Tomahawk Fleet Experimentation, Systems Engineering, and Delivering Capability to the Fleet

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ABSTRACT

The Tactical Tomahawk was delivered to the Fleet in 2004 with new features including network capabilities that allow in-flight communications. To translate the technical to the operational and to realize the Tomahawk's fullest potential, the Johns Hopkins University Applied Physics Laboratory (APL) has assisted the Tomahawk Weapon System Program Office (PMA-280) with using the Tomahawk flight test program and the Fleet experimentation process to demonstrate how the incorporated technology can be used operationally to meet Fleet needs. This process has benefited from the addition of APL technology, such as the Maritime Process Instrumentation System (MPRINS), to help with data analysis. The systems engineering process is the framework used to instantiate these technologies.

BACKGROUND

The Block IV Tactical Tomahawk cruise missile achieved its Initial Operational Capability (IOC) in September 2004. This version of the Tomahawk includes network technologies that allow the missile to receive several different types of in-flight mission modification messages. Essentially, the Tomahawk became a network-enabled weapon with the ability to be redirected to a new target in flight. Enabling the Tomahawk to take full advantage of these network technologies has been the goal of the Tomahawk Weapon System (TWS) Program Office experimentation activities for the past decade.

Recent effort has focused on the warfighter's expressed desire to use the Tactical Tomahawk as a dynamic weapon for moving and maritime targets. The challenge is determining how to take advantage of Tactical Tomahawk technology so that it is interactive with the warfighter, is effective against relocatable and moving targets in a dynamic land or maritime environment, and can achieve these goals in an affordable and timely manner.

The Johns Hopkins University Applied Physics Laboratory (APL), as the Technical Direction Agent (TDA) for the TWS, has been a significant part of the development and maintainability of the Tomahawk missile program since its inception. As a member of the TWS Program Office (PMA-280) Advanced Concepts and Technologies team, APL continues to contribute to the development, innovation, and fielding of new weapon system capabilities. The Advanced Concepts and Technologies team is chartered to investigate opportunities for TWS experimentation. Current venues for experimentation include Trident Warrior, Fleet exercises such as Valiant Shield, Tomahawk flight tests, and other Fleet events. APL has led multiple experimentation efforts that have supported development of third-party targeting, Surface Warfare (SUW) Tomahawk Concept of Employment (CONEMP), and Tomahawk synthetic guidance. These experiments are discussed later in this article. This article explores how systems engineering processes are applied to the experimentation process, and it provides Tomahawk experimentation examples.

FLEET EXPERIMENTATION

The TWS Program Office has followed the Navy's formal Fleet Experimentation (FLEX) process. The FLEX process enables demonstration and testing of potential new technologies, enhancements, and procedures. FLEX includes experimentation during Fleet exercises such as Valiant Shield and experimentation-focused venues such as Trident Warrior and Netted Sensors.

Experimentation Campaign Plan

The Navy's FLEX process is often a long-term and multiyear effort. It starts with the TWS Program Office (PMA-280) Advanced Concepts and Technologies team developing a FLEX campaign plan. Concepts and high-level objectives to explore experimentation are developed as part of an experimentation campaign plan. A campaign plan can help visualize the steps necessary for demonstrating near-term system enhancements. The plan details near-term (3–5 years) system enhancements and matches those objectives to potential Fleet exercise events. Not only does the campaign plan inform the program office team of the potential future path, but it also informs Fleet stakeholders of a potential time frame for system enhancements. A clearly defined experimentation campaign plan that identifies a transition path into a Program of Record (PoR) assists with Fleet support for experiments, including potential financial support. Figure 1 illustrates this multiyear iterative process.

Campaign Plan Considerations

The experimenter needs to consider several things when building an experimentation campaign plan. Understanding the system's current life-cycle phase will help with understanding the ability to make and fund changes. The administrative and funding rigors of the acquisition process for a fielded system make it challenging to insert changes into the system. Funding for experimentation is limited for a fielded system in the production or sustainment phase, and multiple sources of funding, expertise, equipment, and laboratory time have been leveraged. Currently, the TWS is entering a new phase of development and production, with new capabilities being added to the PoR. This may allow new opportunities in capability enhancement. No matter the phase, obtaining funding from outside resources can mitigate any constraints. Additionally, any organization with resources can become part of the experimentation team and can donate its resources. In past experiments, FLEX has provided additional funding, and vendors have donated expertise, equipment, and laboratory time.

