excel-based numerical check cases are performed for all aircraft tests and upon request for automotive tests. A check case begins with analog-to-digital converter outputs, converts these outputs to engineering units via the instrumentation calibrations, and performs the data reduction process to obtain fully corrected stability, wind, or body axis coefficients. It completely mirrors the data reduction process that is performed in FORTRAN on the LSWT Data Acquisition and Reduction System. All facility standard data reduction equations as well as any customer-supplied equations are programmed into the spreadsheet. The six-component balance matrix operations are included, and virtually any balance calibration methodology can be incorporated. The check case results are compared to the FORTRAN results to ensure that the data reduction process, all data reduction variables, and all instrumentation calibrations are correctly applied.

5.3 Uncertainty Quantification

Once statistical quality control has been established and the data reduction process has been verified and validated, it is possible to meaningfully estimate the uncertainty of the measurement process. Analytical tools have been developed to estimate uncertainty for wind tunnel models at the LSWT. Inputs to the uncertainty model include aircraft model dimension data and instrumentation accuracy information. Estimates of instrumentation accuracy are typically measured during calibration and are documented in their respective calibration reports. It is assumed that each of these uncertainties fits a Gaussian distribution.

The standard approach for estimating wind tunnel data uncertainties at the LSWT is to perform a Monte Carlo simulation of the LSWT data reduction routine. Normal/Gaussian probability distributions are assumed, and a confidence level of 95% is reported unless otherwise requested.

Uncertainty quantification is an evolving area of study within Lockheed Martin Aeronautics. Flight Sciences engineers are developing improved UQ methods and tools specific to wind tunnel data analysis, though these tools remain a future improvement.

6 WORKSHOP AND INSTRUMENTATION FACILITIES

6.1 Workshop

A workshop on the first floor of the facility contains basic tools and equipment to make or modify wind tunnel test equipment or to make minor modifications or repairs to wind tunnel models. The equipment found in the wind tunnel workshop includes:

Prusa XL 3D printer
CNC mill (3-axis)
CNC lathe
Drill presses
Table saw
Circular and band saws
Grinders and sanders
Light duty bending brake
Light-duty shear
Gas and electric welding equipment
Benches and bench tools
Surface table and measuring equipment
2000-lb (900-kg) capacity forklift

6.2 Instrumentation Laboratory

A climate-controlled instrumentation laboratory on the first floor of the facility is used to functional-test and check-calibrate various electrical and pneumatic model systems. In some instances, on-site repairs to model instrumentation may be possible. All equipment in the instrumentation laboratory is routinely calibrated by Lockheed Martin Metrology to standards traceable to the National Institute of Standards and Technology (NIST).

The electronic equipment in the laboratory includes, though is not limited to:
Universal counters
Digital voltmeters
Digital multimeters
Analog multimeters
Analog volt-ohm meters
Digital oscilloscopes

Function generators
Decade resistor boxes
Power supplies
Digital thermometers

Equipment available for application of strain gauges is:
Oven, ambient to 400°F (204°C), approximately cubic, 4 ft^3 (0.1 m^3)
Refrigeration for epoxy adhesive storage
Bausch and Lomb microscope, stereoscopic 3-30 power

Mechanical measuring equipment includes:
Vernier angle gauges
Digital protractors
Load indicators
Dial indicators

Model pressure instrumentation equipment includes solid-state electronically scanned pressure (ESP) units, transducers, and calibration manometers and gauges. The equipment available for pressure instrumentation includes:

- Pressure transfer standards, Pennwalt (0.1%):
  - 4.5 psig (31 kPa)
  - 15.5 psig (107 kPa)
  - 60 psig (314 kPa)
  - 300 psig (2068 kPa)
- Manometer, Merriam Model 30EF25 60-inch (1500-mm)
- Manometer, Merriam Model 34FB2 20-inch (500-mm)
- Transducers
  - Differential pressure units ranging from ±0.15 psi (1.0 kPa) to ±25 psi (172 kPa)
  - Absolute pressure units ranging from 100 psi (689 kPa) to 500 psi (3447 kPa)
- Electronically scanned pressure units: contact the LSWT for availability and ranges.

6.3 Model Design and Fabrication

Lockheed Martin is not currently offering start-to-finish wind tunnel model design and fabrication services at the LSWT. In some instances, the LSWT can offer design and fabrication of custom test equipment required to interface a wind tunnel model with the facility motion control systems.

The LSWT may also be able to support specific fabrication requests for individual wind tunnel model components, depending on the level of precision required for the build. Modification or repair work for existing wind tunnel model hardware

The Prusa XL 3D printer listed in Section 6.1features a build volume of 14.17×14.17×14.17 inches (360×360×360 mm) and is compatible with a variety of FDM filaments. The LSWT typically keeps PETG, PLA, and ASA stocked on site, though larger volume builds may require customers to purchase their own materials. Printed material requests can be made through LSWT engineering during pre-test and tunnel occupancy phases.

7 REQUIRED FROM CUSTOMER

7.1 Test Information

Customers of the LSWT are asked to provide a written pre-test plan no later than four weeks prior to the agreed-upon start of model installation. The pre-test plan should include the following:

1. Purpose and scope of test.
2. Security or proprietary classification for the model, test data, and report. Classified tests may require long lead times to secure necessary clearances. LSWT personnel are US citizens and hold DOD Secret level security clearances.
3. Model description: This should include model dimensions necessary for data reduction, model and installation drawings, and configuration nomenclature.
4. A stress report with critical model loads analyzed and the largest total model load estimated for balance range definition.
5. Wind tunnel operating conditions: These will include model attitudes (e.g., angle-of-attack range, angle-of-yaw range), dynamic pressure range, ground-plane positions, etc.
6. Equipment requirements: The equipment to be supplied by the customer and by the wind tunnel should be defined. This should include photographic coverage, compressed air requirements, auxiliary electrical power requirements, etc.
7. Preliminary run matrix and model incidence schedules.
8. Data requirements: Instrumentation signals to be recorded, data reduction details, data output file format, and measuring system units (Imperial or Metric).
9. General: Customer personnel arrival and model delivery dates.

This information is required sufficiently in advance of a test to allow preparation of data reduction programs, model space allotments, and internal accounting procedures. If there is difficulty in meeting the delivery date of the pre-test plan, please contact LSWT engineering.

LSWT engineers will send visit request forms to customer POCs early in the test planning phase. These forms must be completed and returned to the LSWT no later than 2 weeks prior to the requested customer arrival dates. Upon receipt, visitor forms are submitted to Lockheed Martin Aeronautics Security for review. Once approved, visitor identification badges and temporary parking passes will be pre-printed and stored at the security guard station until customer arrival.

7.2 Model Delivery

Models should be delivered to the wind tunnel at least one week before the scheduled test start date. When special instrumentation or calibration is necessary, additional time must be allowed.

The following instructions should be followed for shipment of models, test equipment, material, etc., to the Low Speed Wind Tunnel.

1. Address items to:

   Lockheed Martin Aeronautics Company
   Low Speed Wind Tunnel, L-6
   86 South Cobb Dr
   Marietta, Georgia 30063-0605

2. Freight charges should be prepaid when shipping on a commercial bill of lading.
3. Two copies of each packing list should be enclosed with the shipment. These should contain a detailed description of each item. Classified models will be handled in accordance with security requirements.
4. At the time of shipment, the Wind Tunnel should be notified of the mode and details of transportation, the waybill number, and any other pertinent information.
5. Instructions for returning all materials should accompany the shipment. All return shipments will be made "freight collect" unless prior arrangements are made.

8 REFERENCES

1. Silverstein and White "Wind Tunnel Interference with Particular Reference to Off-Center Positions of the Wing and to the Downwash at the Tail," NACA Report 547, 1935.

2. Sivells and Salmi "Jet Boundary Corrections for Complete and Semispan Swept Wings in Closed Circular Wind Tunnels," NACA TN 2454, 1951.

3. Katzoff and Hannah "Calculation of Tunnel-Induced Upwash Velocities for Swept and Yawed Wings," NACA TN 1748, 1948.

4. Herriot "Blockage Corrections for Three Dimensional Flow Closed Throat Wind Tunnels, with Consideration of the Effect of Compressibility," NACA Report 995, 1950.

5. Maskell "A Theory of the Blockage Effects on Bluff Bodies and Stalled Wings in a Closed Wind Tunnel," A.R.C. R&M 3400, 1963.

6. Hackett and Wilsden "Determination of Low Speed Wake Blockage Corrections via Tunnel Wall Static Pressure Measurements," AGARD CP 174-23, 1975.

7. Hackett, Wilsden, and Stevens "A Review of the Wall Pressure Signature and other Tunnel Constraint Correction Methods for High Angle-of-Attack Tests," AGARD CP 692-2, 1980.

8. Hackett "Living with Solid-Walled Wind Tunnels," AIAA-82-0583, 1982.

9. Hemsch "Development and Status of Data Quality Assurance Program at NASA Langley Research Center – Toward National Standards," AIAA 96-2214, 1996.

10. Shewhart *Statistical Method from the Viewpoint of Quality Control*, Dover, 1986.

11. *NIST/SEMATECH e-Handbook of Statistical Methods*, http://www.itl.nist.gov/div898/handbook/

12. Cahill "Application of Uncertainty Methodology for the Wind Tunnel Facilities at AEDC," AIAA 96-2216, 1996.

13. AIAA Assessment of Experimental Uncertainty with Applications to Wind Tunnel Testing, AIAA S-071A-1999, 1999.

14. Perry Data Quality Assurance at the Lockheed Martin Low Speed Wind Tunnel, internal Lockheed Martin document, 2003.

15. Extend – Performance modeling for decision support, User's Manual for Extend, 1995.

9 FIGURES

Figure 1. Aerial Photograph of the Low Speed Wind Tunnel.

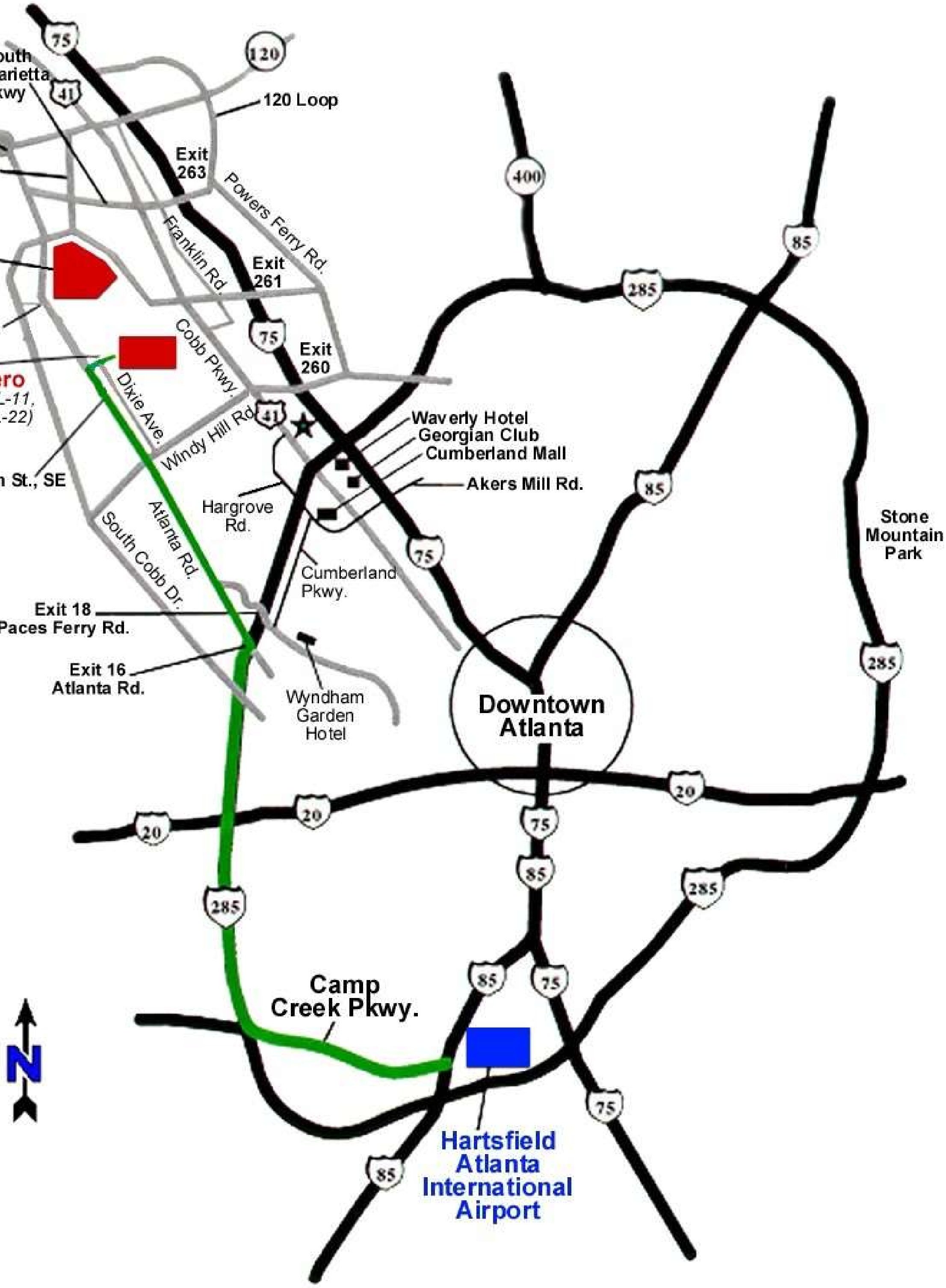


Figure 2. Map of Atlanta Area.

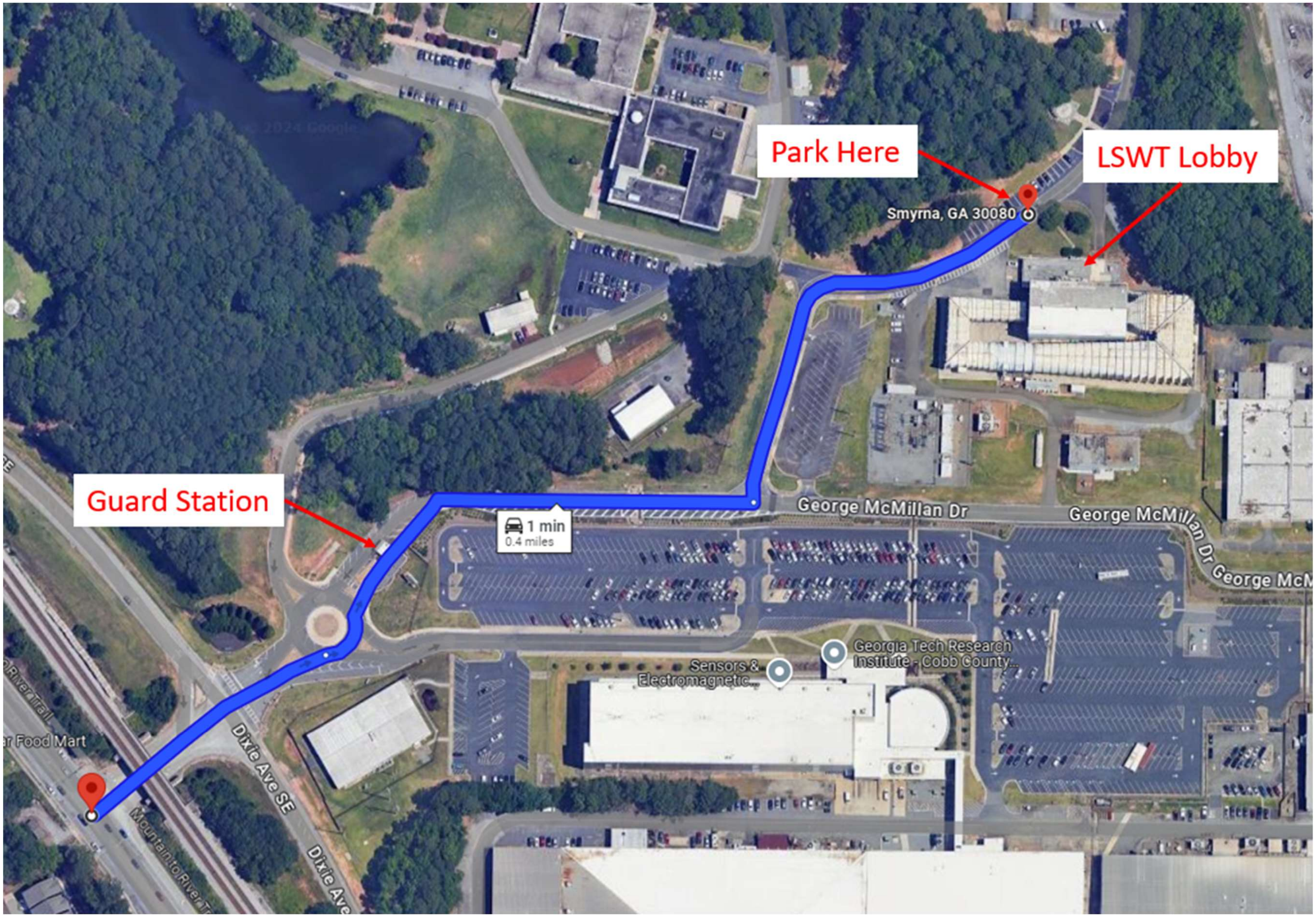


Figure 3. Route to LSWT Parking from Atlanta Road.

