TEST AND VERIFICATION PHILOSOPHY IN DEVELOPMENT OF THE ANTI-ARMOUR PROJECTILE STRIX

Torild Johansson
Saab Missiles AB
Linköping, SWEDEN

Abstract

STRIX is a terminally guided, mortar launched anti-armour projectile, jointly developed by the Swedish companies FFV Ordnance and Saab Missiles AB. In this partnership Saab Missiles AB was assigned the task to perform the system testing. Having no earlier experience in testing smart ammunition, the test and verification methods worked out for "normal" missile programmes were adopted also for the STRIX programme. This task and our approach to it introduced some very special challenges.

These emanated basically from the STRIX concept itself, namely the idea that inside the body of a mortar projectile - with the limited volume of such a projectile, its exposure to very high shocks etc - contain hardware and software to the equivalence of a sophisticated guided missile. Typical system test related aspects that had to be covered were:

- How to perform design- and qualification-tests to prove the sophisticated electronics system's ability to withstand the very high shocks - in the magnitude of 10.000 g's - that STRIX will be exposed to during launch.

- How to perform live firing tests - for evaluation of performance, stability and control - with adequate test data acquisition, when the projectile's limited volume and severe shock environment bring about restraints in test instrumentation design.

- Above this, the traditional balance between live firings and simulations due to cost restrictions etc.

This paper describes Saab Missile's general philosophy for test and verification of a missile's performance characteristics with its main feature, the interaction between live firings and simulations, how this philosophy was applied to the STRIX concept, and also highlights some of the special "test-tools" that had to be developed for this purpose.

I. Introduction

STRIX is a 120 mm mortar launched, terminally guided anti-armour projectile. The launch weight is approx. 18 kg and the length is approx. 830 mm. For guidance it is provided with a passive IR-seeker combined with proportional navigation. Trajectory corrections are achieved by side thruster rockets. The electronics are made up of highly integrated microelectronic circuits, mounted on ceramic boards, with very high packing density.

To sum up, the STRIX projectile is a very small vehicle, highly packed with electronics equipment, providing no spare volume for any voluminous test instrumentation. On top of this, the STRIX projectile - which is designed to be handled and operated in the field in the same way as a standard mortar round - will be exposed to very high shocks at launch when fired from a mortar: design criteria is 8.000 g's during 10 msec for full function and above 10.000 g's for ammunition safety reasons.

II. General Philosophy

The general Saab Missiles philosophy of system performance verification is outlined in this chapter.

With performance verification we mean the process of making it to the highest possible degree likely that the missile system that we deliver to a customer fulfils all its performance requirements. There are mainly two ways of performing the verification process, namely:

- Direct verification, by which we mean the process of proving that the specified performance characteristics are fulfilled by testing the specified function and measuring the specified performance parameters.

- Indirect verification, by which we mean the process of proving that the specified performance characteristics are fulfilled by calculating them by means of measured parameters.

At Saab Missiles we generally use a combination of direct and indirect verification. Target seeker performance parameters such as range, search rate, target discrimination capabilities etc are directly verified in laboratory, ground and captive flight testing of one or more seeker prototypes, whereas such system performance measures as total target acquisition probability (including both seeker properties and missile midcourse navigation accuracy), launch areas, probability of target hit etc are computed with a six-degrees-of-freedom digital simulation model covering the whole missile trajectory from launch to target impact.

There are several more or less obvious reasons for indirect verification of system performance:

- The system performance parameters specified are often of a stochastic nature (e.g. probability of target hit) which means that they must be verified by some sort of statistical test, e.g. Monte Carlo trials.

- Since missiles generally are one-shot items, such trials would become very expensive if they were performed as full scale test firings of complete test missiles. The amount of complete missile trajectories computed in our 6-D.O.F.-models in a verification process is in the magnitude several hundreds or even thousands. A small country like Sweden could never afford a live-firing campaign of such an extent.

- There are also pure technical obstacles to a direct test firing performance verification, such as lack of relevant targets, peace time safety regulations, test range limitations etc.

- The simulation models used for indirect verification are flexible, have short access time and are relatively cheap in operation. Complex multitarget situations can be handled. Performance at maximum range and under extreme environmental conditions can be established etc.

