The APL Guidance System Evaluation Laboratory

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The Guidance System Evaluation Laboratory (GSEL) is a primary tool used in APL's role as the Technical Direction Agent for the Navy's Standard Missile (SM) Program. This facility tests the SM guidance section, its interfaces to the weapon system and other missile sections, and missile performance in all tactical conditions. GSEL provides support for all phases of missile development and tactical operation, from concept through production, as well as in-service Fleet backup. The facility is continuously evolving, providing for advanced missile versions developed to improve performance and counter new threats.

INTRODUCTION

The evolution of the APL Guidance System Evaluation Laboratory (GSEL) generally parallels the growth of Standard Missile (SM) and the ever-increasing threat since SM's inception in the 1950s. Initially SM was an X-band beam-riding missile designed primarily as a high-altitude anti-air weapon to counter large Soviet aircraft. In the 1970s cruise missiles started to appear. By the 1980s and 1990s cruise missiles had rapidly evolved into formidable high-speed, sea-skimming threats that maintained a very low radar reflectivity, making them difficult to detect and engage with the then-current missile systems. During the Persian Gulf War (1991), the general public quickly learned of the ability of rogue states to use tactical ballistic missiles with conventional, biological, and nuclear warheads. Into this new century the threat has expanded to include much longer-range, higher-altitude ballistic missile systems that may employ decoys and other countermeasures. Today the Navy is investigating the use of SM in a national missile defense role.

Figure 1 shows the evolution of the many SM variants and the expanding capabilities of GSEL. Historically, each facility has served a purpose for 10 to 15 years before technologies incorporated into SM and the emergence of new threats have necessitated these changes.

BACKGROUND

The first APL RF GSEL was built in 1963 on the second floor of Building 1. This relatively simple, manually operated facility used mechanically moved targets, and its primary purpose was to evaluate self-screening countermeasures. The second GSEL, on the first floor of Building 1, was built in 1979–1980,[1] coinciding with the development of SM-2 and the Aegis Weapon System.[2] New features included multiple electronically moved targets using a wide-angle array (for standoff jamming), a larger chamber, multipath and clutter environments, missile initialization, midcourse flight with Aegis command uplink, and closed loop homing

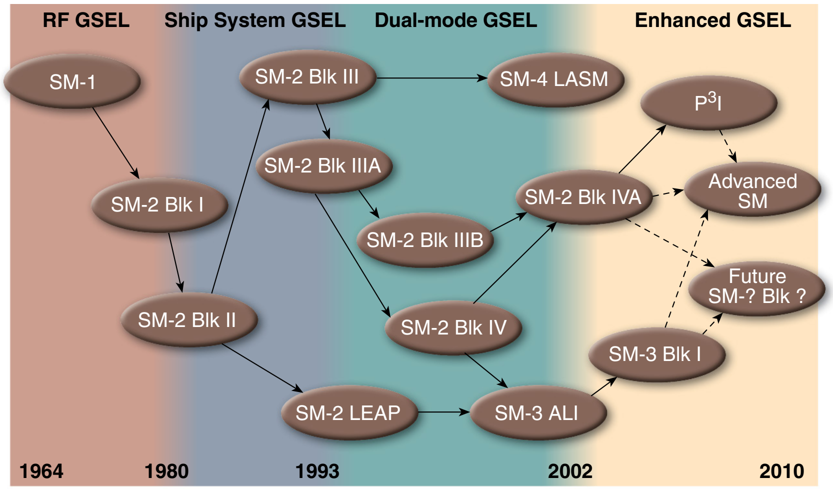


Figure 1. The evolution of SM over the past four decades from a single-frequency missile to several multimode, multimission variants roughly parallels the associated growth of GSEL (P^3I = preplanned product improvement).

capability. These new attributes made GSEL an engagement test facility.

In 1992–1994, GSEL was upgraded to accommodate infrared (IR) and dual-mode (IR/radar) guidance. IR targets, backgrounds (clutter), and heated dome environments were added.[3] Separate IR seeker and radar guidance section test stations, which initially were connected electrically, provided the dual-mode test capability. Later a dual-mode anechoic chamber was built to test tactical radar/IR guidance sections.