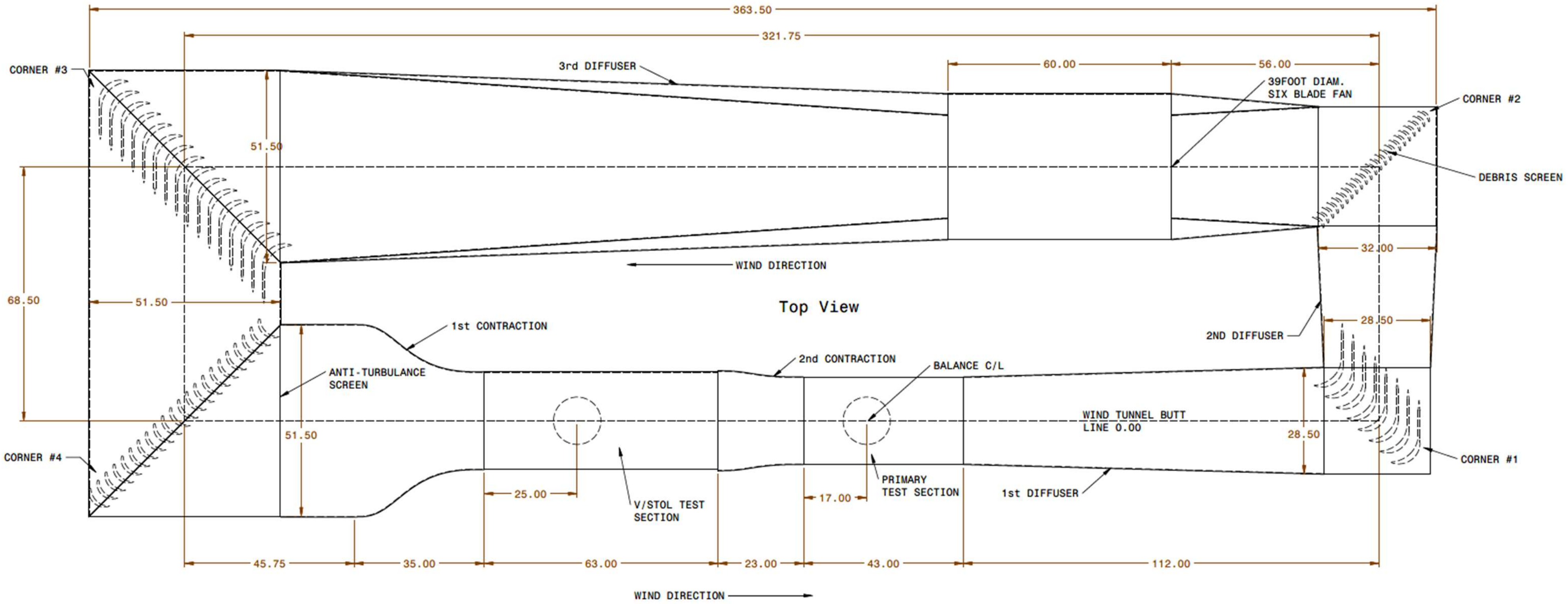


Figure 4. General Arrangement of the Low Speed Wind Tunnel.

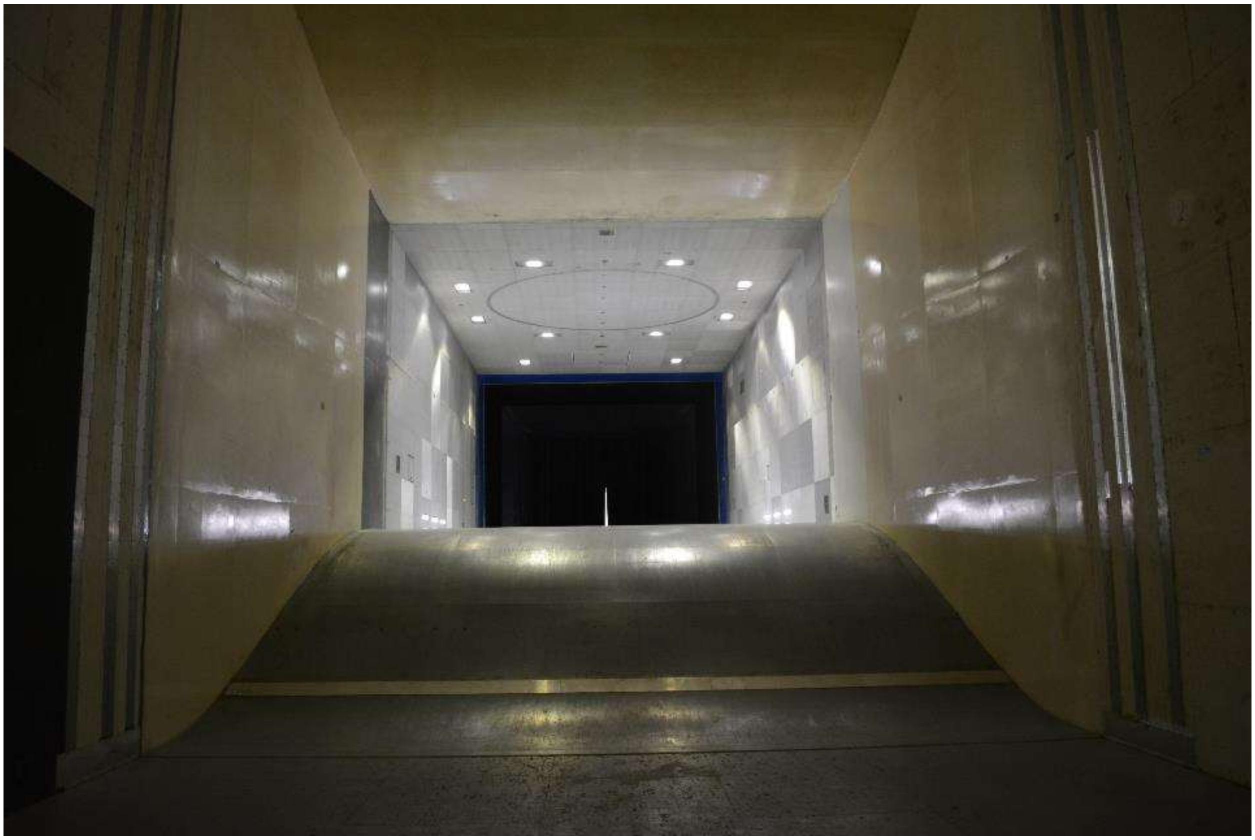


Figure 5. View Looking Downstream Through Both Test Sections.

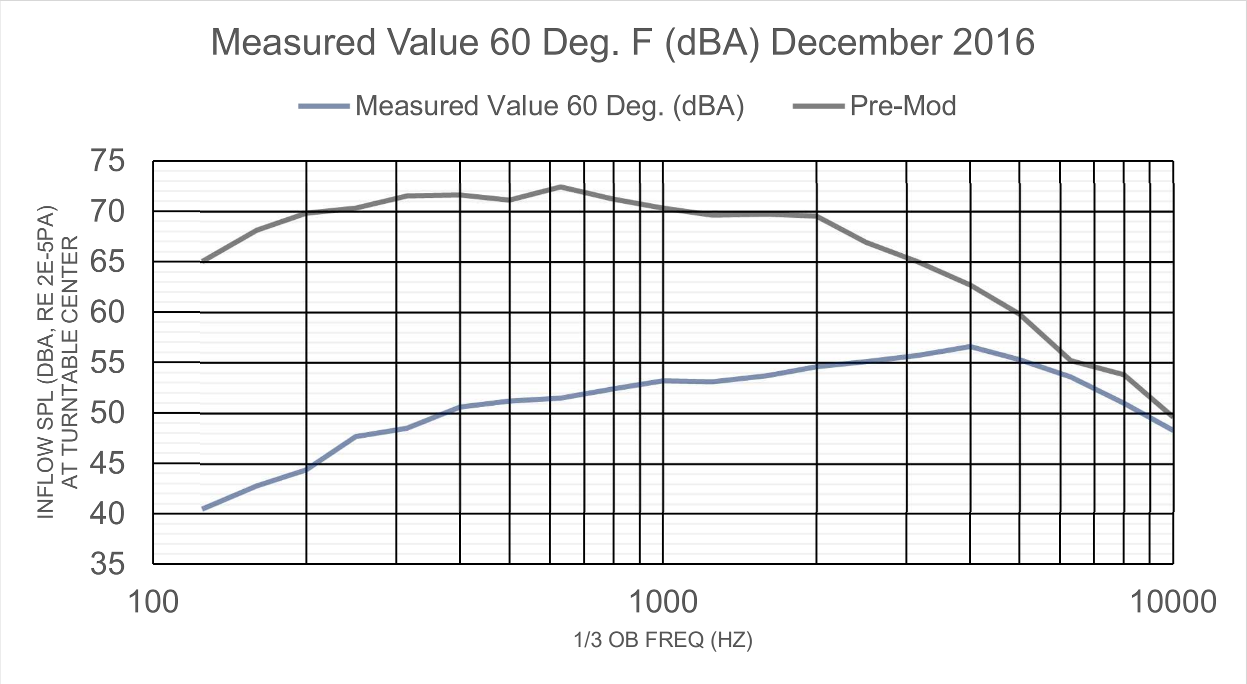


Figure 6. Empty Test Section Background Noise Level, Pre- and Post-Modification, Measured at 70 Miles Per Hour.

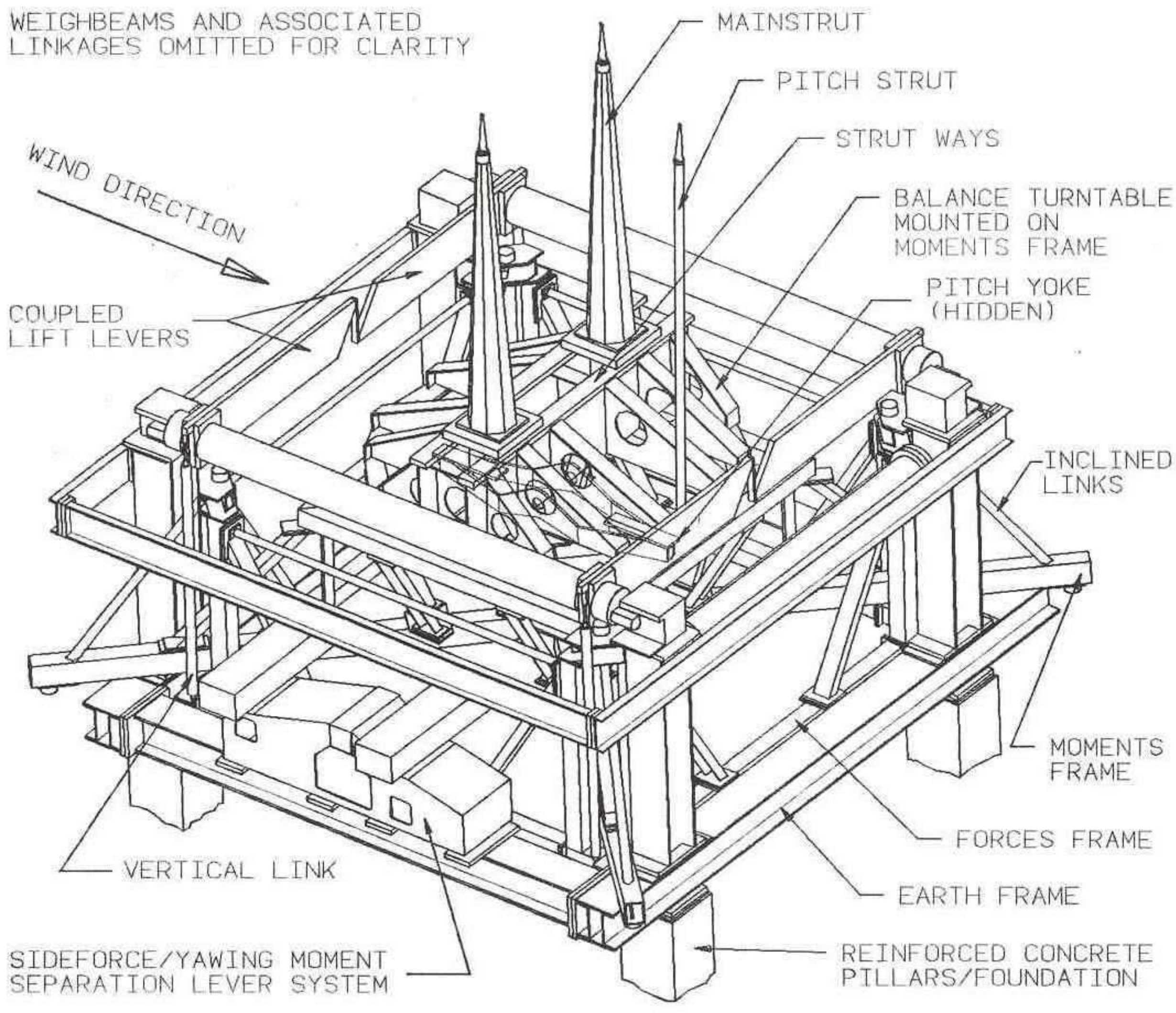


Figure 7. Isometric View of External Six-Component Balance.

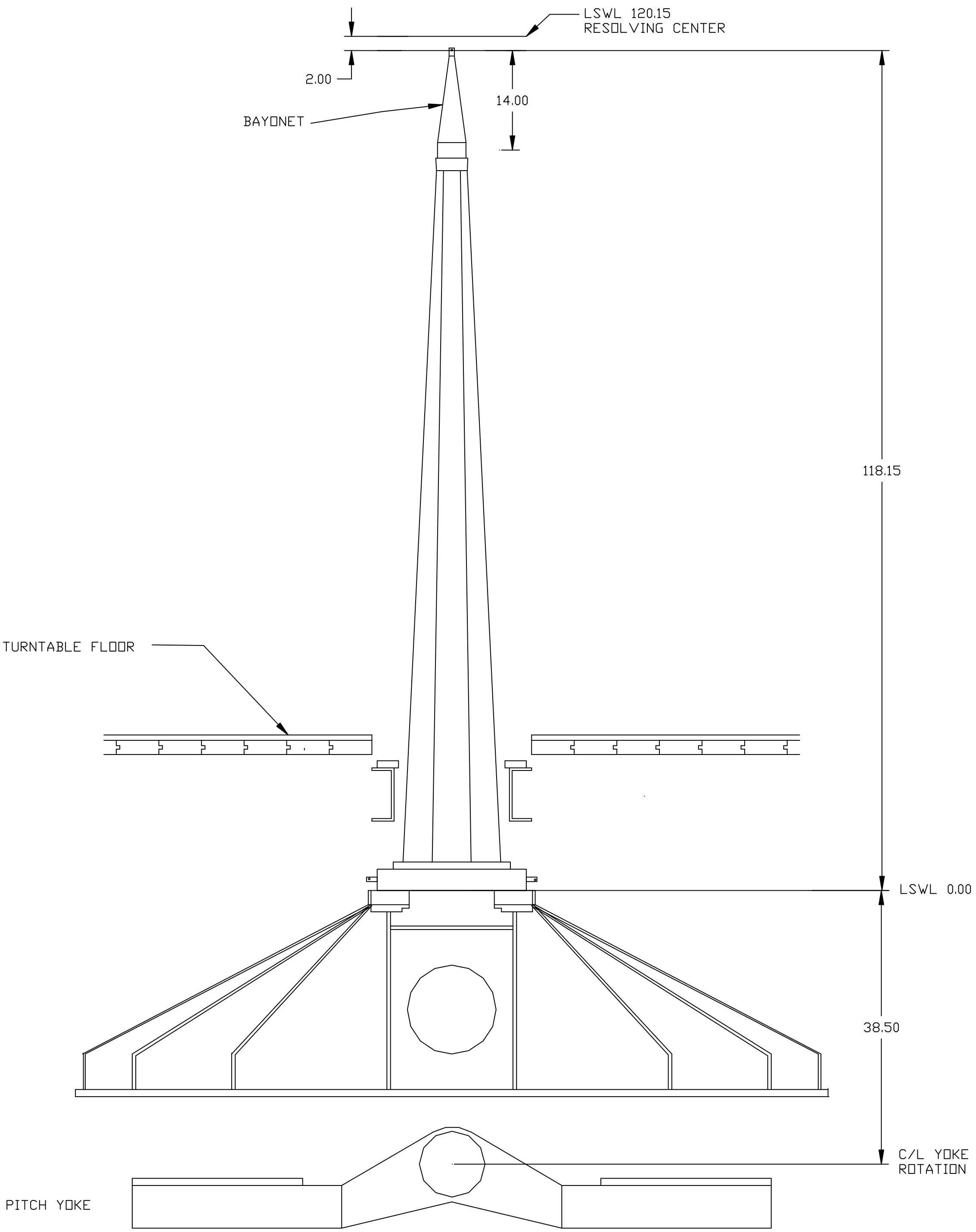


Figure 8. External Balance Resolving Centers.