In order to be valid for a reliable determination of system performance such a simulation model must be properly validated. Such a validation procedure is carried out using results from all sorts of tests on all levels - unit, subsystem as well as system level. Some tests are used to establish unit parameters and their variations with e.g. environmental conditions. Some tests are performed with the sole reason of generating data for the model. One example of the latter is frequency analysis under different load conditions of control surface servos. Some tests are carried out with the purpose of both direct performance verification and model validation. Examples of that are various captive flight trials with e.g. target seekers. Such seeker flight tests are aimed at direct verification of seeker performance, but they are also a link in the indirect verification process in the sense that performance parameters, recorded under the environmental circumstances that were prevailing during the tests, have to be recalculated to the conditions under which performance is specified, with the help of the mathematical model of the seeker.

The number of examples of tests that play a part both in the direct and indirect verification process could be extended, but that is of no use here. What is important is that they are used as a direct verification of the proper function of the missile and its subsystems under the prevailing test conditions and that they are used for model validation purpose. The combination of simulation and testing and the interaction between them can be described as follows.

Through the extensive use of simulation during the system testing and verification process we have been able to reduce the number of test firings to an absolute minimum. We also have the full support from our Swedish customer, the Swedish Defence Material Administration (FMV), in this approach to system testing and verification, by obvious economical reasons.

In our recent missile programmes we have fired considerably fewer missiles than in previous missile programmes. The more important then that these tests are planned and performed to produce as much relevant results as possible.

Simulation activities play an important part both in the planning of the tests and in the evaluation of the test results. The pre-launch simulations serve several purposes:

- To design the different experiments that are to be performed in each launch test, in order to use each missile as effectively as possible.

- To simulate malfunctions and parameter discrepancies and try out evaluation methods in advance.

- To generate information for splash pattern/risk zones boundaries.

- To generate information for test site preparations, etc.

Post-launch simulations serve the double purpose of on one hand being an instrument for the evaluation of the missile behaviour during the test, on the other hand comparison of the test and the simulation results in order to adjust the model until it produces trajectories and time histories identical to those of the actual test missile. This process is partially performed semiautomatically with the aid of a program package based on process identification techniques from modern control theory.

An excellent example of where this procedure has proven to work well is the final evaluation of the missile's aerodynamic properties, provided that experiments adjusted for this purpose are specially designed for some test firings.

Now, establishing a general philosophy as described above is one thing, putting it into practice is something else.

To achieve the objectives with this philosophy - a reliable, accurate and cost-effective verification of the missile's performance characteristics - some conditions are crucial:

- The ability to build complex, accurate simulation models is one corner-stone: a staff of skilled, well-trained system analysts, also being talented in both mathematical modelling of technical functions and processes as in codeing, is prerequisite. Naturally this staff must be provided access to modern, powerful computers.

- The availability of modern, powerful data acquisition systems is the second corner-stone: by making use of modern electronics it is today possible to build compact, reliable test instruments. Primarily important in this matter are telemetry systems, that facilitate the acquisition of information - in volume and quality - from one single test firing that earlier required several firings.

Although these two technologies, and a deliberate policy to emphasize the exploitation of them, form the basic corner-stones in the practical application of the verification philosophy, a third factor should also be mentioned here as being important in achieving success with this philosophy:

A meticulous test planning and preparation process must be started right at the beginning of the design and development phase, running in parallel with this work. This process must involve test planners and engineers, system analysts and mathematical model builders, design engineers etc, in an overall effort to secure maximum benefit from every single test to be performed with respect to validation of the mathematical models.

Below the presentation will turn from the general view on Saab Missiles test and verification philosophy to how this philosophy was applied to the STRIX development programme, and then particularly on the test set-up and test instrumentation aspects of this work.

III. Mission Profile, Event Sequence

A very simplified illustration of the STRIX mission profile is given in figure 1. The event sequence for firing a STRIX projectile is roughly as follows.

Programming and loading

The projectile is prepared for firing, which includes the programming of the projectile's guidance package with parameters relevant for the firing case.

The mortar tube is loaded with - in order - a separate launch unit, a separate sustainer motor (if needed, for extended firing ranges) and the STRIX projectile.

Firing and inner-ballistic phase

The launch unit's charges are ignited and a sequence is started that includes the physical docking of the sustainer motor (if loaded) to the STRIX projectile, and the vehicle is beginning its inner-ballistic launch phase in the mortar tube.