In the later 1990s, new missions arose leading to several new versions of SM. These missions included endo- and exo-atmospheric tactical ballistic missiles, overland cruise missiles, and land targets. In early 1997, the Laboratory announced plans for construction of Building 26 primarily to meet the needs of the Air Defense Systems Department (ADSD). Plans for a new, enhanced GSEL to meet future needs were quickly developed, accepted by the Laboratory's Executive Committee, and endorsed by the Navy. The new GSEL would support

- Concept development
  - New threat and new algorithm assessment
  - Technology assessment
  - Critical experiments
- Engineering development
  - Performance measurements
  - Simulation development and validation
  - Interface evaluations
  - Flight test planning and predictions
  - Certification of flight readiness
  - Supplementary design agent testing
  - Failure analysis
- Production and Fleet support
  - Production surveillance
  - Operational test planning and testing integration of SM with foreign combat systems

Because of the impact that an abrupt transfer to Building 26 might have on SM programs currently being supported in the Building 1 chambers, a gradual transfer is planned. New programs that can most benefit from the features of the enhanced GSEL will be integrated when they begin. Initial uses of the facility will focus on those systems and subsystems (IR electronics, for example) that rely less on the ingrained infrastructure of the Building 1 equipment suite.

WHY A NEW GSEL?

The need for each new GSEL arises from current and anticipated requirements. One important issue is the size of the facility. For example, the dual-mode facility in Building 1 is 2900 ft^2. Increasing its size, as was done when the IR capability was added, is a complex task that must be coordinated with ongoing projects. The enhanced ground-floor GSEL in Building 26, at approximately 8880 ft^2, is built to overcome the structural limitations of the dual-mode facility and allows for

- A much larger anechoic chamber sized to accommodate much higher frequencies than that of current missile variants (specifications for the chamber go up to 100 GHz)
- Relief of overcrowding
- Rapid reconfiguration to accommodate current testing of several missile variants
- Much greater weight and flexibility for future growth (e.g., rate tables, flight motion simulators, and other unanticipated needs)
- Special facilities, e.g., its own loading dock, a dedicated hydraulics room, liquid nitrogen from a nearby outdoor 2000-gallon storage tank, and a bridge crane

An important attribute of the enhanced GSEL is its readiness for use as a Special Programs Facility (SPF) for work that requires a high degree of security and classification. A second smaller room within the larger area can also be maintained at a high security level for storage and data analysis when GSEL is being used for more traditional programs.

THE ENHANCED GSEL

Facility Layout

In 1997 planning for a new building was started to address the need for more office space. A baseline plan for a two-story, 50,000 ft^2 structure was developed with columns at 20 ft on center. During the project-programming phase of Building 26, the future occupants were identified but their needs were found to exceed the baseline. A third floor was added and a lobby for direct public access was therefore integrated into the building design. The need for unique laboratory space required several changes to the structural plans such as increasing the floor-to-ceiling heights and expanding the spacing between columns. As this phase continued, a new Warfare Analysis Laboratory was designated for the third floor,[4] and laboratories for several Cooperative Engagement Capability programs were selected for the second and a portion of the first floors. The remainder of the first floor was identified for ADSD SM test facilities. The design of the areas where these laboratories were planned was "frozen" while construction of the office areas continued.