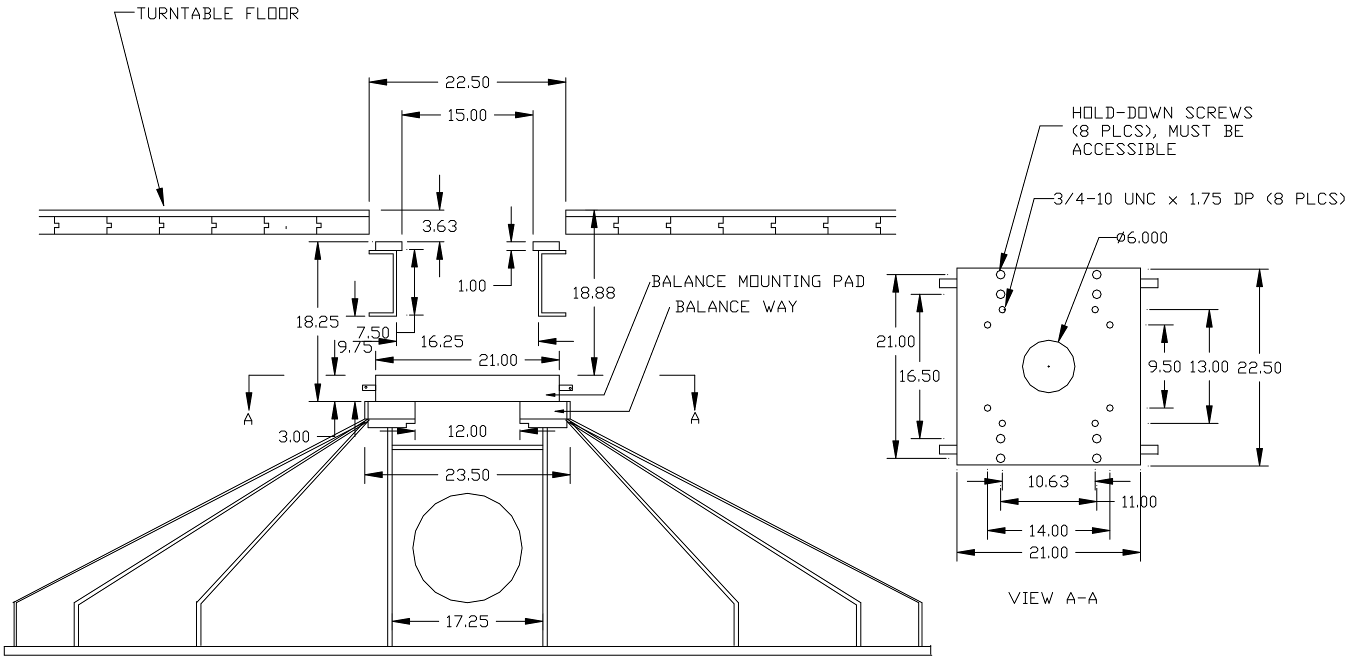


Figure 9. External Balance Attachment Details.

Figure 10. Three-strut Installation.

Figure 11. Two-strut Installation.

Figure 12. Fork-mounted Model.

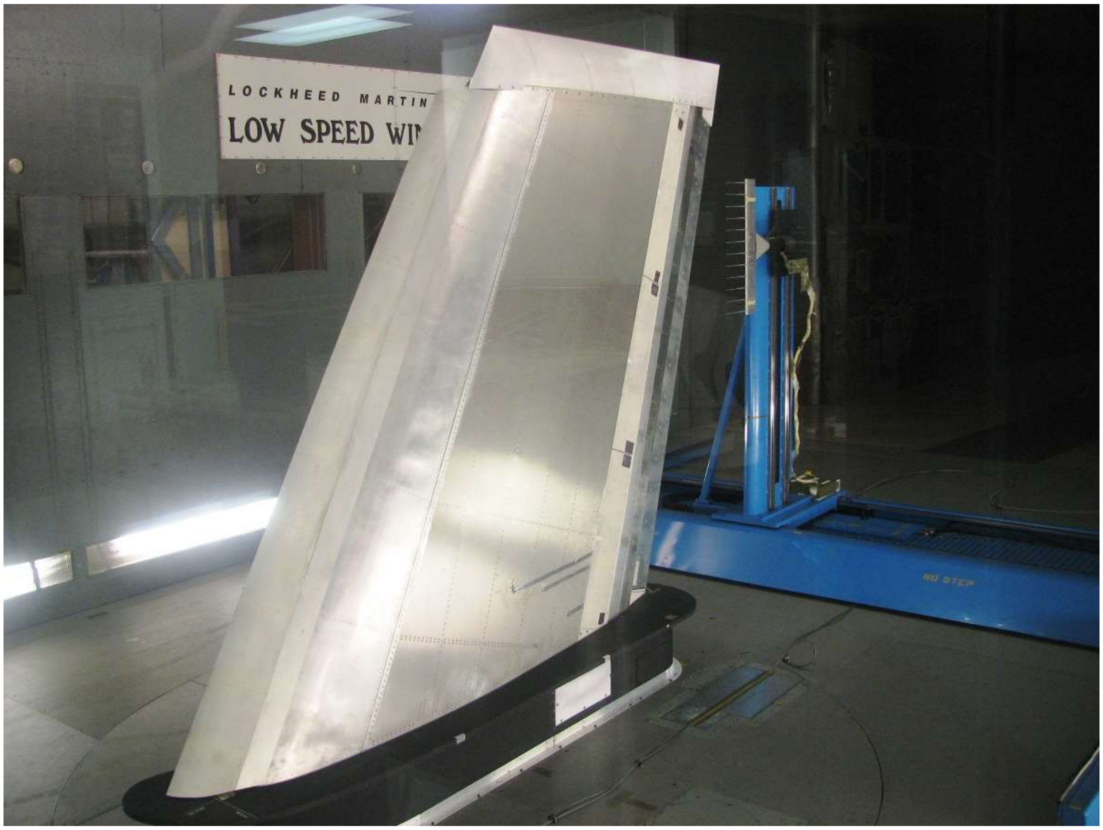


Figure 13. Panel Model Installed with Wake Survey System.

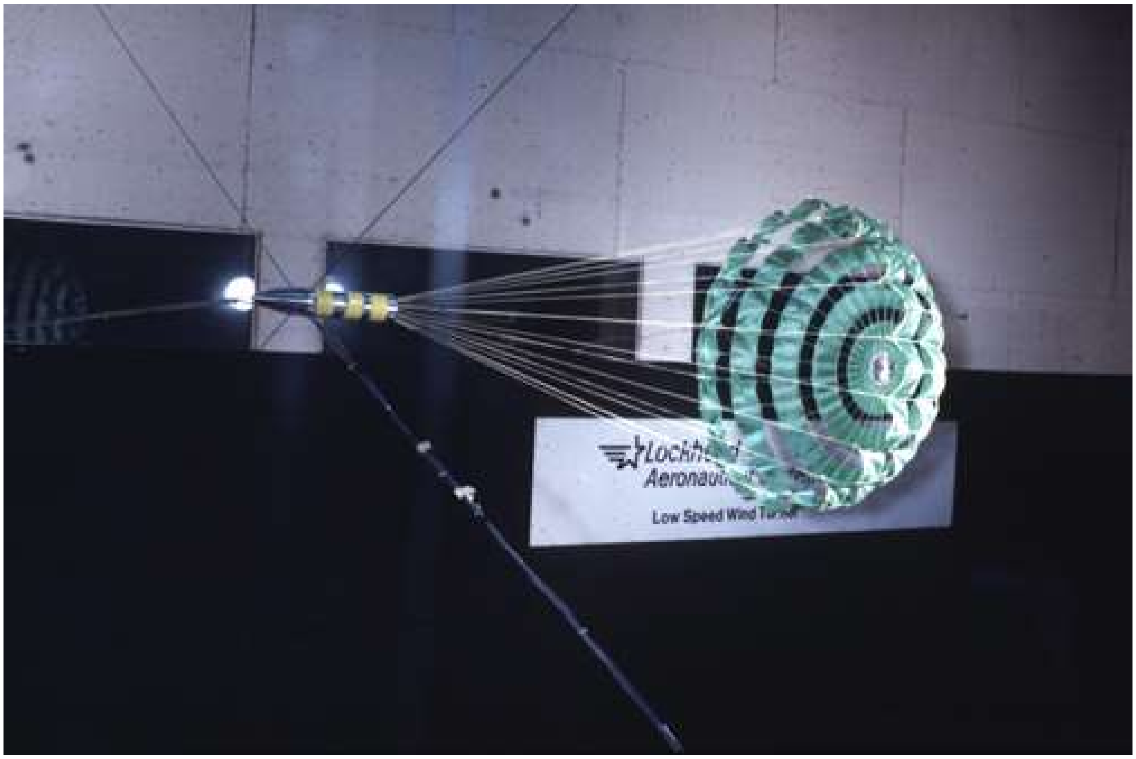


Figure 14. Special Aerospace (Parachute) Installation.

Figure 15. Architectural Model (Lighting Fixture) Installation.

Figure 16. Antenna Installation.

Figure 17. Automotive Clay Model Installation.

Figure 18. IMSA Race Car Installation.

Figure 19. NASCAR Race Car Installation.

Figure 20. Motorcycle Installation.

Figure 21. 0.3-Scale Tractor/Trailer Model Installation.

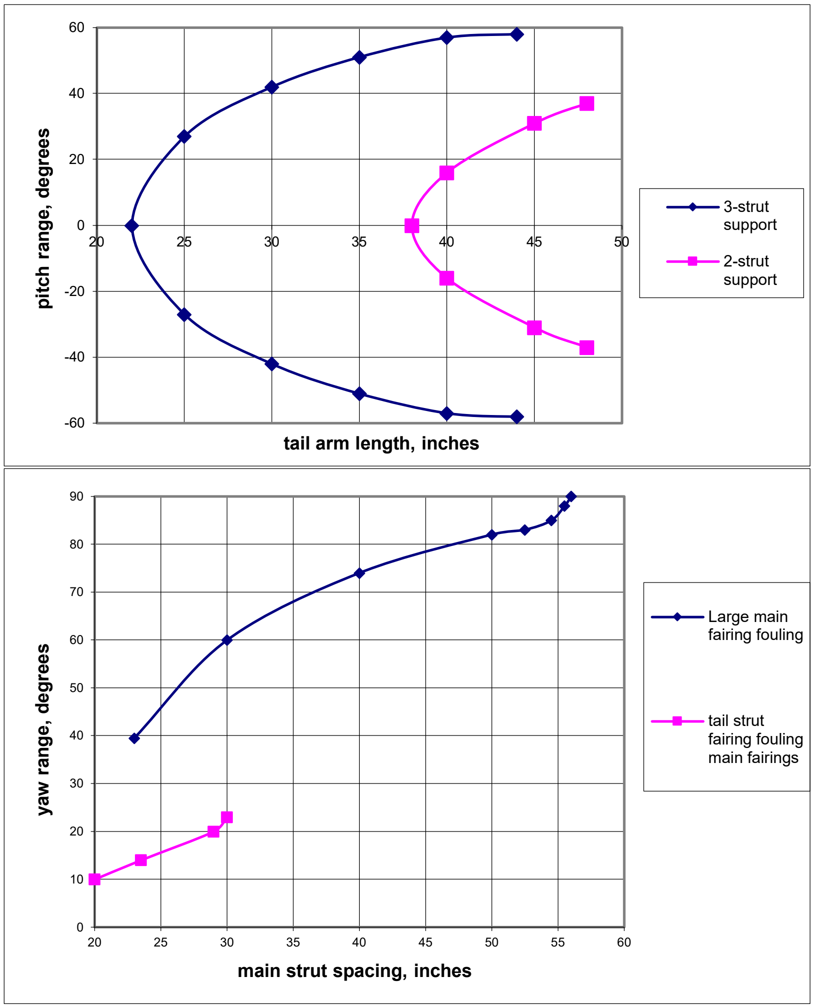


Figure 22. Effects of Strut Spacing on Model Incidence Ranges.

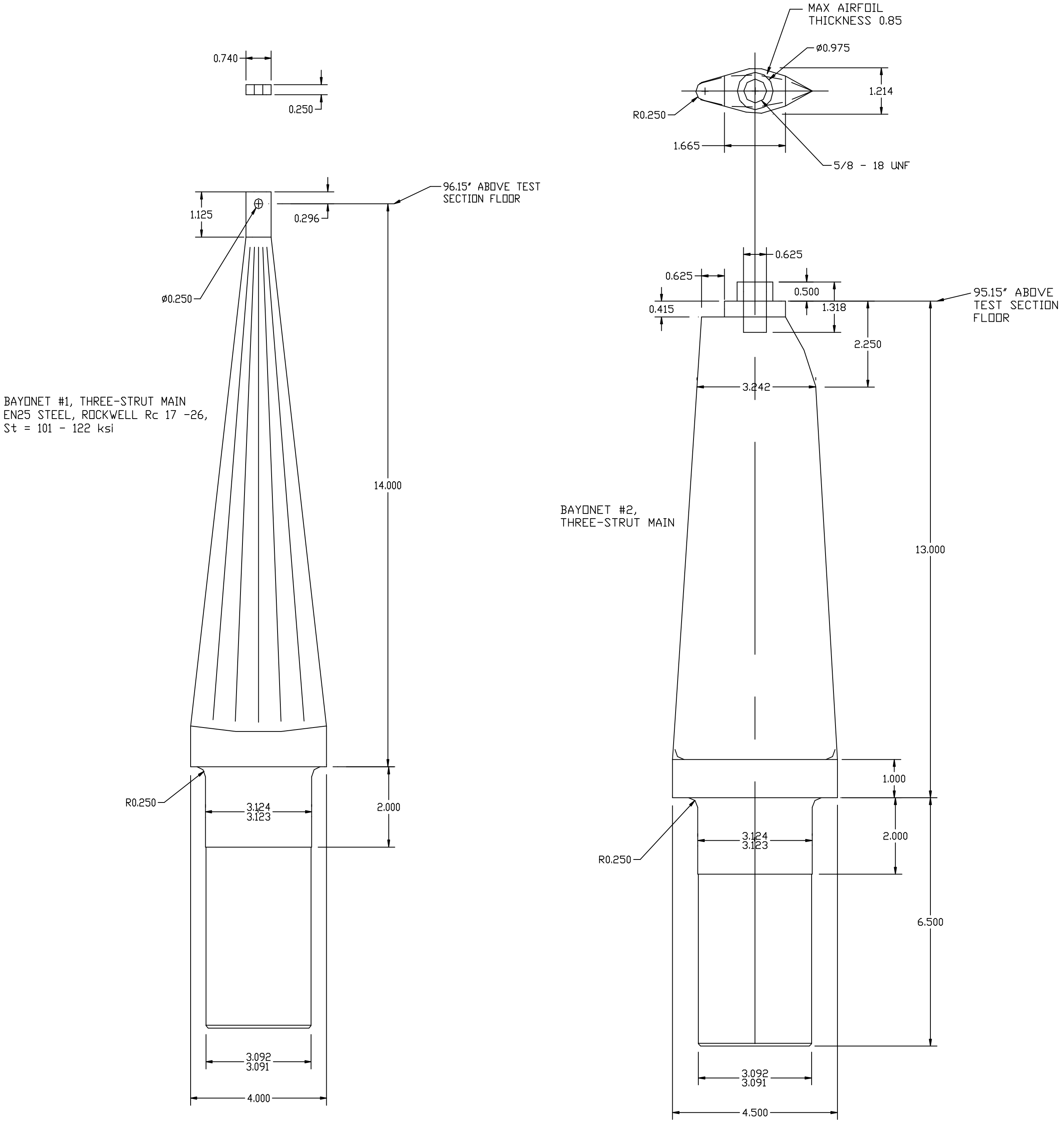


Figure 23. Three-strut Main Bayonets.