During this phase certain events are indicated in the projectile, e.g. in the projectiles safety unit, that initiates the activation of the system: the mechanical arming sequence starts, the battery is activated.

Launch

When the vehicle passes the mortar tube's muzzle the tail fins are un-folded and generate the projectile's spinning up, the launch unit is ejected, etc.

Outer-ballistic phase

The projectile's system is successively started up, e.g. pre-programmed firing parameters are fed into the guidance processor from the preparation memory, the sustainer motor (if loaded) is ignited and burns for several seconds, etc.

After passing apogee the sustainer motor (if loaded) is separated.

Preparations for target seeker activation are made.

Guidance phase

The target seeker is activated and starts target search and acquisition process. When a target is indicated and selected by the target seeker's image processor, it is tracked during the rest of the flight.

The radial thrusters correct the final approach trajectory and the guidance system controls the projectile all the way to target impact.

IV. Test Set-Up, "Test Stages"

After thorough analysis of this mission profile and its corresponding event sequence, and also taking into consideration technical, time-schedule and test aspects, a number of "test-stages" were identified as also indicated in figure 1.

Some of the reasons behind the selection of these specific "test-stages" were as follows:

"Test-stage" inner- and outer-ballistic tests

One of the two participating companies, FFV Ordnance, with a long experience in mortar and mortar munition development, took on this specific "test-stage" with the main objectives to match firing charges, sustainer motor performance and STRIX-vehicle lay-out in order to achieve a well-balanced configuration that places the STRIX projectile - after its ballistic flight path - in a well defined spatial volume, required as starting point for the guided flight phase.

The analysis showed that this specific "test-stage" did not require any specific new "inventions" as far as testing was concerned: Naturally it was preceded by traditional wind-tunnel investigations of the STRIX vehicle lay-out to establish its aerodynamic properties etc, but test firings could start very early by means of relatively simple test vehicles fired from mortars. In the final stage these tests will also provide required statistical information for establishing tabulated firing parameters to be used by those army units who are to operate the STRIX system in the field.

"Test-stage" environmental tests to cover system survival and start-up

Already during the initial study and project definition phases of the STRIX system it was obvious that one important area to be adressed was the mapping of what environmental conditions the STRIX projectile and its sophisticated equipment would be exposed to during the firing and launch phase. Especially important was the shock-environment and its influence on the projectile's vital components and subsystems.

It stood quite clear that traditional testing on vibrators, in shock-machines etc would not be sufficient in these aspects where we had to deal with accelerations in the magnitude of 10.000 g's with a duration of several milli-seconds. After having analysed various possible methods, such as firing test vehicles from real mortars and recover them by parachutes, firing test vehicles into blinds filled with sand etc, it was decided to build a special test tool for this purpose, a rail-gun facility, which is described in more detail below. This facility, which would complement the more traditional test tools and test methods, turned out to be the real work-horse for design-testning as well as qualification-testing of components, sub-systems and complete STRIX projectiles.

However, to fully derive advantage from this facility, a family of test vehicles, suitable for repeated firings, had to be specified and designed.

The simplest tests were those where the sole purpose was to establish whether a component or a sub-system just survived the tough conditions at firing/launch. Hundreds of firings have been performed for this purpose, with inspection and tests before and after shock exposure.

The more difficult part was to establish what conditions that really existed during the firing and launch phase besides the requirements to monitor the performance of vital sub-systems that were activated and operating during this phase.

For this purpose some specific test vehicles were specified, designed and manufactured. As a vital data acquisition and registration system in these vehicles a special-purpose FM/FM telemetry system was specified, designed and manufactured. This system is also described in more detail below.

This combination - the rail-gun facility and the specific telemetry system for recording the environmental conditions during the initial firing and launch phase - has proven to be a highly useful and valuable tool in the STRIX development work, and is a good example of the thesis stated earlier that the availability of modern, powerful data acquisition systems is one corner-stone in making the described general verification philosophy work in practice.