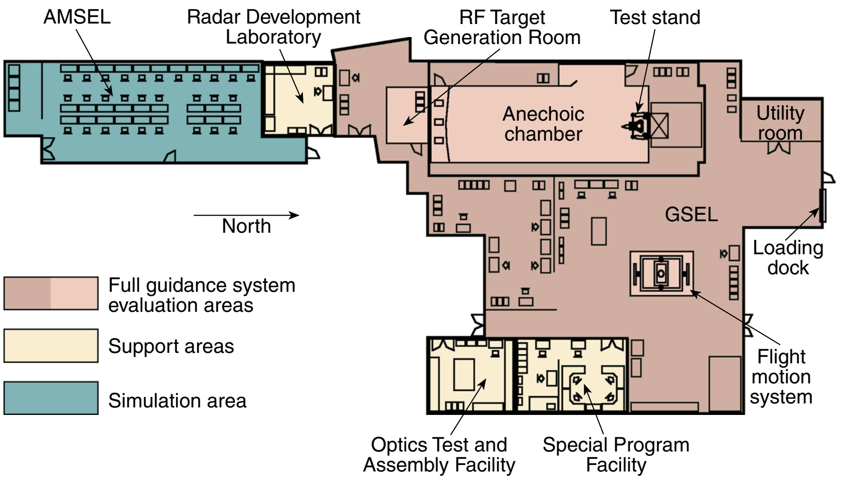


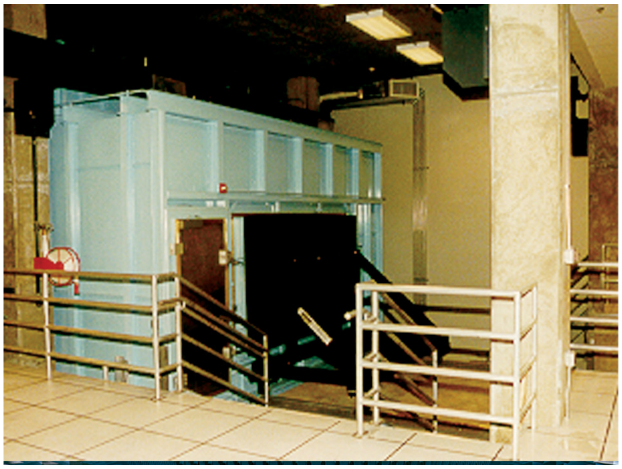
Figure 2. The ADSD Missile Engineering Branch laboratory facilities located on the first floor in Building 26. Areas are dedicated to simulation, full guidance section evaluation, and support. The proximity of these areas to one another helps realize the goal of providing SM with a high-fidelity, hardware-in-the-loop facility.

The current SM evaluation spaces are separated into three primary areas: simulation, full guidance section test, and support. The project-programming for Building 26 allowed the designers to integrate all three into one large space (Fig. 2).

The dependence on simulation to evaluate missile design during development has increased significantly in the last 15 years as a means to offset the high cost of actual flight tests. Existing missile simulation laboratories place restrictions on the ability to perform future testing. For example, the SM simulation facility has expanded several times over the years to occupy three separate small facilities in Building 1, a cumbersome arrangement for staff. Therefore, 1900 ft^2 have been dedicated to the new AMSEL (Advanced Missile Simulation and Evaluation Laboratory) in Building 26, where high-fidelity, six-degree-of-freedom (6-DOF) simulations of the complete SM engagement sequence are performed.

The largest portion of the ADSD Missile Engineering Branch laboratory space in Building 26 is for the GSEL. The focal point of the facility is a shielded anechoic chamber located in a 2200 ft^2 open area (Fig. 3). Anechoic properties of the chamber enable testing without concern for stray electromagnetic reflections off nearby objects or walls that would not be experienced in flight. A shielded anechoic chamber not only absorbs RF energy incident on its surfaces, but also isolates the test region from any outside RF interference.

Equipment to support testing in the chamber is located in areas surrounding it. A second, smaller shielded room for RF target generation lies to the south of the anechoic chamber. Here, signal generators



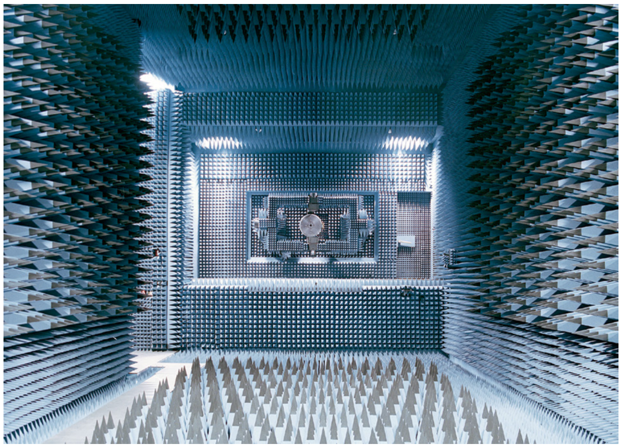


Figure 3. GSEL anechoic chamber in Building 26: the outside north end of the chamber (top) and an inside view looking north toward the test stand where a guidance section would be mounted (bottom).

are used to create an RF target signal that is transmitted toward a guidance section mounted at the far end of the chamber. These two chambers must be isolated so that signals passing between them can be carefully controlled. This is required since many intermediate signals are used to create the target signal which, if not controlled, could interfere with operation of the equipment under test.