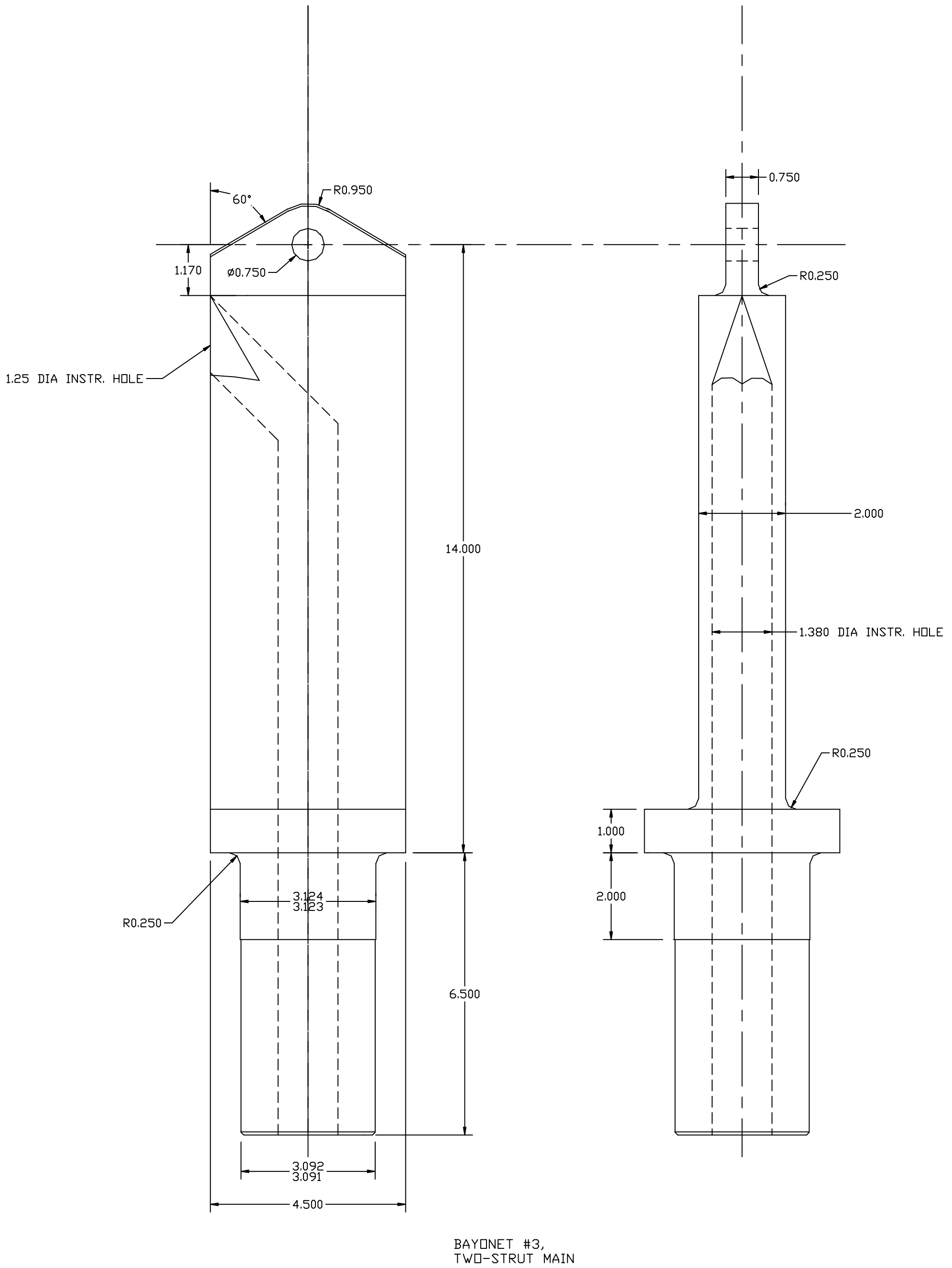
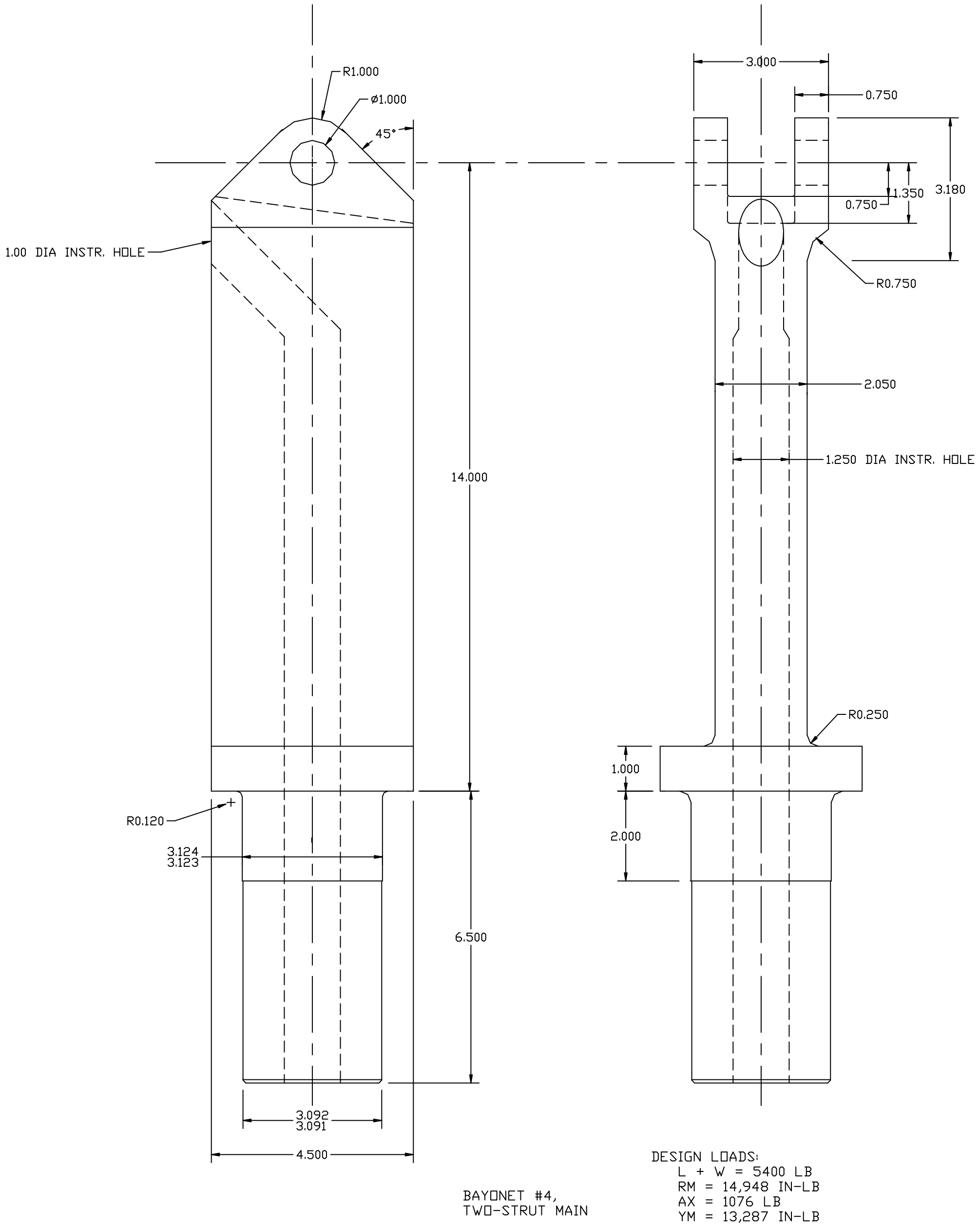


Figure 24. Two-strut Main Bayonets.



BAYONET #4,
TWO-STRUT MAIN

DESIGN LOADS:
L + W = 5400 LB
RM = 14,948 IN-LB
AX = 1076 LB
YM = 13,287 IN-LB

Figure 24. Two-strut Main Bayonets (continued).

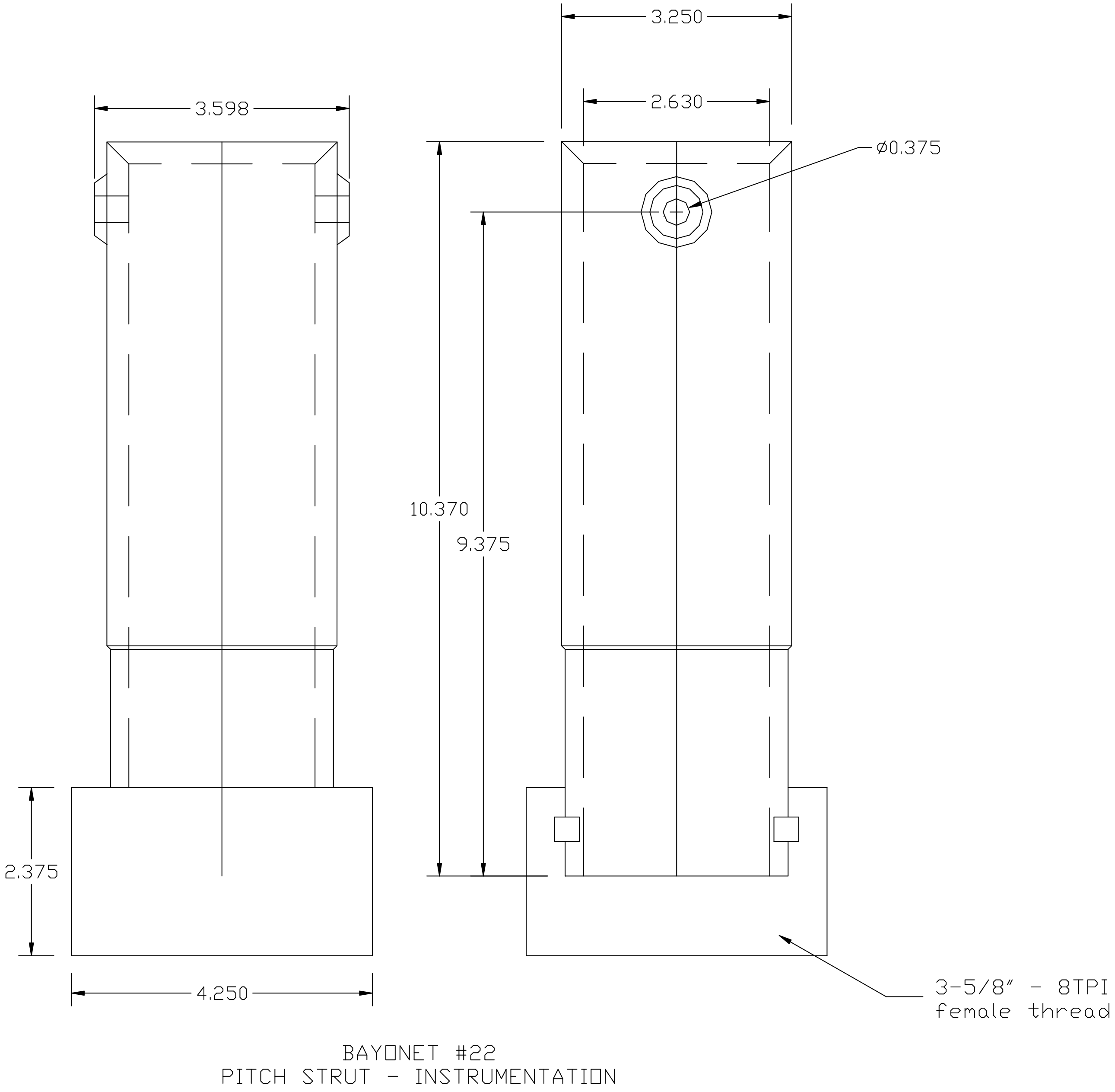


Figure 25. Pitch Bayonets.

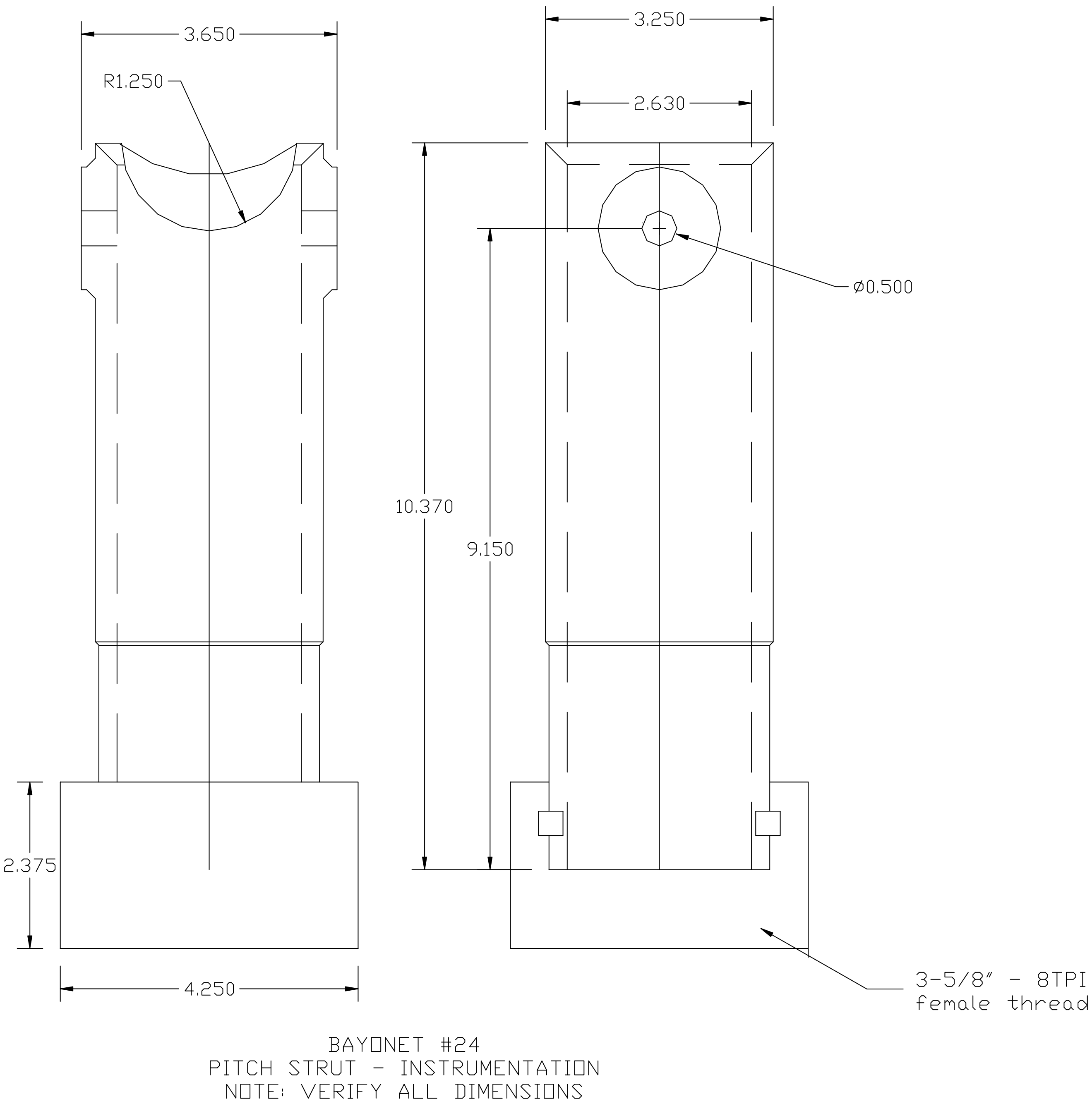


Figure 25. Pitch Bayonets (continued).

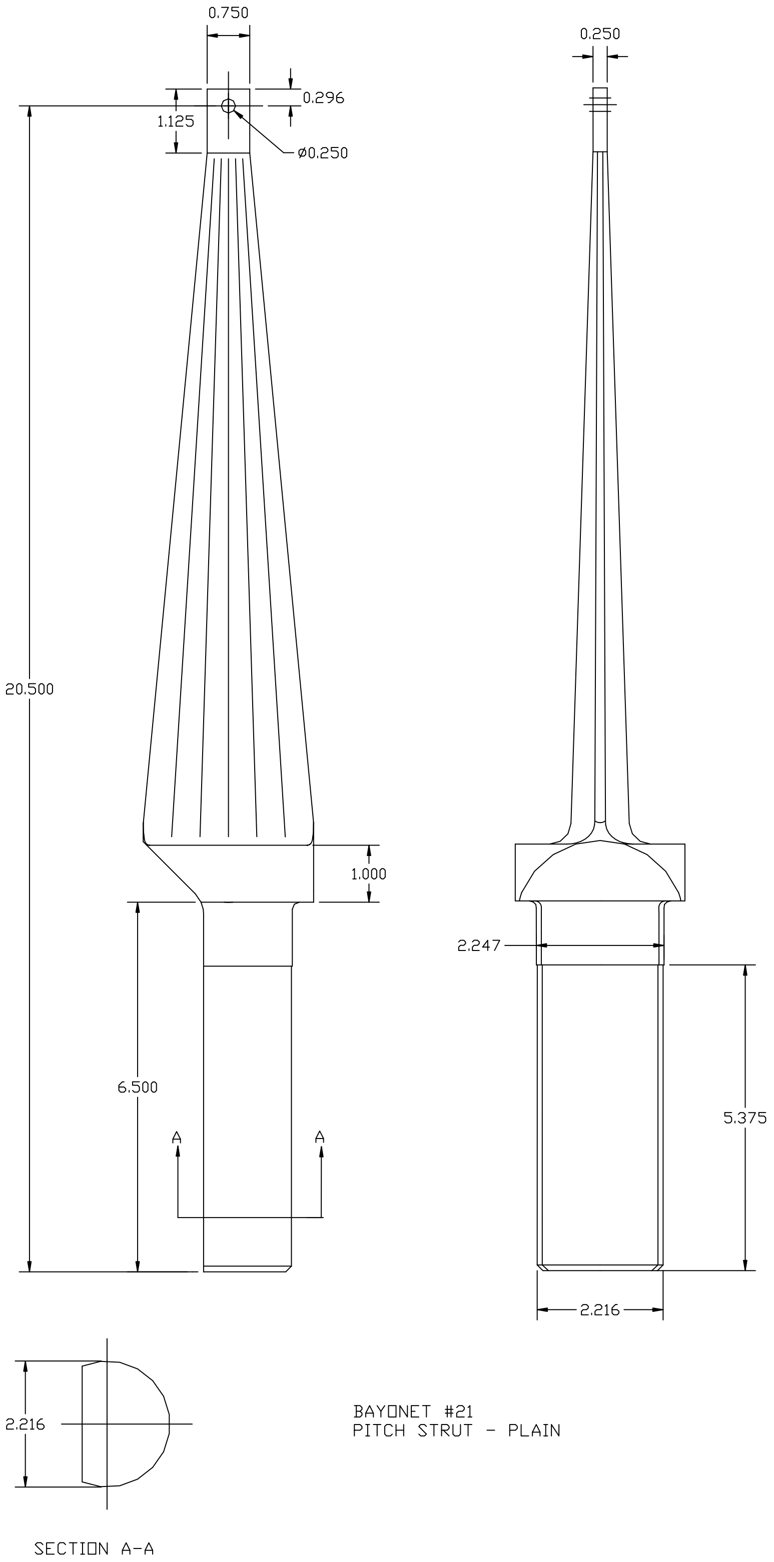


Figure 25. Pitch Bayonets (continued).