"Test-stage" aerodynamics and guidance system test firings

Very early in the development phase there was a need to get a feed-back from live firings to establish how the guidance system, including the un-orthodox method to generate course changes by firing side-thruster rocket motors, worked in practice. At this early phase no sub-systems were available, qualified for mortar launch conditions. For this purpose some specific test vehicles were designed and manufactured. They contained an experimental guidance system, excluding the target seeker but including the side-thrusters. They were launched by means of re-built rocket motors from old air-to-ground attack rockets, which allowed the test vehicles to be injected into a flight path very well corresponding to the real flight path, except that the launch shock-conditions were much relaxed. The test vehicles were equipped with a PCM/FM telemetry system.

This "test-stage" is also representative for our philosophy from another aspect: Once the test vehicle had been injected into its real flight path, it was subjected to a series of well defined, specially designed maneuvering experiments, executed by specially programmed sequences in the guidance processor. All relevant on-board data were acquired and transmitted by the telemetry system to the ground where they, off-line, together with all acquired trajectory data from theodolites and tracking radars, were fed into the earlier mentioned process identification procedure.

"Test-stage" full-system test-firings I

This "test-stage" represents the next step in the carefully planned, systematic sequence of escalated test complexity. Compared to the earlier described "test-stage", this time the target seeker was integrated into the STRIX system, and the STRIX projectile now had to detect, lock-on to and home in on a target (a target area was made up of a number of special artificial targets with controllable IR signature, designed to represent selected battle tanks, APC´s etc).

At this "test-stage" the STRIX test vehicles were also injected into its ballistic flight path by means of rocket launchers, since mortar condition qualified sub-systems were still not available. These live firings with operating target seekers were preceded by a sequence of thorough sub-system design and qualification tests, laboratory tests, field tests etc including captive flight tests.

A worthwhile tool in the preparations for these first live firings - and also afterwards - was a special-purpose built hardware-in-the-loop simulator for STRIX. Both for development work on the target seeker hardware and on the software for as well the target seeker´s image processor as the guidance processor and the interaction between these two processors, this simulator proved to be outstanding. It should, however, be emphasized that this simulator was used as a complement to the central digital simulation model, but never as a replacement.

The test vehicles used during these firings were equipped with specially designed PCM/FM telemetry systems, the first ones in a series that later on also equipped the mortar launched STRIX prototypes. During both these "test-stages" the complete target seeker image was transmitted to the ground stations, besides other relevant acquired on-board signals. These PCM/FM systems are also described in more detail below, as they, too, are very good examples of the earlier stated thesis that modern, powerful data acquisition systems is one corner-stone in putting our test and verification philosophy into practice.

"Test-stage" full-system test-firings II

Now the final stages of live firings were reached, in the sense that the STRIX prototypes now fired were launched from a mortar.

At this time all components and sub-systems entered into the fired test projectiles were mortar condition qualified - ultimately in the rail-gun facility. Naturally the telemetry systems, of the same kind as used during the previous rocket-launched live firings, were also qualified through rail-gun testing as the ultimate method.

From other aspects the live firing performance at this "test-stage" was very similar to the previous "test-stage".

"Test-stage" full-system test-firings III

The live firings at this "test-stage" were performed with pre-production STRIX projectiles, that is they contained a live warhead, but no telemetry system.

V. Some Specific Test-Tools

As has been indicated earlier some specific test-tools had to be designed and manufactured especially for the STRIX test and verification programme, investments required in order to make it possible to comply - from the test aspects of this programme - with the highly set ambitions regarding our test and verification philosophy.

Most interesting from this point of view are the earlier referred to special purpose hardware-in-the-loop (HWIL) simulation facility, the rail-gun facility and two of the telemetry systems, the FM/FM system for rail-gun firings and the PCM/FM system for the live firings ("test-stages" I and II).

The special purpose HWIL-simulator

The special purpose STRIX hardware-in-the-loop (HWIL) simulator was designed and manufactured as a development and verification tool for the STRIX guidance system. The simulator makes it possible to simulate, in real time, the guidance phase until impact. The simulation is performed in closed loop, which means that the output from the guidance system sensors depends on the guidance commands.

Figure 2 shows the principle construction of the HWIL simulator. The simulation computer controls the following parts:

- The motion of the target scene towards the projectile. This motion simulates the motion of the projectile towards the target. The target scene is heated to generate a realistic IR-scene.

- The motion of the mirrors that simulate the pitch and yaw motion of the projectile. The mirrors deflect the IR-radiation on to the target seeker.