Adjacent to the primary facility are smaller rooms dedicated to the assembly and test of guidance system components. The Optics Test and Assembly Facility contains optical benches and related test equipment for independent evaluation of optical components. It also contains a laminar flow "cleanbench" where highly filtered air is directed across a workbench, creating a small, dust-free region that enables assembly of optical components without the need for a dedicated cleanroom. Similarly, the Radar Development Laboratory provides a dedicated area for the assembly and test of RF components. Equipment will be transferred as needed between these smaller facilities and the primary facility for full guidance system and component-level testing. These facilities will also help support field tests of SM as needed.

GSEL Impact on Building 26 Construction

As noted previously, the basic requirements for the enhanced GSEL were identified while the design for the base building continued. These included the performance specifications and services needed to support the proposed facility.

A primary driver for the new anechoic chamber is wide angular coverage in both azimuth and elevation to match the angular coverage of the antenna system. With a long chamber baseline to support high-frequency operation, it follows that a wide and tall chamber is needed. The original plans for Building 26 called for concrete columns to be located on 20-ft centers and a floor-to-ceiling height of 11.5 ft. A compromise between technical and structural constraints settled on a chamber design of approximately 60 ft long × 20 ft wide × 20 ft tall. To effectuate the required dimensions of the chamber, the plan and vertical dimensions had to be changed. First, to achieve the vertical height and allow space above for the utilities, the first-floor ceiling height was increased to 15 ft by lowering the floor 2.5 ft, raising the second floor 2 ft, and incorporating an 8-ft-deep pit into the building plans to attain an overall height of 23 ft. Second, the distance between columns was increased by 2.5 ft to 22.5 ft on centers. These changes rippled through the rest of the building but had a relatively minor impact on the remaining plans and construction costs.

The chamber design called for the inclusion of a future flight motion simulator, an electronically controlled mechanical device that simulates angular movement of the missile in flight. A three-axis system can move a unit under test in the roll, pitch, and yaw rotational axes. In closed loop testing, control signals from the guidance section to the rocket motors and tail fins are input to the flight motion system on which the guidance section is mounted. In this manner, full guidance system response to simulated targets can be measured.

The size and movement of a flight motion system put heavy constraints on building construction. The high dynamic loading of the unit requires that it be mounted on a foundation separate from the building foundation so that modulations cannot be transferred from system movement to the building or vice versa. The rotation point for the flight motion system must be on the anechoic chamber centerline, requiring mounting on an elevated pad approximately 5 ft high.

Integration of this device is not planned for several years, so a manually positioned test stand with a similar form factor was included into the anechoic chamber design. Unlike the Building 1 chamber, where the test stand is completely contained within the chamber and a guidance section is brought into the chamber via a small door, the design of the test stand in Building 26 is such that it lies on rails. Therefore it can be pulled back from the chamber and the guidance section can be installed externally (Fig. 4). The base of the test stand must then become a portion of, and must maintain, the chamber shield.

The three-axis system just described can be designed as the inner portion of a larger five-axis flight motion system (Fig. 5). The inner three-axis (roll, yaw, and pitch) portion of the system under test is combined

Figure 4. The three-axis test stand, shown pulled back from the anechoic chamber, is used to hold the guidance section under test. The test stand allows movement in the roll, yaw, and pitch rotational axes. The stand is treated with a radar absorber, as is the rest of the chamber, to reduce undesirable reflections.

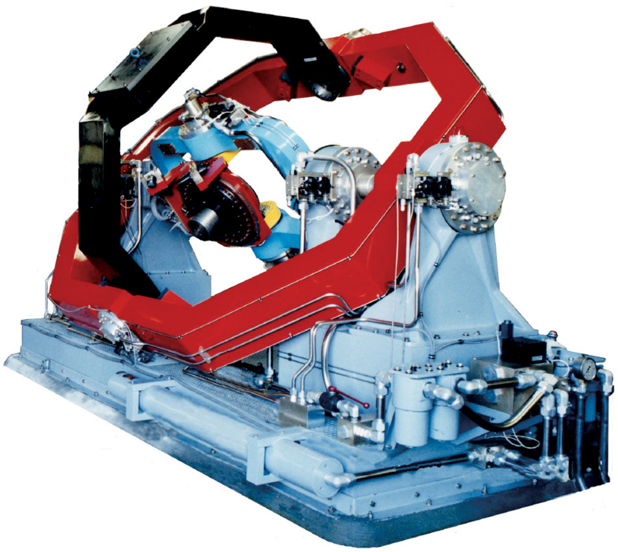


Figure 5. The five-axis flight motion system. This unit combines the roll, yaw, and pitch movements of a missile seeker mounted on the inner blue and yellow gimbals; the azimuth and elevation movements of a simulated target are mounted on the outer rust-colored and black gimbals. (Photograph courtesy of Carco Electronics.)