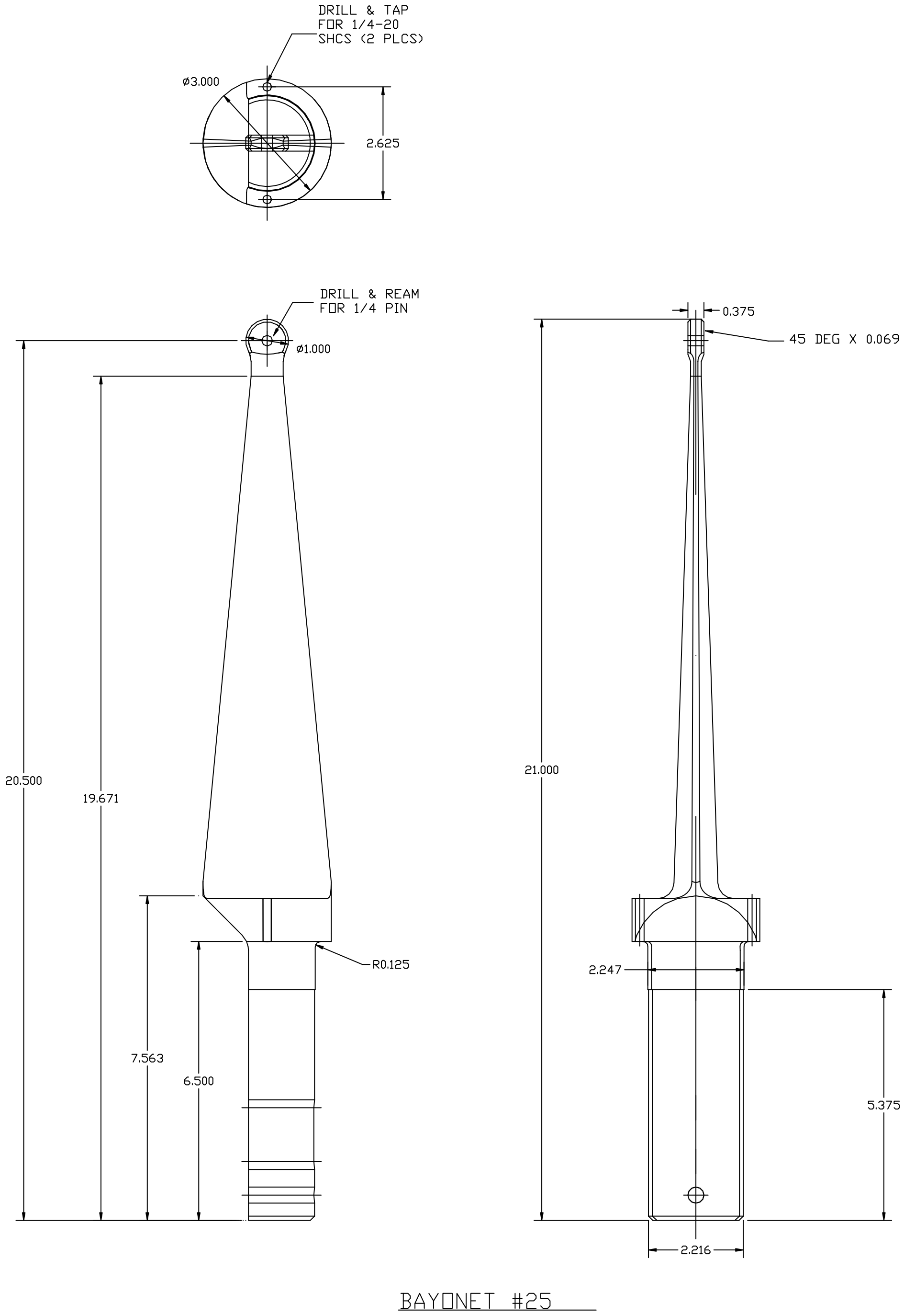


Figure 25. Pitch Bayonets (continued).

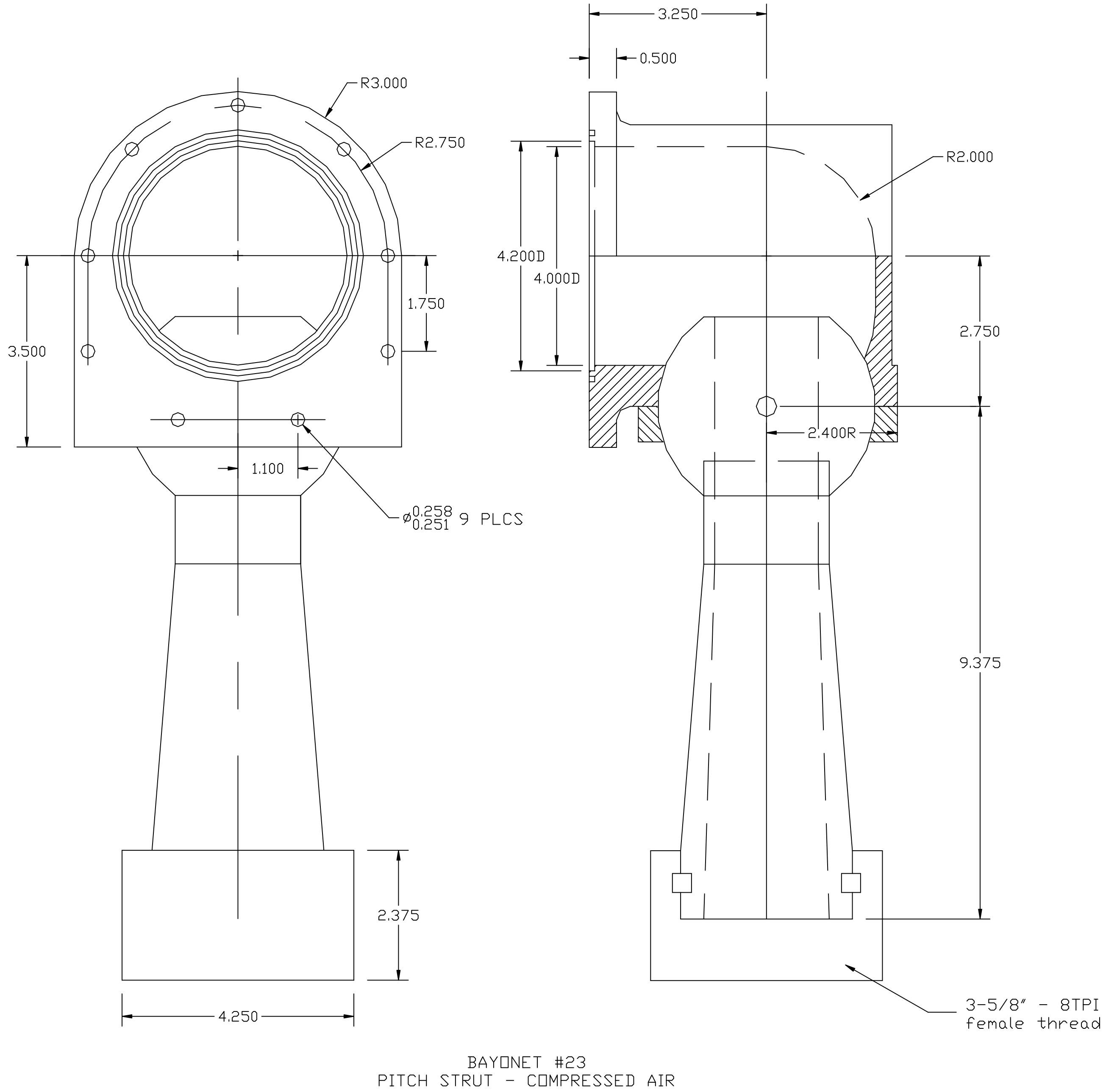


Figure 26. Air-carrying Pitch Bayonet.

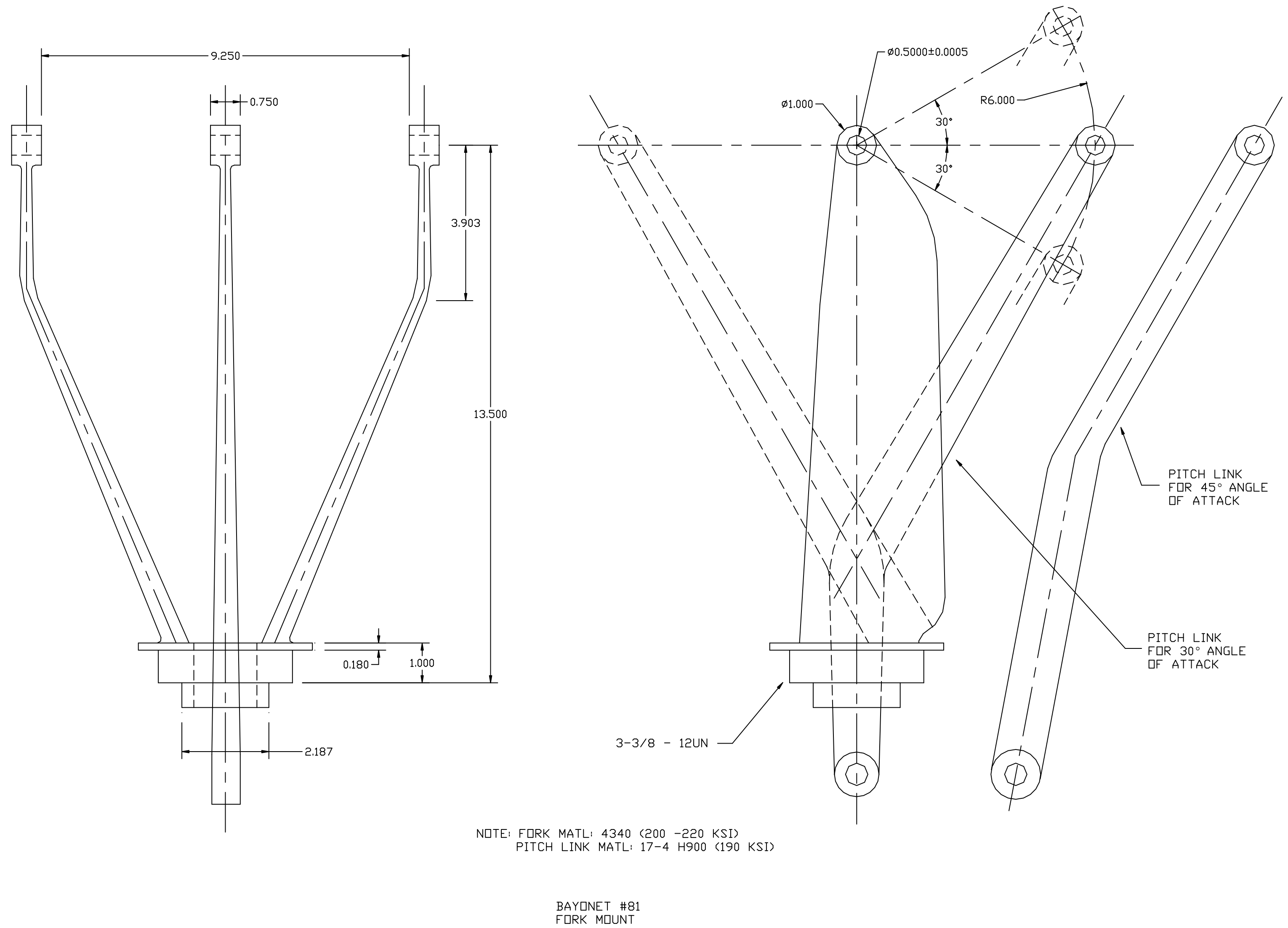


Figure 27. Fork-mount Bayonet.

Note: Other forks are also available. Contact the Wind Tunnel for details.

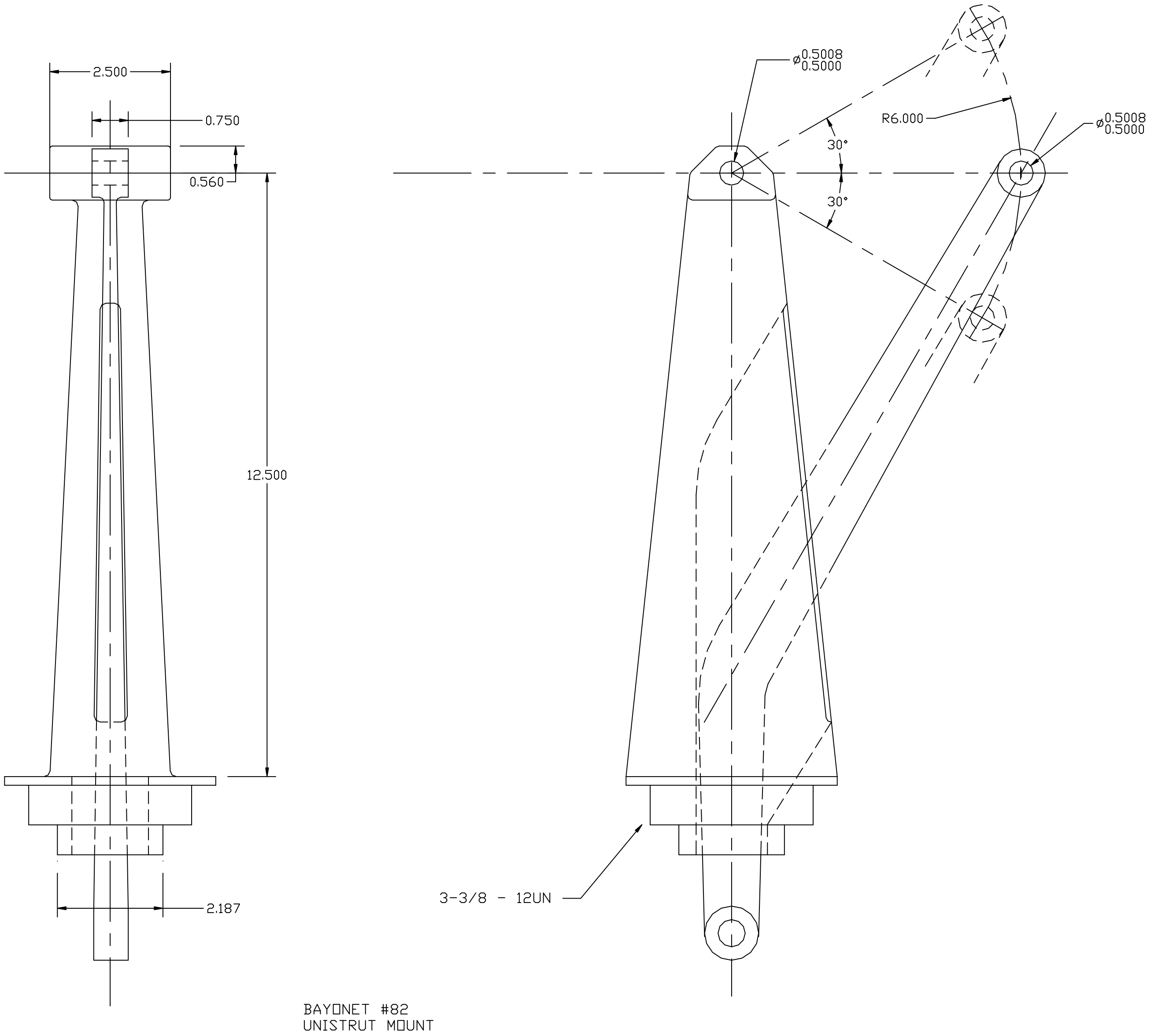


Figure 28. Unistrut Bayonet.