- The spin unit which spins the projectile.

The projectile hardware utilized in the simulator is equipped with a real target seeker and electronics (seeker electronics, interface with sensors and signal processing). From the guidance processor the guidance commands are fed back to the simulation computer which closes the guidance loop. The results from the simulation are investigated with the assistance of the software development system and the data receiver.

The purpose with the STRIX HWIL simulator is primarily to make it possible to stimulate the system with realistic inputs in real time, in order to verify:

- The function of the hardware (seeker and electronics).

- The function of the seeker processor software.

- The function of the guidance processor software.

- The interaction between the above mentioned parts.

The simulator is thus used to verify the function of the guidance system, while system performance verification, e.g. the hit probability, is verified by means of the main digital simulation model.

The rail-gun facility

This facility was specified by the two industries responsible for the STRIX development programme, but was designed and built by one of the Swedish government-controlled test ranges, namely the FFK test range at Karlsborg in southern Sweden. Thus the rail-gun facility formally is regarded as a customer furnished facility in the STRIX programme.

The rail-gun facility was built during the summer 1985, and at the end of june that year the first firings were performed. Since then some 800 firings have been executed.

The main purpose with a rail-gun is to create a facility that enables launching of projectiles from a tube/barrel under correct, realistic conditions and then be able to recover the projectile in an unaffected status. This presumes that a sufficiently smooth and controlled retardation can be achieved that does not expose the test vehicle to any harmful deceleration forces. During launch phase as well as during retardation phase acquisition of test data from two different systems are performed:

- Transducers, installed at various locations in the rail-gun, delivering test data to a measuring central.

- Transducers, installed in the test vehicle, recording test data to be processed after the firing, or transmitted by means of a telemetry system (see below, the FM/FM telemetry system). Both alternatives are utilized.

The rail-gun facility consists of the following main parts:

- The launching device, which in this case is a converted gun with a smooth-bored 120 mm barrel. It corresponds very well to the launch tube of a 120 mm mortar. It is mounted to a concrete bed and is very carefully aligned with the pressure-relieving and retardation tubes.

- The pressure-relieving tube is designed to allow the expanding powder gases to flow freely behind the projectile in the same way as when the projectile is launched from a mortar. This tube is manufactured from a very solid tube blank that has been slotted with longitudinal recesses. The length of the pressure relieving tube is 2.5 m, and the front end is fix-bolted to the retardation tube.

- The retardation tube consists of a number of long steel pipe sections, mounted in special slide bearings, all in all giving a 300 m long tube. At the end of this long tube a "throttle stop" is mounted. Depending on what velocity and mass a specific test vehicle has, it is possible to achieve a required "braking distance" in the tube by adjusting the "throttle stop" device. The projectile is retarded by the air cushion that is compressed in the tube in front of the projectile plus the vacuum effect behind it. Recovery of the projectile from the tube is achieved by means of compressed air.

Some complementary data:

- Maximum allowed pressure in the gun, 160 MPa (for STRIX firings maximum 153 MPa is utilized).

- Maximum achievable velocity of exit, V_0 650-700 m/sec, depending on projectile mass (for STRIX firings V_0 is less than 350 m/sec).

A photograph of the rail-gun facility is shown in figure 3.

The FM/FM telemetry system

The final environmental qualification of the STRIX projectile´s components, sub-systems and overall system had to be performed by firings in the described rail-gun facility. In order to monitor what environmental conditions that were actually occurring at these firings, specific telemetry systems had to be designed. These systems - that as one main feature had to be reusable - were also used in a few mortar launches of parachute recovered test vehicles, in order to compare the launch environmental conditions in the rail-gun versus the conditions in a real mortar.

In reference 1 the specifications of these telemetry systems, the design approach and the conceptual mechanical and electrical structure etc are presented in detail, and therefore only a brief summary of the more noticeable characteristics will be given here.

The telemetry system is a 14 channel constant bandwidth FM multiplex with signal conditioning for 13 channels of vibration data (from piezoelectric transducers) and 1 channel for monitoring of the internal power supply. The specification stated that the frequency range for each data channel should be 10 kHz.