with an outer two-axis (azimuth and elevation) gimbal that provides independent control of a simulated target. Five-axis operation is typically used for IR/optical testing and takes place in an area adjacent to the anechoic chamber. A separate isolated equipment pad for the five-axis unit is included in the building design. Figure 6 illustrates the sequence to extract the inner three-axis unit from the larger simulator (see http://techdigest.jhuapl.edu/td/td2203/GSEL26.html for digital animation of the sequence). The inner system weighs approximately 8000 lb; therefore, a 5-ton bridge crane system has been integrated into the facility to lift the three-axis system from the five-axis pedestal to the anechoic chamber equipment pad.

The hallways of the base building design that would have served the typical office layout were integrated into the facility to increase laboratory space. This allowed the GSEL to stretch to the north end of the building and incorporate the loading dock into the design, allowing guidance sections and other large equipment to be brought in easily.

The GSEL facility was constructed to Director of Central Intelligence Directives (DCID) 1/21 standards to meet the security requirements of the SPF. For ex-ample, to prevent eavesdropping on classified conversations within the facility, three layers of drywall or other approved wallboard material are required to effectively attenuate sound waves; ductwork greater than 96 in^2 must include a welded grid to prevent covert access; and power, network, and phone penetrations must be minimal.

As the enhanced GSEL plan and the auxiliary equipment were identified, the locations for liquid nitrogen outlets and communications jacks were selected to serve the assigned equipment. Because of the increased ceiling height requirement within the laboratory, a provision was made to run the majority of piping and cabling under the floor. To meet this need and to allow for future growth and flexibility, the concrete slab was depressed 12 in. and a raised floor was installed to allow a seamless transition from the hallway into the laboratory.

All of these changes were integrated into the fit-up design phase of the project while the foundation for the base building was completed and well under construction. However, when the test stand design was completed it was discovered that there was inadequate space to maneuver a guidance section around the test stand with the bridge crane during the mounting process. Therefore, a portion of the base building floor slab north of the existing test stand pad was removed to increase the distance the test stand could be rolled back from the chamber.

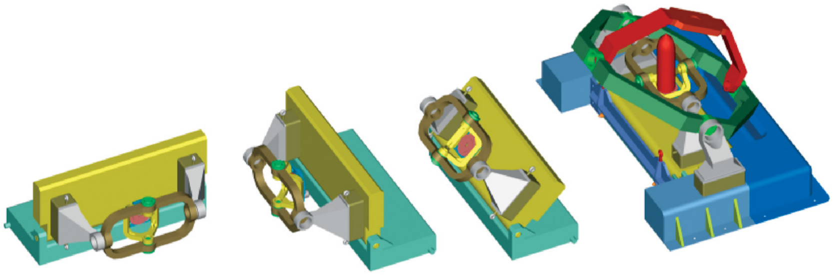


Figure 6. Sequence (from right to left) showing the reconfiguration of the flight motion system from a nested five-axis orientation to a three-axis configuration for use in the anechoic chamber. The three-axis unit would replace the current test stand shown in Fig. 4 (see http://techdigest.jhuapl.edu/td/td2203/GSEL26.html for digital animation).

Anechoic Chamber

Given the physical limitations imposed on the anechoic chamber by the parent building, chamber design started with three primary objectives: (1) retain the basic performance characteristics of the Building 1 GSEL, (2) incorporate the ability to support high-frequency operation, and (3) support future inclusion of a flight motion system.

As noted earlier, the Building 1 chamber supports X-band semiactive and IR (dual-mode) guidance section testing. An X-band horn array provides wide-angle (>45°) single-axis coverage. To support dual-mode testing, IR targets are generated on optical tables that are located outside the chamber shield below the guidance section. The scene is presented to the IR sensor on the guidance section using a "periscope" arrangement that directs the scene upward through the shield and back toward the sensor. Figure 7 illustrates the layout of the Building 26 anechoic chamber.