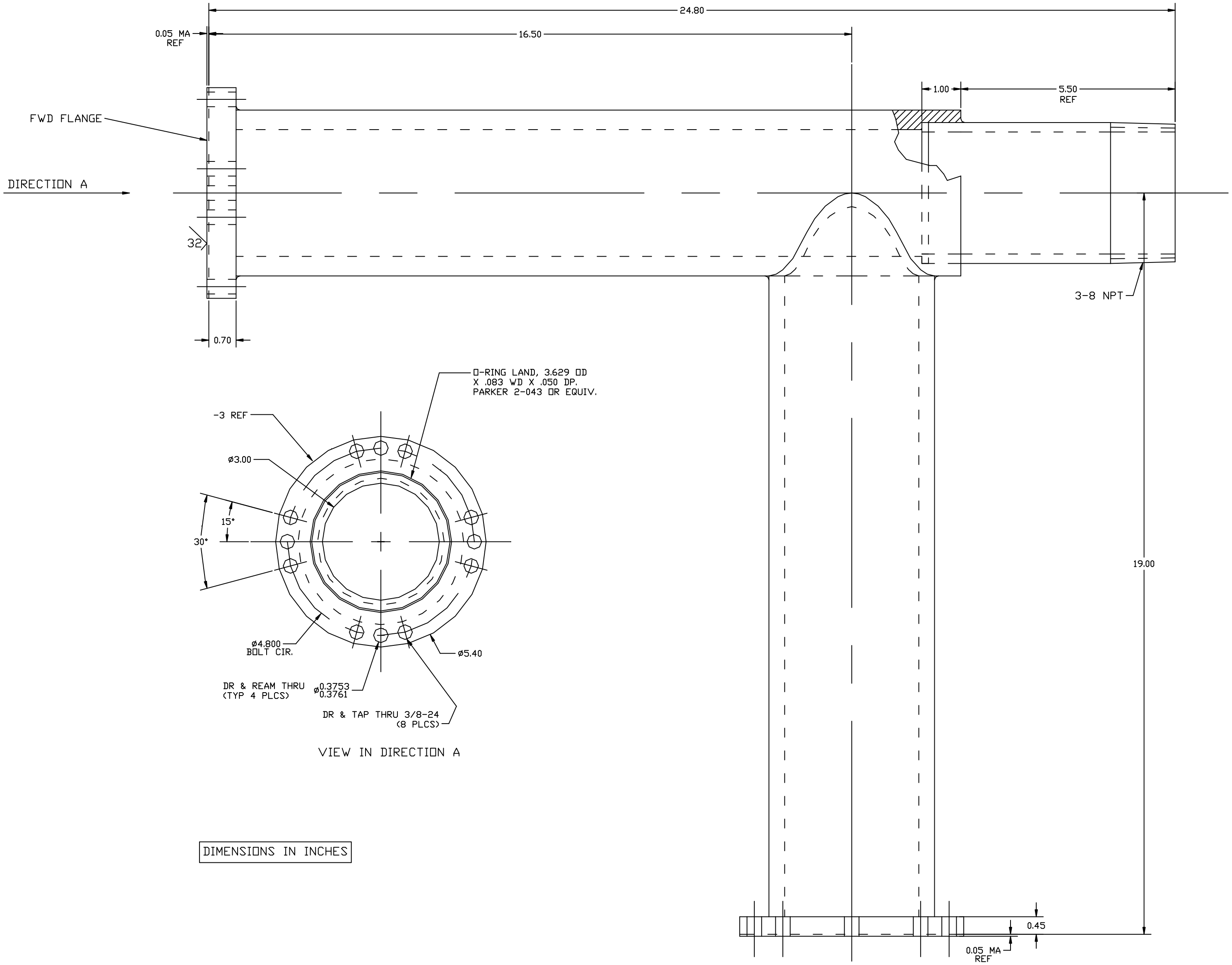


Figure 29. Light Duty Sting.

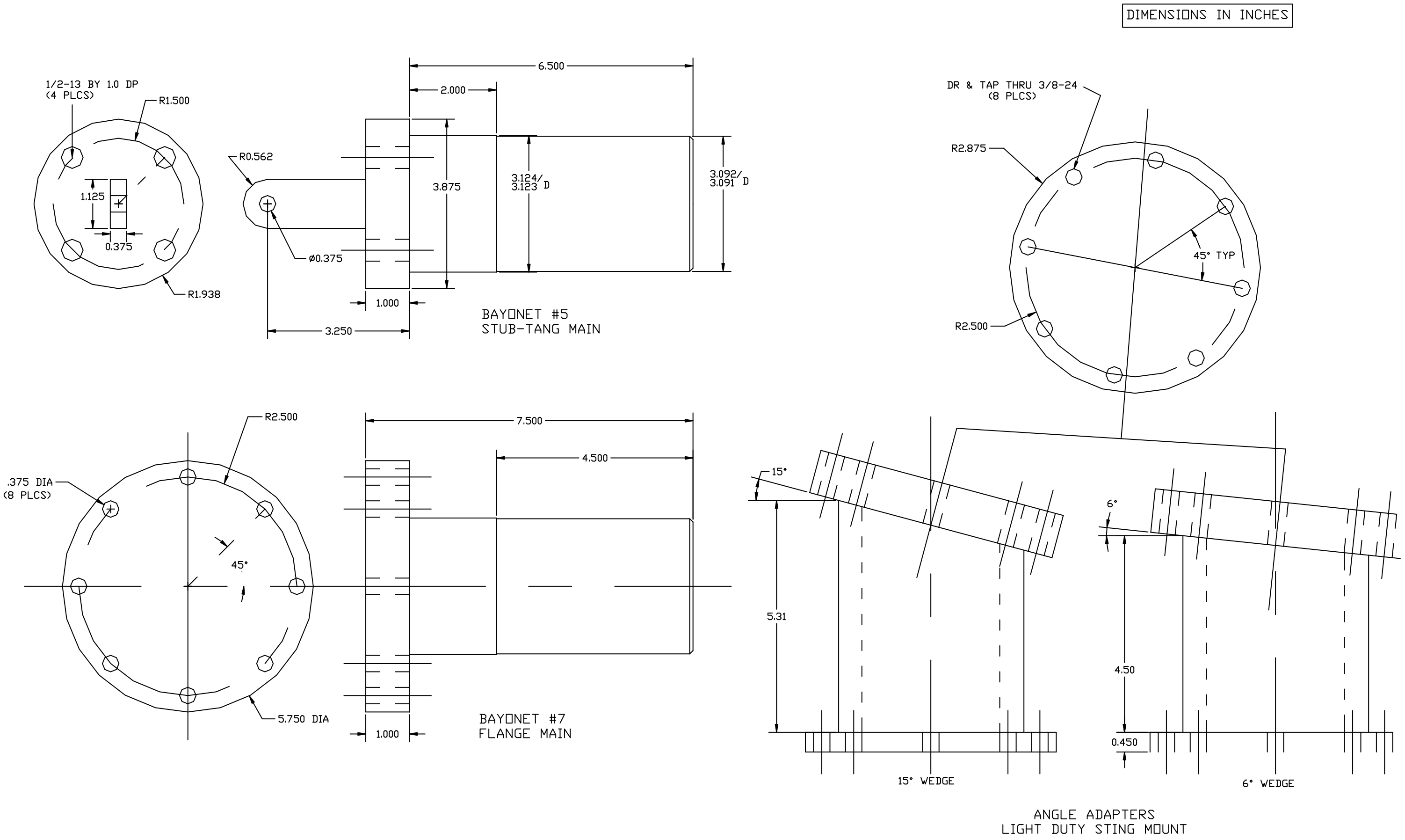


Figure 30. Miscellaneous Mounting Hardware.

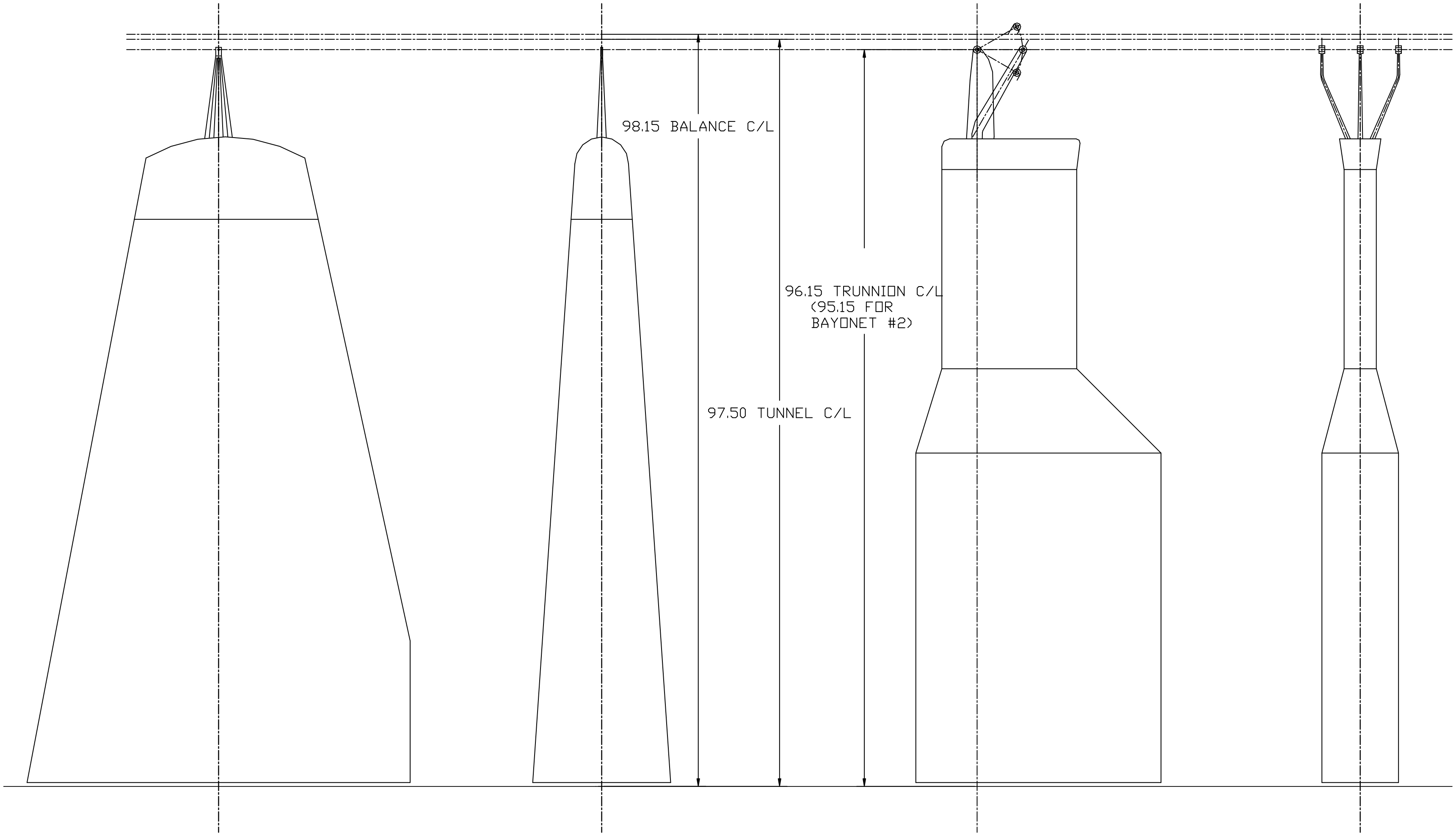
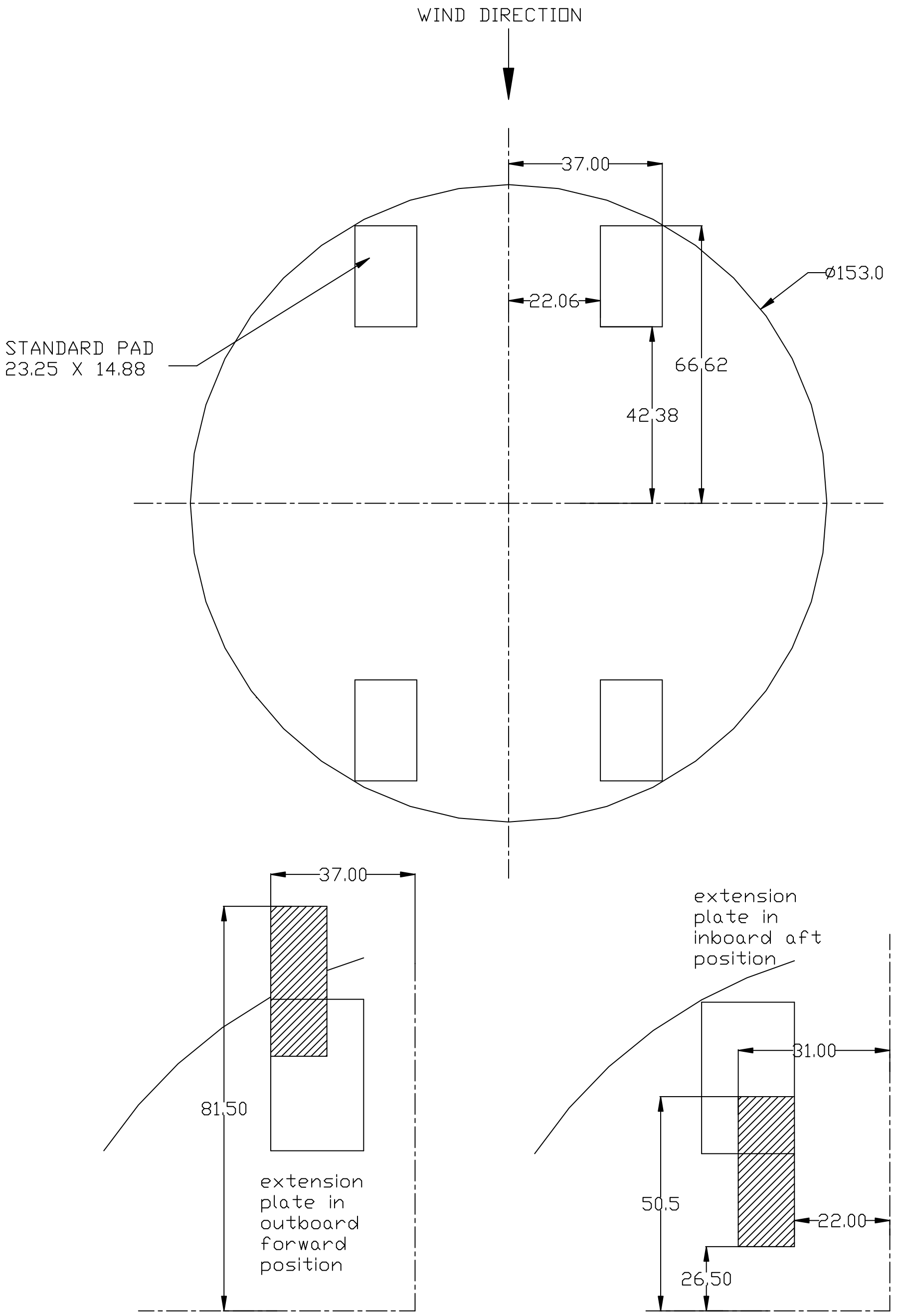


Figure 31. Windshields.



NOTE: Extension plates can be placed inboard or outboard, forward or aft to accomodate various track/wheelbase combinations. Contact Wind Tunnel for more information.

Figure 32. Turntable and Automotive Pad Details.

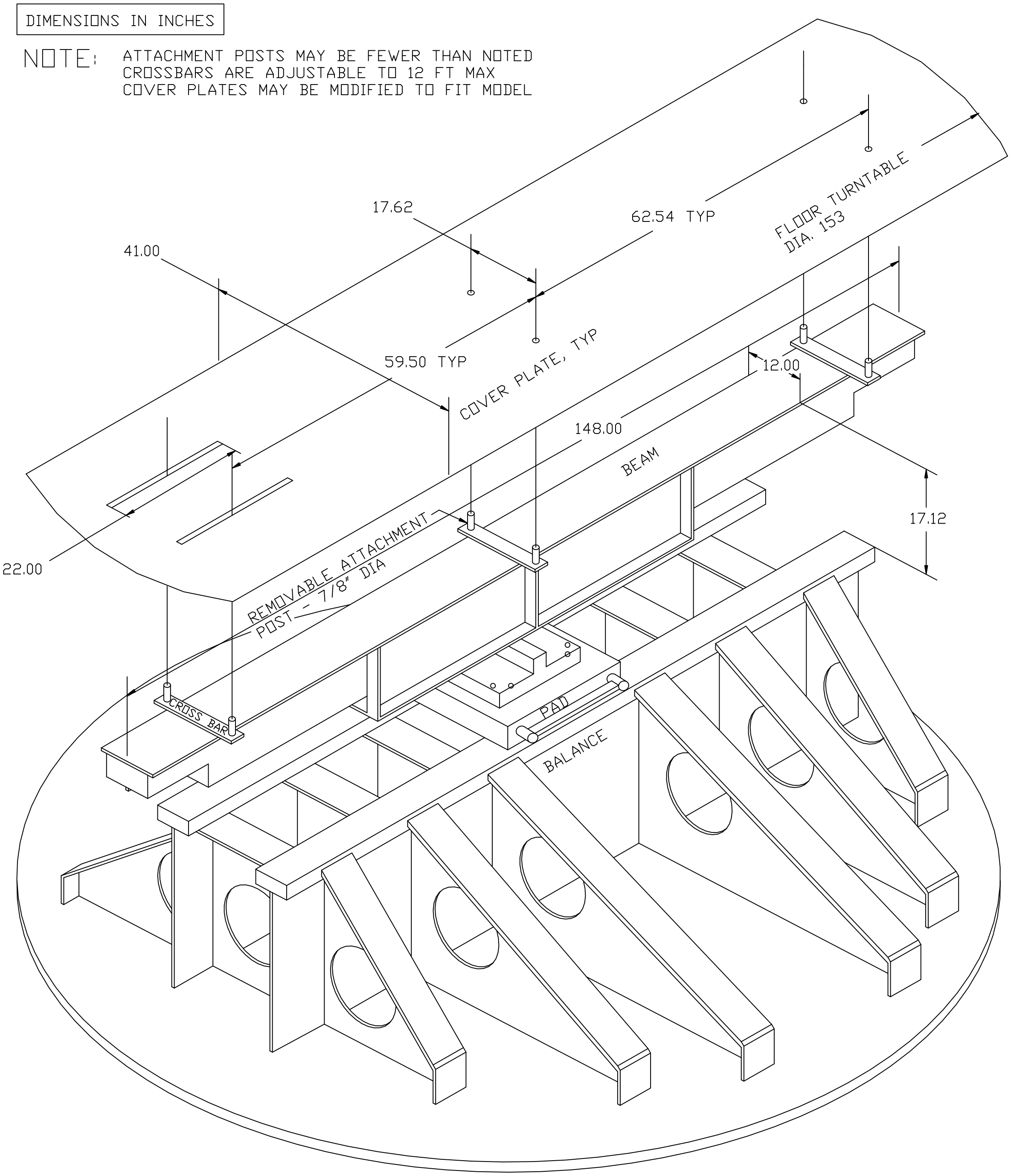


Figure 33. Scale Model Mounting Beam.