Due to limitations in telemetry standards - a sufficient number of standard subcarrier oscillator channels could not be provided - a single multiplex, accommodating the required number of data inputs having a frequency response of 0 to 10 kHz, was not feasible. A certain technique had thus to be utilized, where a set of special subcarrier channels had to be developed.

In principle the technical solution is achieved by having a baseband group of five wideband subcarriers and two translated groups (subcarriers translated up to a higher frequency band) of four wideband subcarriers each. (For further information on this specific technique, see reference 1).

Some complementary characteristics:

- The system contains a FM telemetry transmitter, S-band, and has an output of min 200 mW.

- The system is designed and quaranteed to withstand at least 5 test firings without any operational degradation; all delivered systems have in reality been fired at least 10 times each. To enable this re-use of the systems the internal power source is a rechargeable battery.

- The system meets the very severe environmental specifications, see reference 1.

- The system is built up using microminiature electronics packaging and is thus sufficiently small to fit into the available volume, and the weight is approximately 2.5 kg.

To summarize, these FM/FM telemetry systems have functioned very well and have - by producing adequate and reliable test data from the rail-gun firings - to a very high extent contributed to the mapping and understanding of what environmental conditions that are prevailing during the firing and launch phase for the STRIX projectile.

The PCM/FM telemetry system

For the system test firings during "test-stages" I and II a miniatured, high-shock resistant, computerized telemetry system had to be designed and developed.

In reference 2 the specifications of this telemetry system, the design approach and the conceptual mechanical and electrical stucture etc are presented in detail, and therefore only a brief summary of the more noticeable characteristics will be given here.

The PCM/FM telemetry system consists of the following three main parts:

- battery/power converters
- signal conditioning/PCM encoder
- telemetry transmitter

The signal conditioning/PCM encoder section is designed to accept different types of input signals:

- 2 parallel digital data interfaces (micro processor ports)
- 1 pulse counter input
- 20 discrete bi-level signals
- 32 analog signals

The PCM format can be easily modified by reprogramming of an accessible, UV-eraseable PROM-device. The PCM format has the following specifications:

- Word structure:

  11 bits/word (10 bits data, 1 bit odd parity), binary coded analog data

- Frame structure:

  128 words/subframe
  32 subframes/format

- Frame synchronization:

  2 words frame sync
  1 word sub-frame identification (SFID)

Based on the format specifications, sample rates from 15 Hz to 15 kHz (commutation rates of 1:32 through 32:1) are available and selectable under PROM-control.

The telemetry system also provides outputs for electrical supply of transducers.

The transmitter operates in the upper S-band frequency, with a typical output power of 250 mW.

The system meets the very severe environmental specifications, see reference 2; the final high shock testing was performed in the rail-gun facility.

To summarize, these PCM/FM telemetry systems have functioned very well and have delivered adequate and reliable test data from the live firings and thus proved to be the ultimate, expected test tool for achieving data for simulation model validation, in accordance with our general test and verification philosophy.