A guidance section will be mounted on the test stand located at the north end of the chamber. The south end is reserved for a primary antenna system that transmits a simulated RF target signature toward the guidance section. The long chamber baseline required for wideband frequency coverage, coupled with parent building restrictions, limits angular coverage to approximately ±10°, far lower than that of the Building 1 chamber. To retain some measure of a wide-angle capability, an alcove that will contain a secondary vertical antenna array was incorporated into the west sidewall. As in the Building 1 chamber, optical tables can be located outside the chamber below the guidance section where IR target scenes can be generated and presented to the guidance section via the periscope.

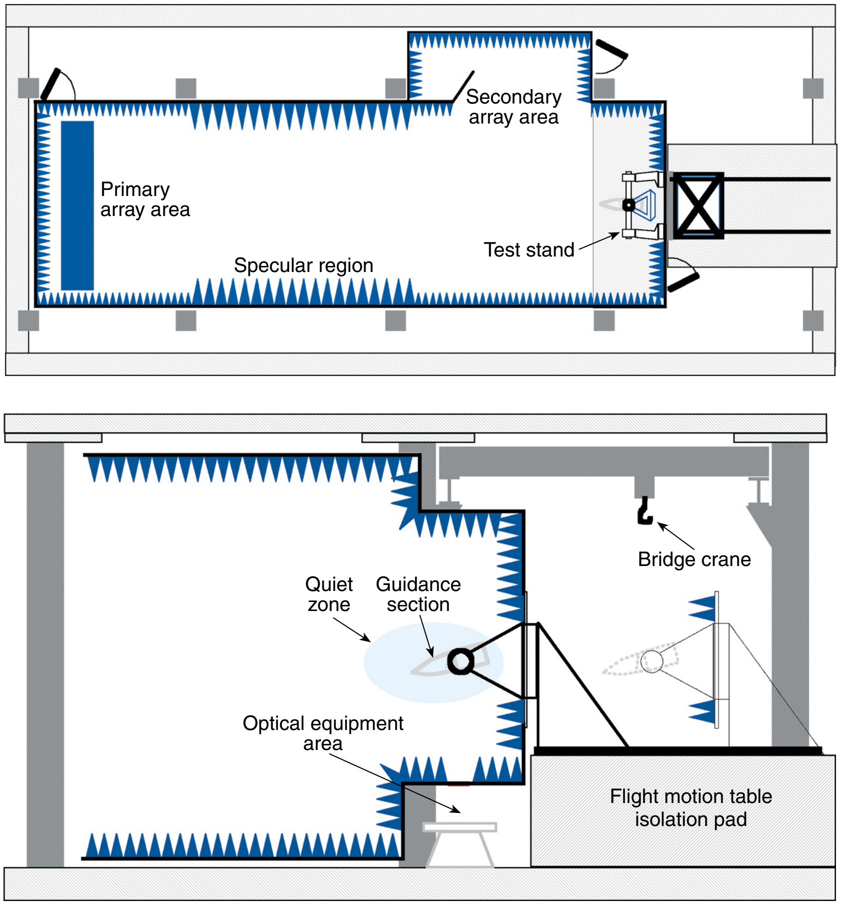


Figure 7. Building 26 anechoic chamber layout. The plan view (top) shows the relationship of the antenna array areas to a guidance section mounted on the test stand. The partial side view (bottom) similarly shows functionally where optical equipment will be located relative to a guidance section under test. The guidance section is placed in the chamber quiet zone, a region in which stray reflections have been carefully characterized and minimized.

Evaluation of Anechoic Performance

Again, a shielded anechoic chamber allows testing of missile electronics without concern for stray electromagnetic reflections off nearby objects or walls that would not be experienced in flight. Chamber *reflectivity* is a quantity defined to characterize the imperfection of an anechoic chamber and is often taken to mean the ratio of unwanted reflected signals to the incident, direct-path signal energy at the same spatial position of an anechoic chamber. The chamber *quiet zone*, where the missile guidance section is placed, is a spatial region where the reflectivity properties have been proven to be less than a defined value. The quiet zone may not necessarily be the "quietest" region in the chamber, and the quietest region may not always be the best location to stage the missile guidance section for test.

In chamber design, RF absorber treatment is applied in a trade-off to minimize reflections off sidewalls into the quiet zone and contain absorber cost. The highest-performance absorber (24-in. "black-tipped") is placed in the specular chamber regions—center chamber areas of walls, floor, and ceiling—that typically are the greatest source of reflected signals. A lower-performance absorber of differing thickness is placed in other areas to maintain the performance established by the critical specular regions. Personnel walkways and ventilation grills have specialized absorbers to address dual needs.