Figure 34. Aircraft Model Mounted on Sting Support System.

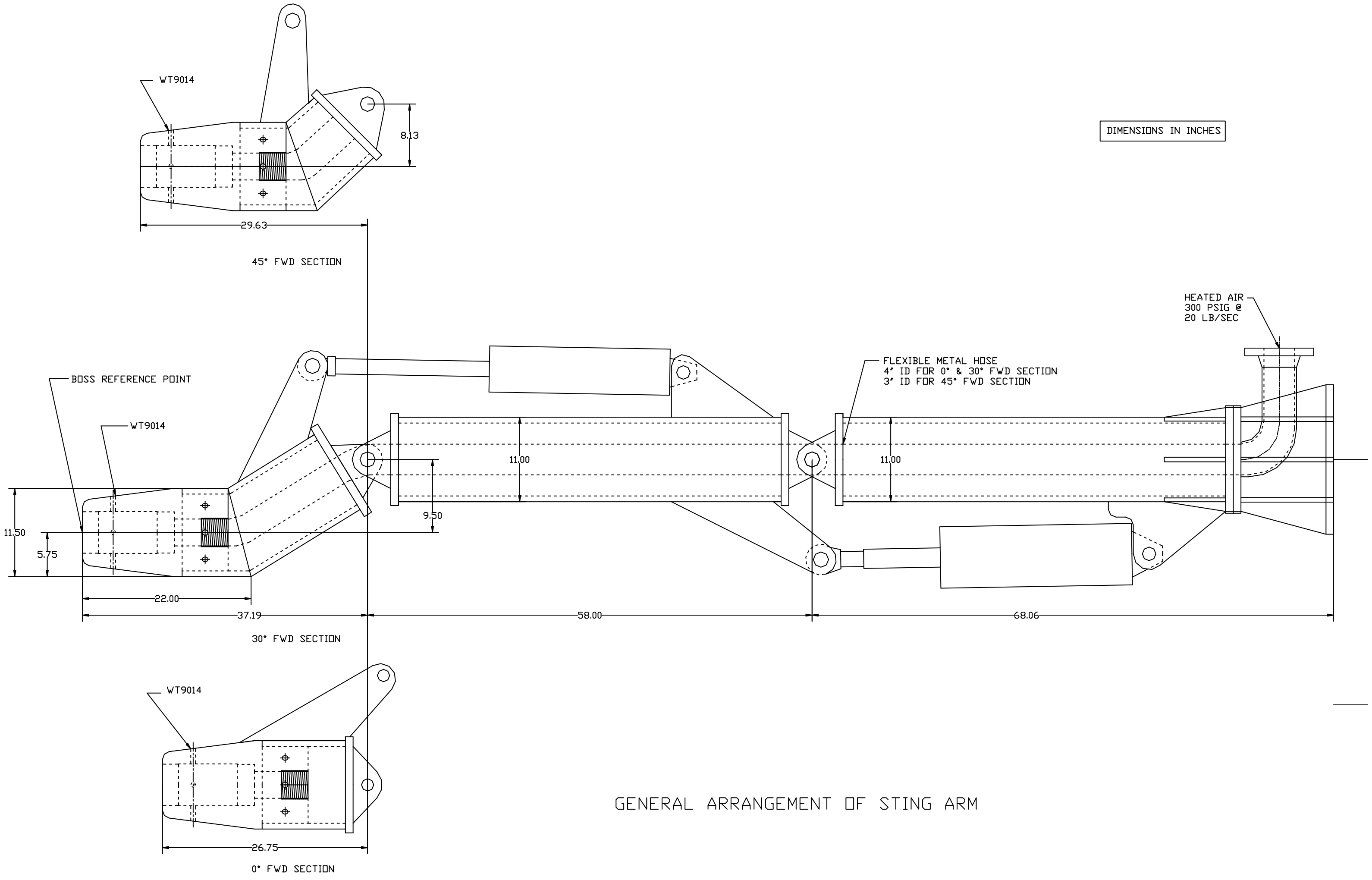


Figure 35a. Articulated Sting Arm Details – Zero Vertical Offset.

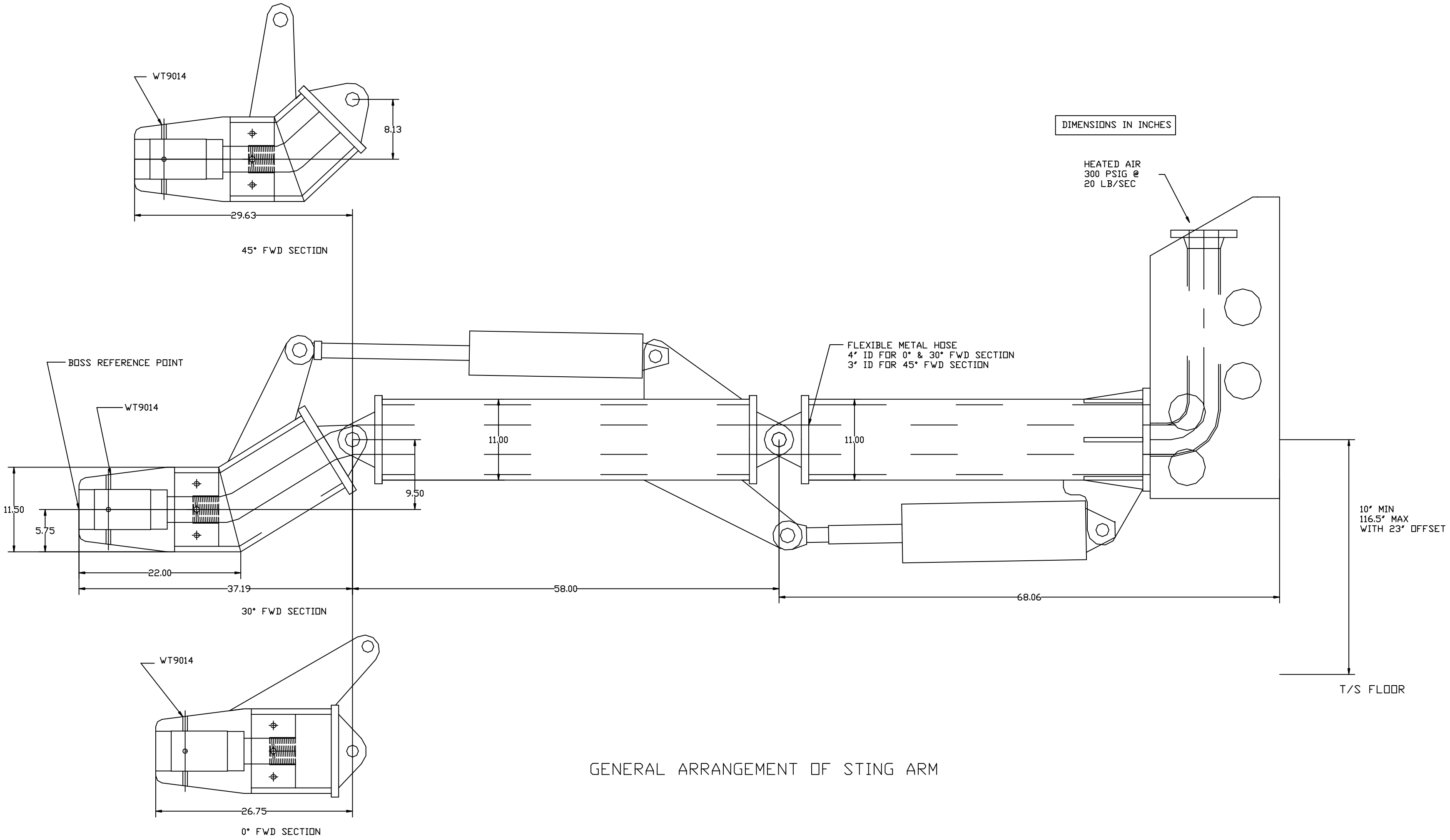


Figure 35b. Articulated Sting Arm Details – 23" Vertical Offset.

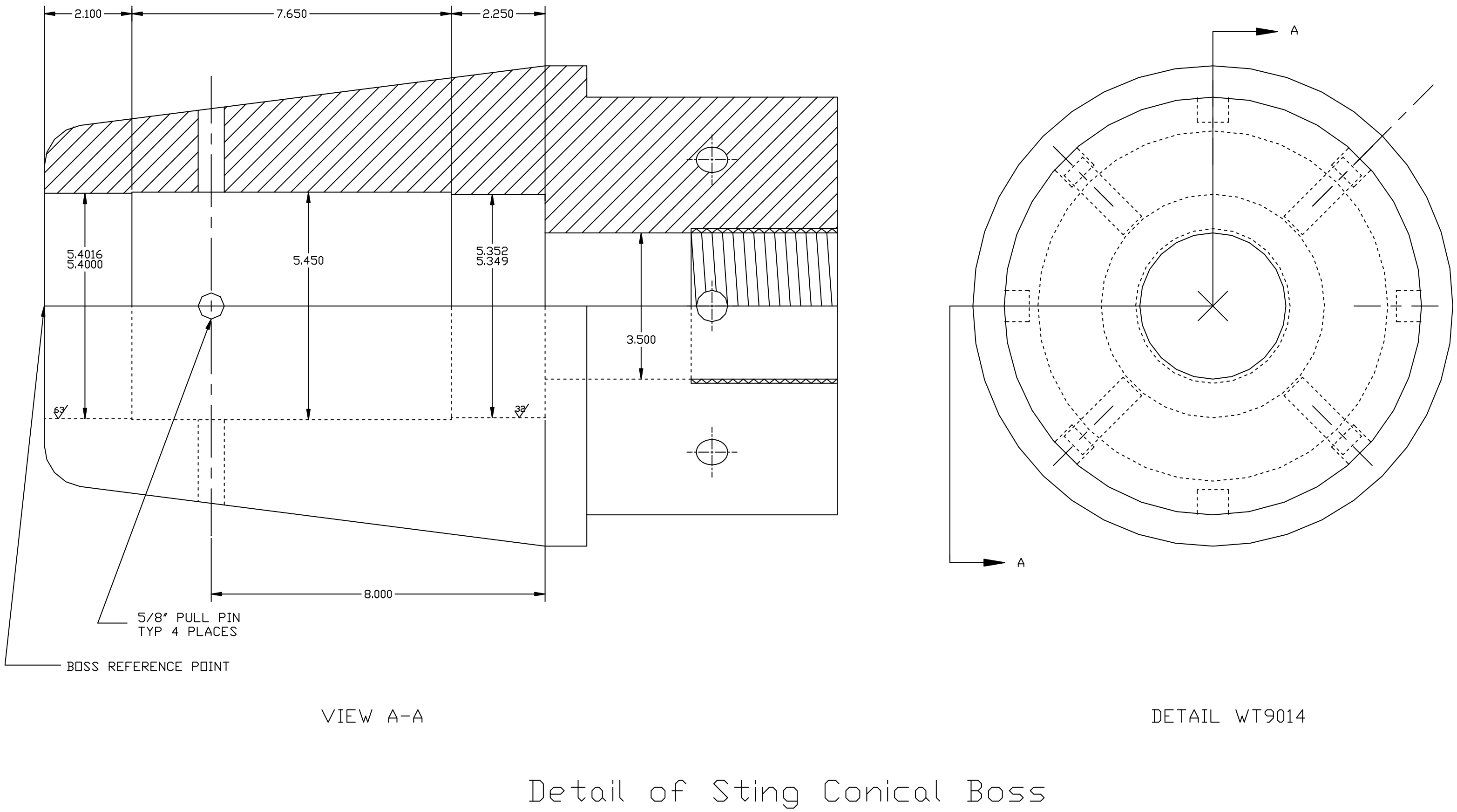


Figure 36. WT-9014 Sting Boss Details.

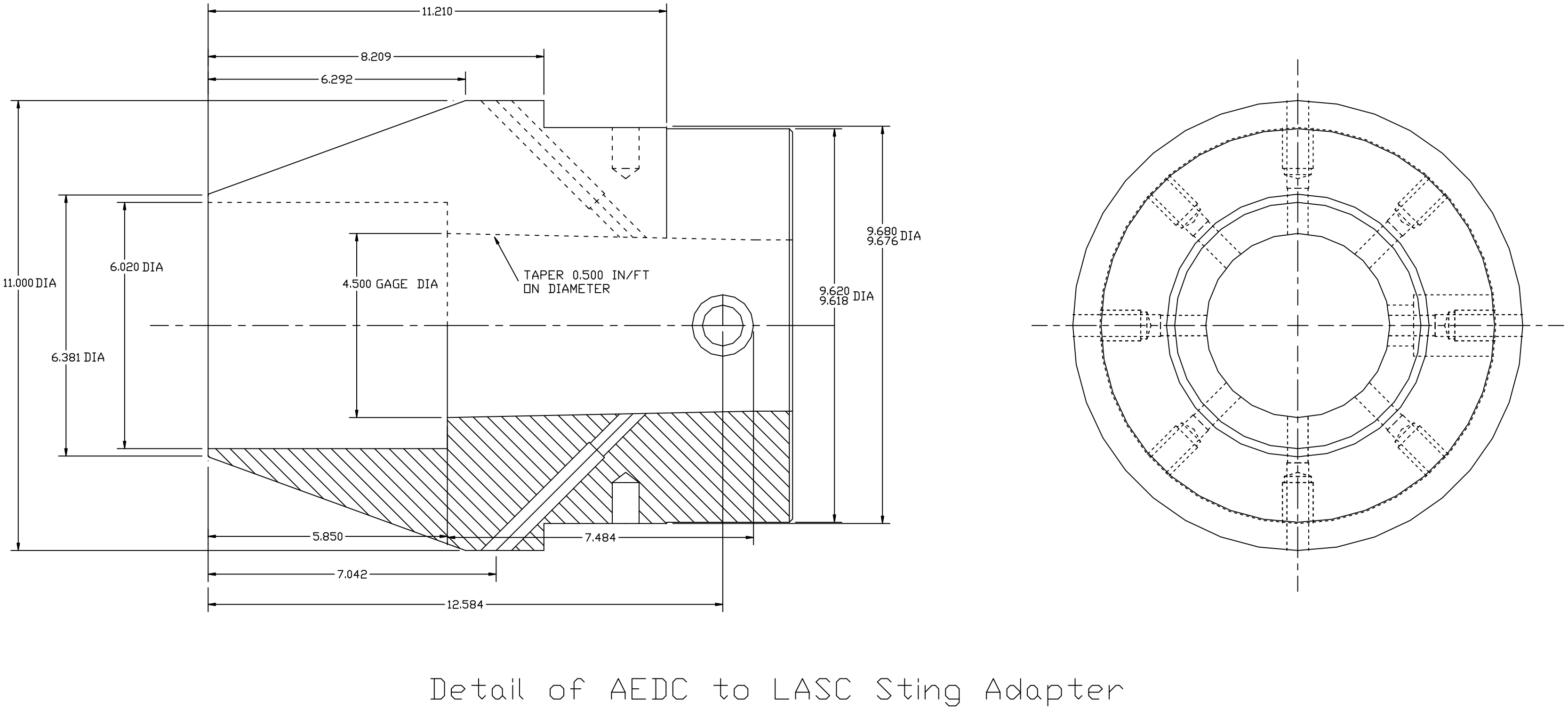


Figure 37. ZS453-15 Sting Boss Details.

Figure 38. Main Drive System – View Looking Upstream.