References

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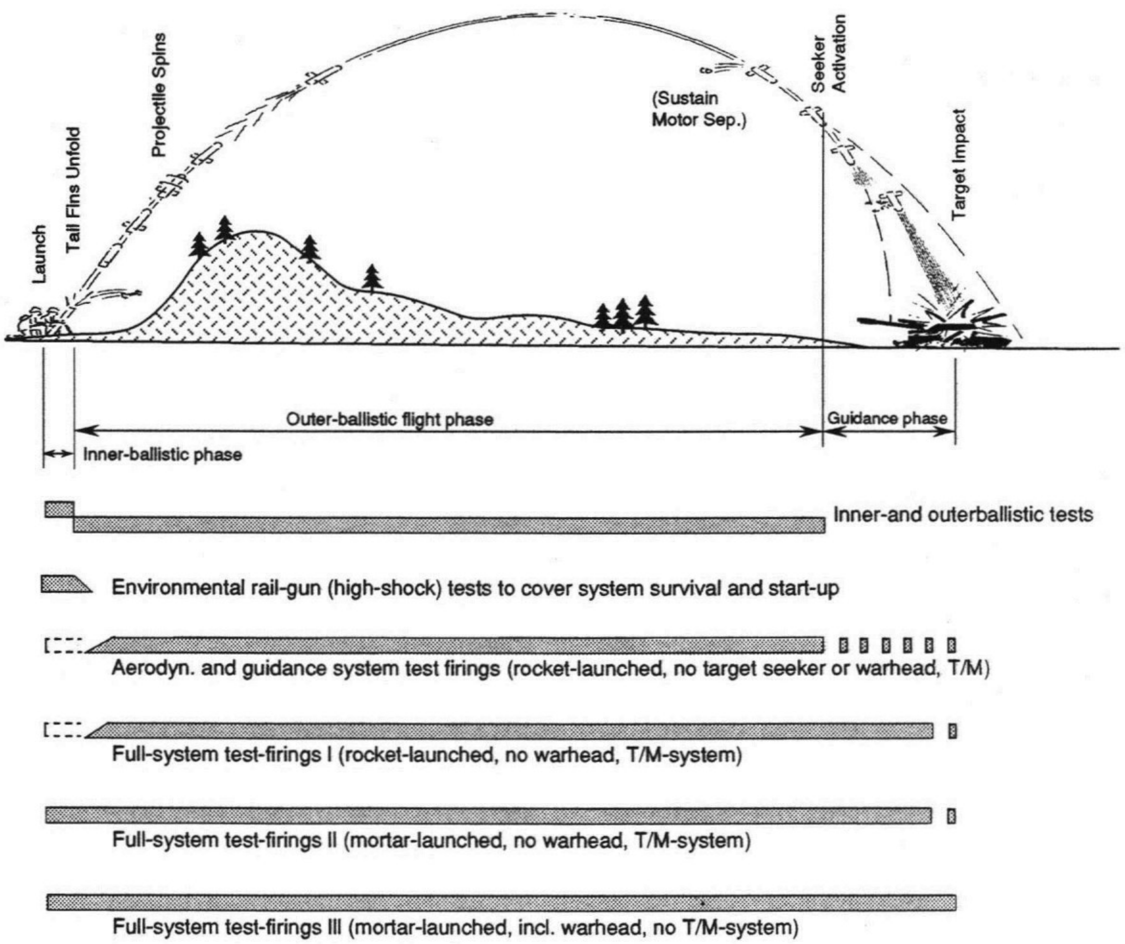

FIGURE 1. Top: STRIX mission profile (in principle)
Below: Mission profile broken down into "Test-Stages" with escalated test complexity.

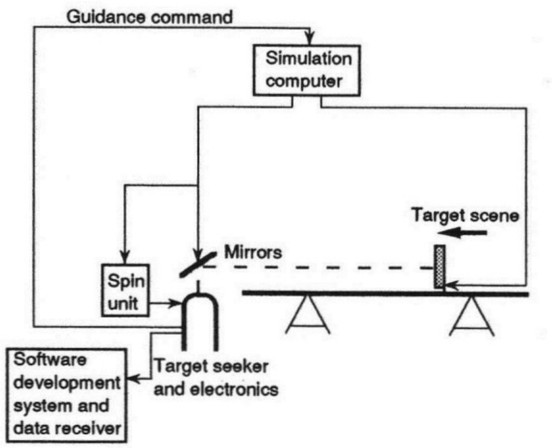

FIGURE 2. The STRIX Hardware-In-The-Loop Simulator

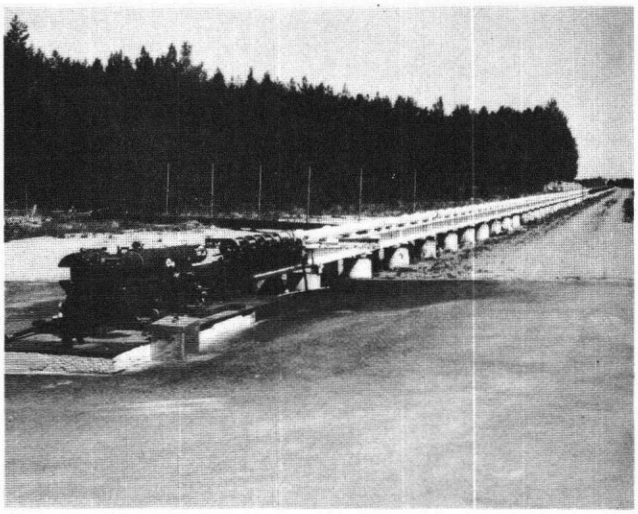

FIGURE 3. The rail-gun facility