Chamber quiet zone and reflectivity performance are evaluated via two methods.[5] Regardless of the method, measurement accuracy requires isolation of the direct signal energy from the reflected signal energy during the measurement. The first method is a measurement of reflected signal interference on the direct path signal. During calibration, a direct free space measurement is made by transmitting a static frequency signal from an antenna located at the far end of the chamber directly toward a receive antenna located in the quiet zone. After calibration, additional measurements are collected while probing the quiet zone, with the receive antenna directed away from boresight to help isolate the reflected signal from the direct path signal. The cyclic constructive and destructive interference on the direct signal by the reflected signal creates a standing wave ratio that is compared with the free space measurement to determine chamber reflectivity, hence this technique's name, free space VSWR (voltage standing wave ratio) measurement.

The second method, called the swept-frequency time-gating vector measurement and the type employed in the Building 26 chamber performance evaluation, uses time to isolate the direct and reflected signal energy. Since the reflected signal energy will arrive at the receive antenna horn nearly instantaneously with the direct signal path, a series of frequency/time transformations is employed to isolate the two signals. Figure 8 shows the test setup where swept-frequency (amplitude and phase) data are collected over a somewhat wider frequency band than the primary region of interest.

Through the use of inverse fast Fourier transforms (IFFT), the measured signal is transformed into the time domain, and this time domain signal (Fig. 9) simulates the arrival time sequence of direct and reflected signals. Once in the time domain, the later-arriving reflected signal is clearly distinct using the high resolution afforded by the capture of wide-bandwidth data prior to the IFFT. As shown in the figure, the direct signal can be gated out and an FFT operation performed on the gated portion, resulting in a measurement of reflectivity over a continuous frequency span. In this manner the swept-frequency method for measuring reflectivity performance is superior to the traditional VSWR technique.

Integration with Other Facilities

The location of the GSEL in Building 26 allows for easy integration with other laboratory facilities. A primary goal of ADSD is a tight coupling between AMSEL and GSEL activities. "Plug-and-play" between high-fidelity, real-time 6-DOF simulation elements running in AMSEL and GSEL hardware tests are possible as the speed and capability of computers increase. Once GSEL/AMSEL integration occurs, AMSEL simulations can be driven by output of a missile system under test in GSEL, which in turn reacts to test equipment and target generators controlled by the simulation, thus forming a closed loop system. As in the past, GSEL will be extensively used for simulation model development and validation.

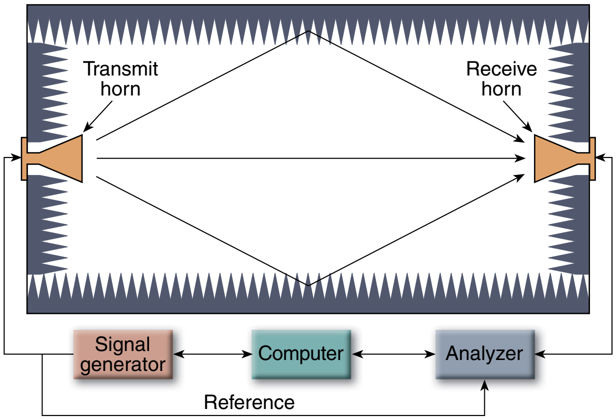


Figure 8. Test setup for performing a swept-frequency vector measurement. A calibration sequence to provide a reference is performed by collecting swept-frequency measurements when the antennas are boresighted as shown in the figure. Once calibration is complete, additional measurements are taken with the receive antenna horn pointing at a series of angles off the direct line of sight.

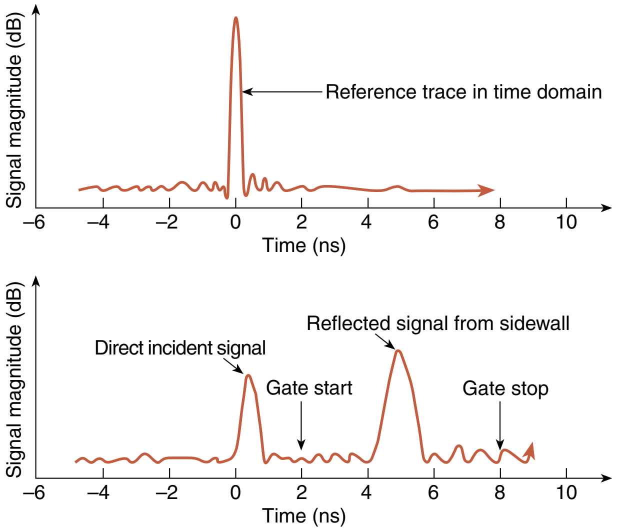


Figure 9. Time-domain representation of the calibration reference trace and off-boresight reflectivity data. These traces are generated by performing an IFFT on the original frequency domain data. On the bottom trace, the direct incident signal can be gated away before performing an FFT to yield the final reflectivity measurement as a function of frequency.