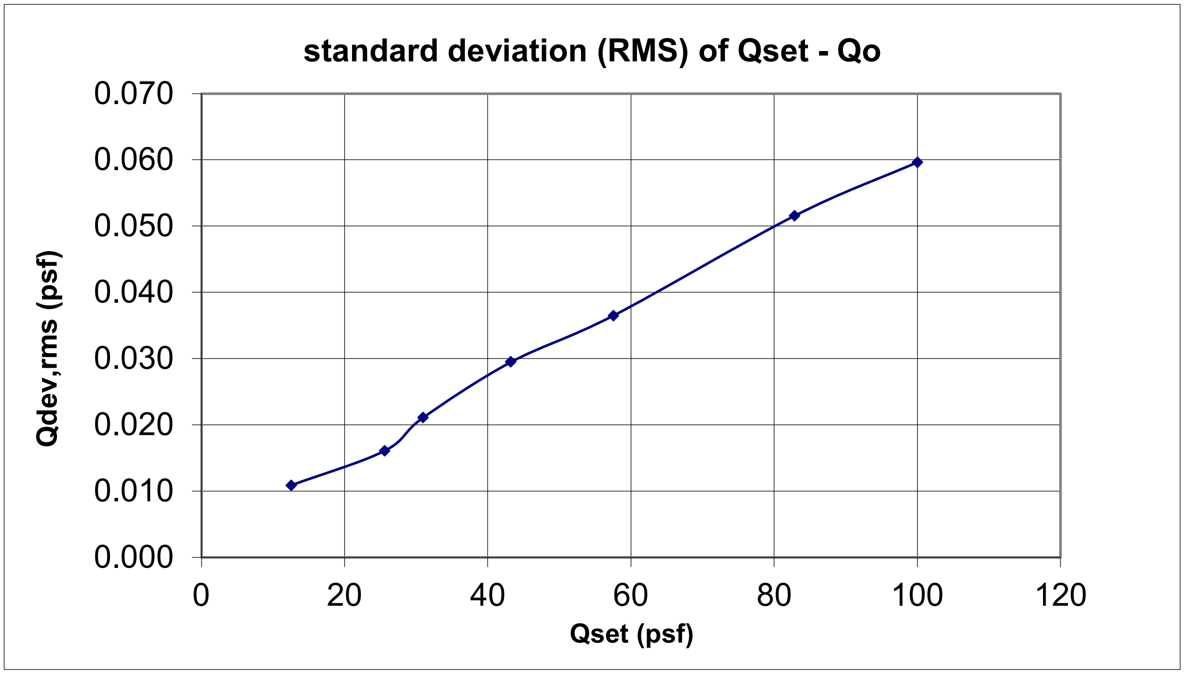


Figure 39. Deviation of Dynamic Pressure from Set Point.

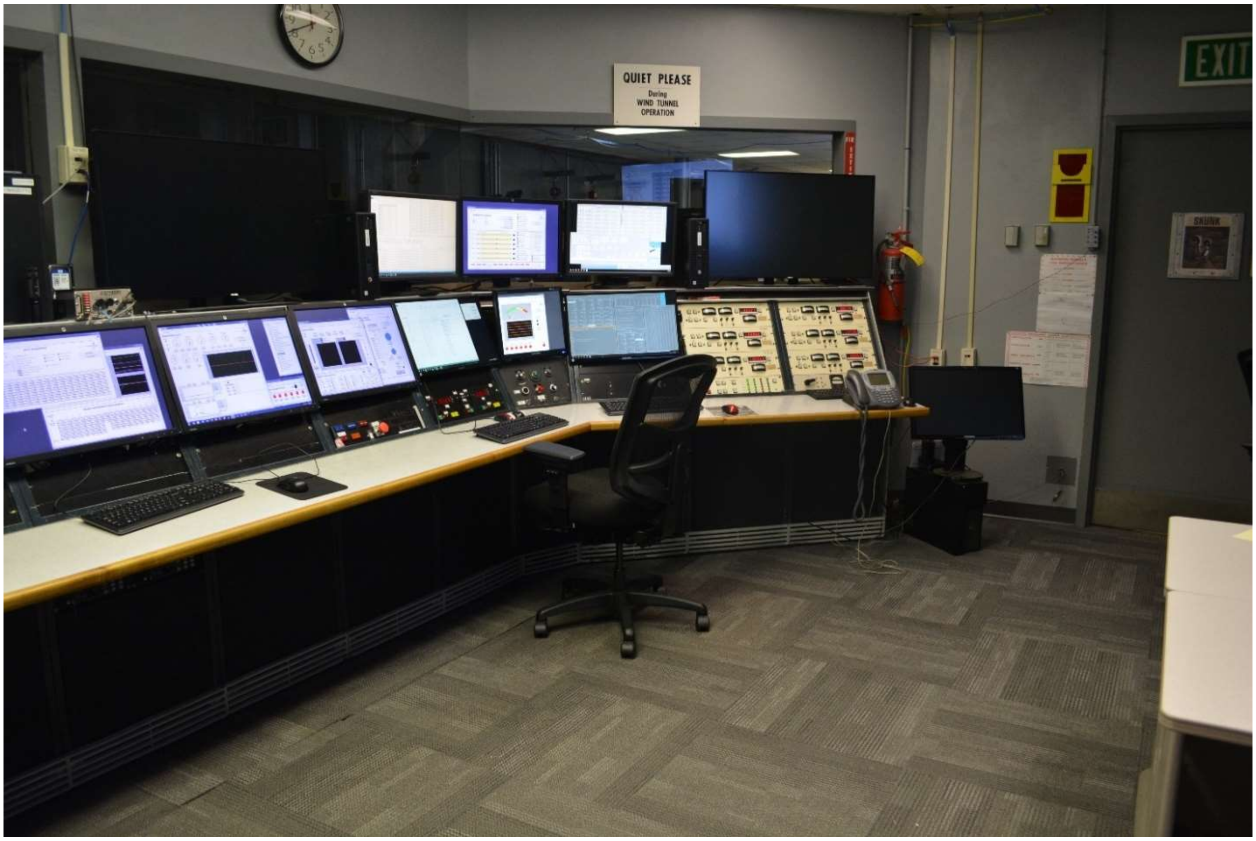


Figure 40. View of Control Room.

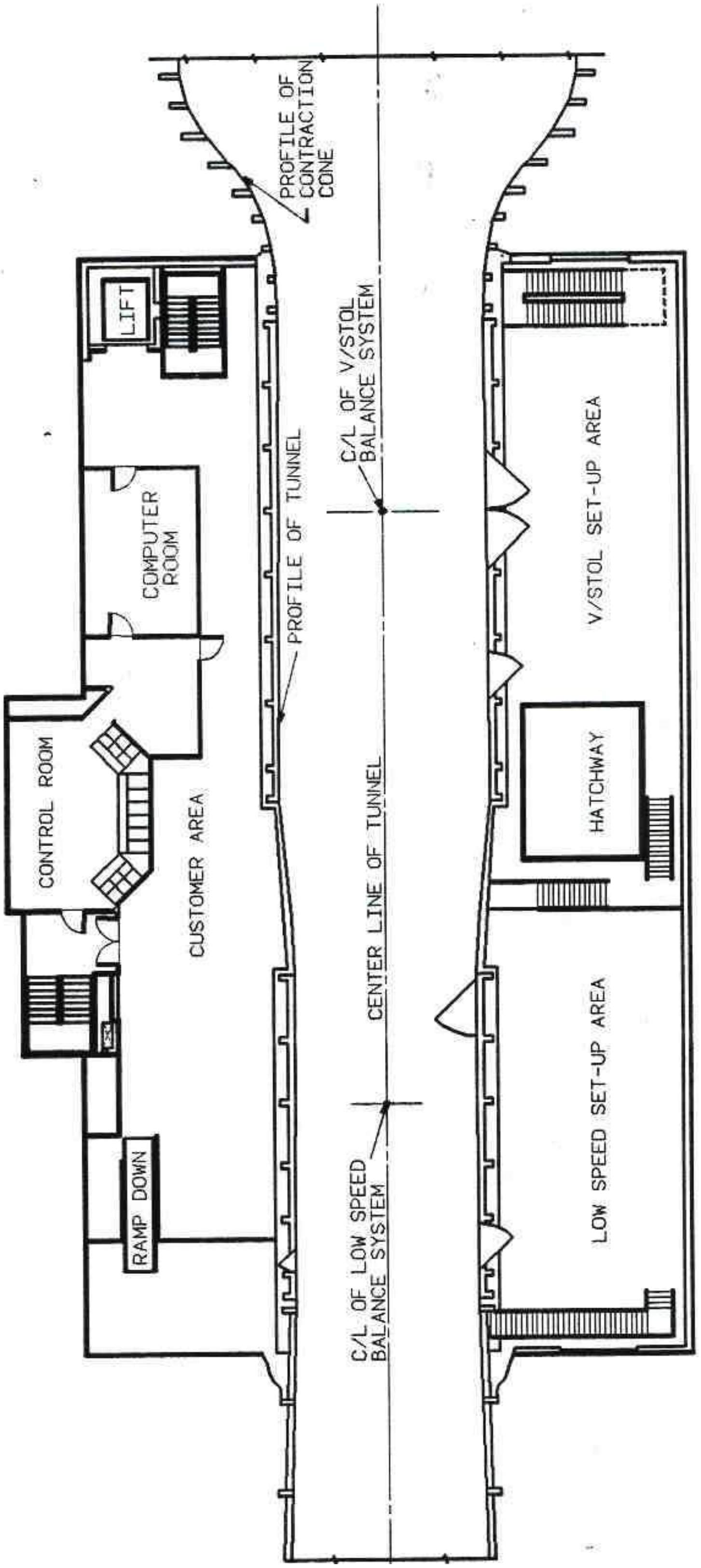


Figure 41. Plan of Operational Floor Areas.

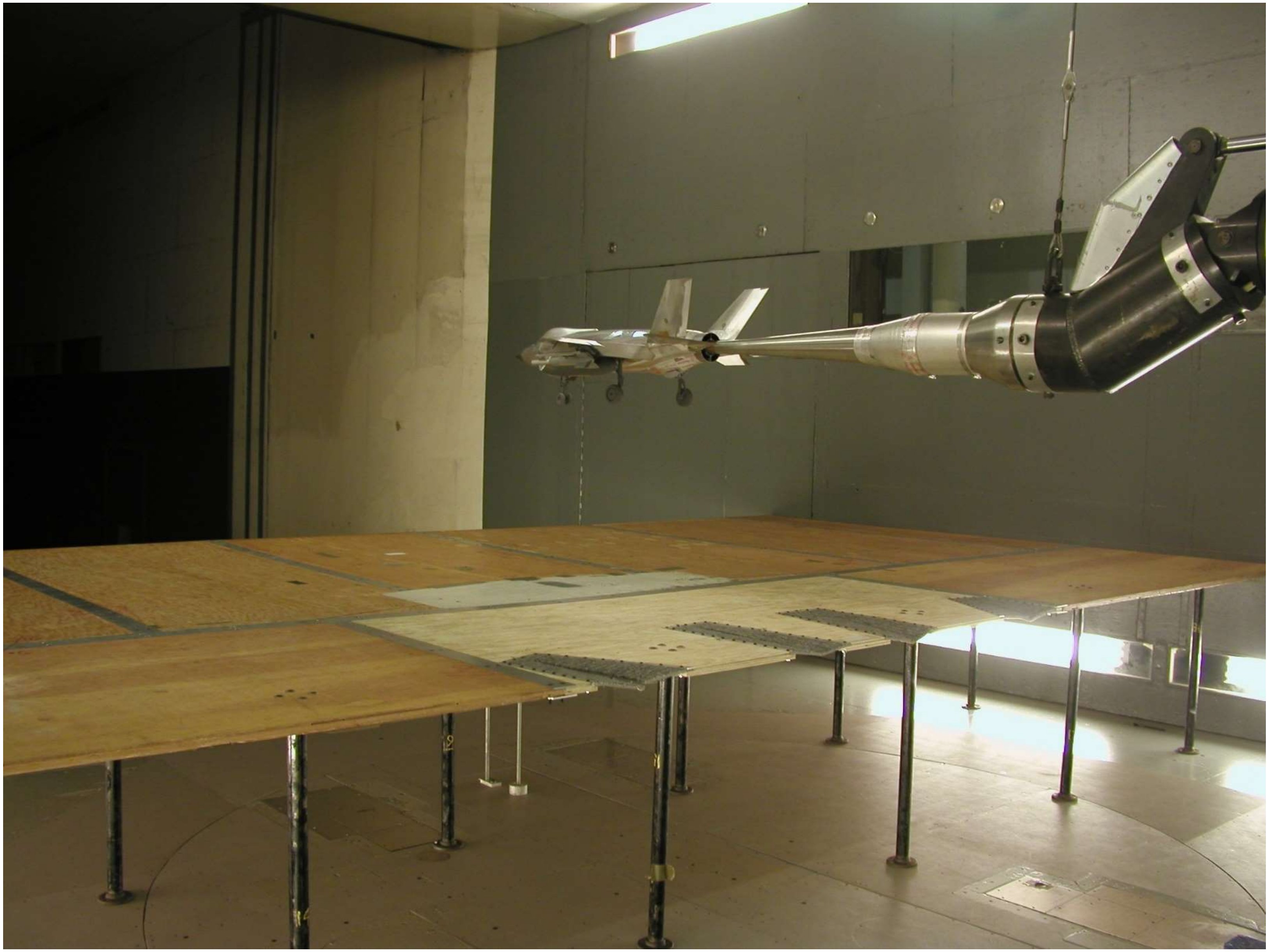


Figure 42. Removable Ground Board, 12ft Configuration.

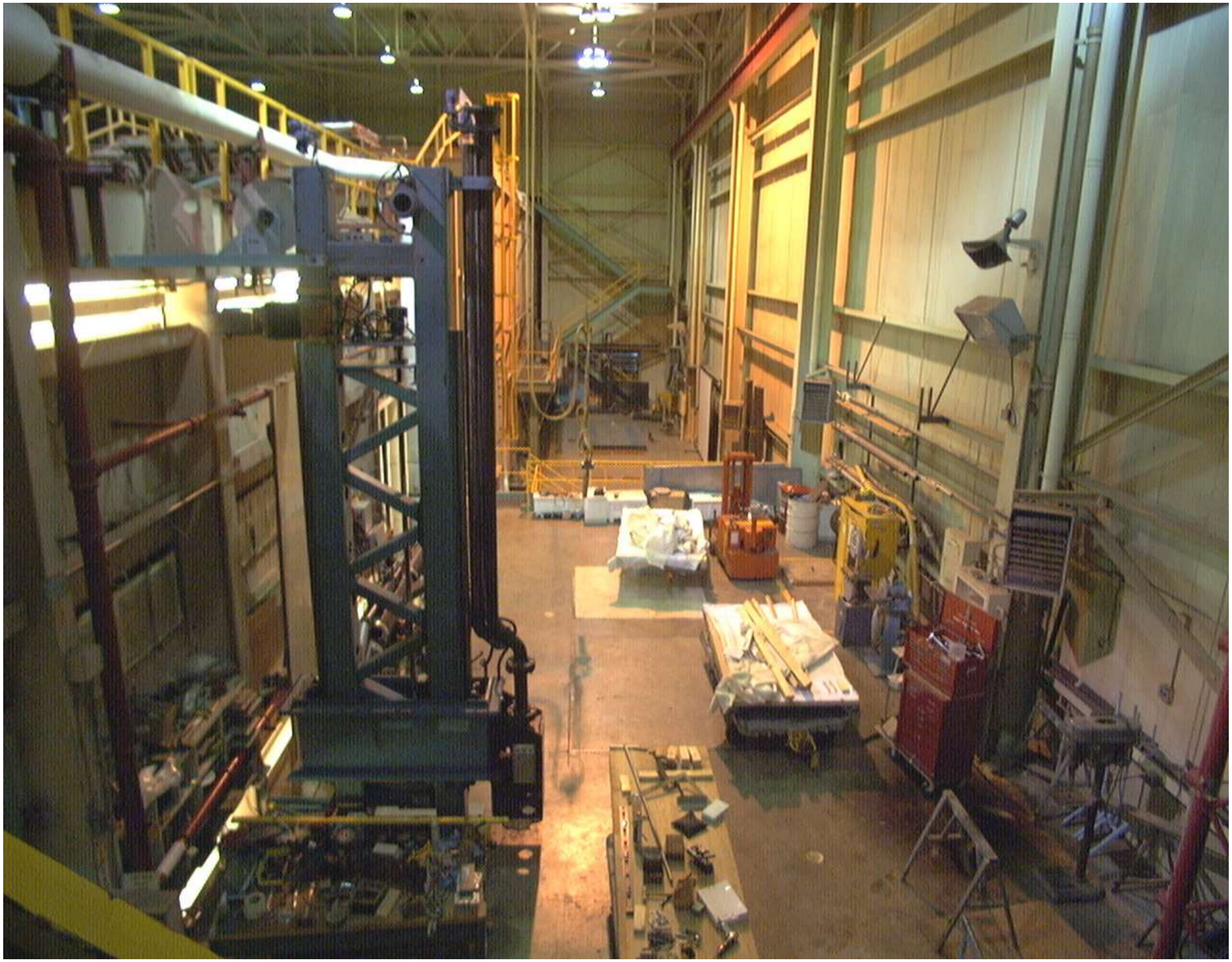


Figure 43. View of Model Hoist and Rigging Areas.

10 PHOTOGRAPH ACKNOWLEDGEMENTS

Figure	Subject	Courtesy of
Figure 15	Architectural Model (Lighting Fixture) Installation.	G.E. Lighting
Figure 16	Antenna Installation.	Prodelin Corporation
Figure 17	Automotive Clay Model Installation.	Ford Motor Company
Figure 18	IMSA Race Car Installation.	Riley Technologies
Figure 19	NASCAR Race Car Installation.	RAD Aerodynamics, LLC
Figure 20	Motorcycle Installation.	Harley Davidson Motor Company
Figure 21	0.3-Scale Tractor/Trailer Model Installation.	Ford Motor Company