Other laboratory facilities that will be used in conjunction with the GSEL are ADSD's Rooftop Facility (Fig. 10) and the SM Captive Seeker System (Fig. 11).[6] The Rooftop Facility, located atop Building 13, is configured so that the missile seeker under test can view the sky and acquire and track real targets. For IR or other optical-based systems, the effects of background radiation or stray light can be evaluated. The Captive Seeker System has been used numerous times over the past 12 years to collect land and sea clutter data and has been used most recently to prove the compatibility of SM and foreign military radar systems. Data collected during Captive Seeker experiments can be replayed back into missile electronics in the GSEL for further analysis to see how the guidance section responds to real-environment signals such as sea or land clutter, which, because of their spatially distributed nature, can be very difficult to simulate in a laboratory.

Finally, telemetry data are extremely important for the analysis of actual missile firings. High-bandwidth satellite links make it possible for missile telemetry to be transmitted directly to GSEL for immediate review and analysis.

Figure 10. ADSD's Rooftop Facility is located on the roof of Building 13 and affords an unobstructed view of a large portion of the sky. It provides a cost-effective means to test seekers in an open-air environment.

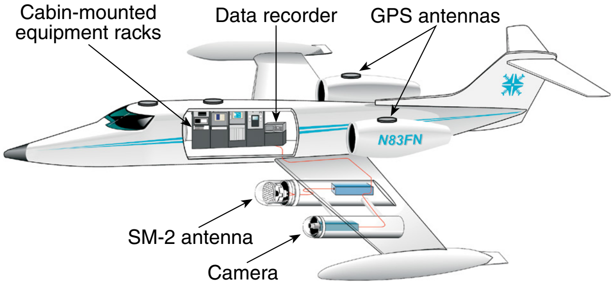


Figure 11. The Captive Seeker System. The equipment includes a production SM seeker antenna and gimbal assembly mounted in a reconfigured chaff pod. The antenna can be controlled by the Global Positioning System (GPS), TV, or angle tracker. The pod is mounted underneath a Learjet and used in conjunction with an APL-developed equipment suite. Real-time processing of data is performed on five cabin-mounted racks.

CONTINUED FACILITY DEVELOPMENT

The facility infrastructure is now being developed. This task includes installation of waveguide and cabling for signal transport and test control, a new digital computer and hardware interfaces, power supplies, and radar target generators. These basic facility subsystems provide a common test capability for all missiles. Guidance section testing is scheduled for the summer of 2001, with a gradual transition of test activities to the new facility over the next year.

In addition, a mechanical target positioning system is under development for the radar chamber. This provides precisely controlled two-dimensional motion of two independent targets at the far end of the anechoic chamber. Preliminary system design was completed in February 2001. Construction of the target positioning system is under way, with final installation slated for early 2002.

A key feature of the enhanced GSEL is its ability to accommodate our future needs such as the flight motion table discussed previously. Other new test capabilities under consideration include a cryogenic vacuum chamber for space sensors, a laser radar sensor test suite, and a one-dimensional radar target array.

SUMMARY

The enhanced GSEL facility in Building 26 provides a great increase in capability to augment the dual-mode facilities in Building 1. The larger chamber allows testing and evaluation of missile systems as they take advantage of high-frequency technological advances to counter the increasing capability of threat variants. The increased work area around the chamber relieves serious overcrowding in the current dual-mode facilities and allows for considerable future growth. Infrastructure designed into the GSEL in Building 26 will accommodate simulated flight motion and easy integration with other facilities around the laboratory.

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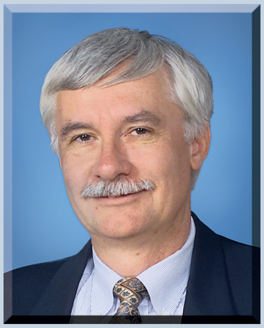

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