Funding considerations make it important for the experimenter to manage the campaign plan to ensure that its goals are attainable with the resources available. Unclear objectives or scope creep can debilitate a project. A possible materiel solution (i.e., extensive hardware modifications or a complicated software project) may not be viable. Nonmateriel solutions, such as changing Tactics, Techniques, and Procedures (TTPs), are almost always less expensive than introducing a materiel change. This approach may require only data collection and analysis of an experimentation or demonstration event to introduce system improvements. The data and the final report on the FLEX results become the documentation to support a TTP or a technical note supporting the nonmateriel change.

The experimentation campaign plan should also recognize a transition path for system enhancements. In other words, the capability must have a way of becoming part of the PoR. It is not necessary that the proposed capability be part of a transition program; it is only necessary that a transition path be attainable. A high-priority Fleet need supported by the program office has a very good chance of obtaining Fleet support when it is viewed as something that can be introduced to the Fleet in the near term. An example is the Tomahawk Maritime Targeting Capability (MTC; formerly synthetic guidance) project; it was selected as a Chief of Naval Operations Speed-to-Fleet project.

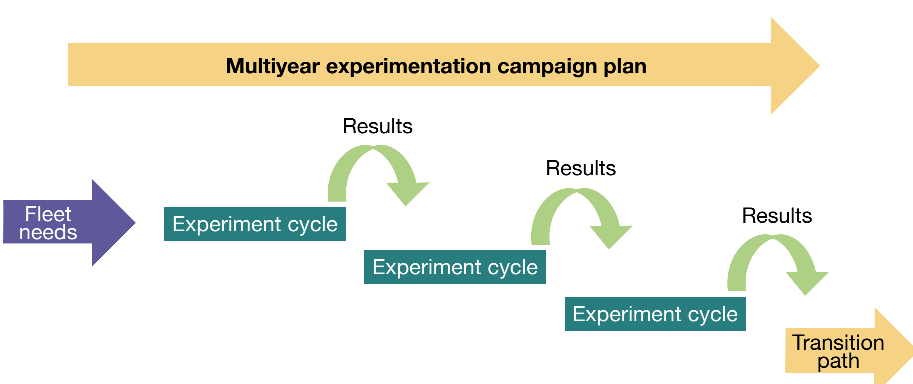

Figure 1. The multiyear experimentation campaign plan illustrates that Fleet needs provide the impetus for FLEX. Experimentation cycles provide results that are typically used in the following year's cycle. Ultimately, a transition plan is necessary.

The FLEX Process

FLEX is administered by the Navy Warfare Development Command (NWDC), the primary partner for Navy experimentation. NWDC is "an integral part of the

Navy's warfighting development system, delivering and integrating new capability to the Fleet at the tactical and operational levels of war. . . . The Navy looks to NWDC to lead innovation and accelerate the development of operational capabilities."[1]

FLEX initiatives are submitted to, and approved by, NWDC. Initiatives must have a Navy sponsor before they can proceed. All initiatives are entered into the FLEX Information Management System (a classified website) in a template that allows the submitter to describe the experiment, including experiment objectives, architectures, Fleet resources required, and personnel required. More importantly, the experimenter is given the opportunity to map the experiment's objectives to the Fleet's needs. Without an identifiable Fleet need and sponsor, experiments will not be approved. The FLEX Information Management System also gives stakeholders and other interested parties information about the focus of the experiment, allowing for greater potential collaboration. Once an experiment is approved, a focus area lead is assigned to lead the experiment through the numerous processes required for participation in a Fleet experiment. NWDC assists the experimenter by sharing vast knowledge and resources on areas including information assurance, data collection, experiment objectives, shipboard scheduling, and experimentation logistics. Figure 2 demonstrates the approximately yearlong process required to install a system on a ship or shore site for a Fleet exercise.

It cannot be overemphasized that the FLEX process for a mature system or prototype can take a year or longer. The process involves three planning conferences: the Initial Planning Conference (IPC), the Mid Planning Conference (MPC), and the Final Planning Conference (FPC). These conferences enable communication and collaboration as well as planning, allowing the experimenter to communicate the experiment's objectives and needs to NWDC and the exercise organizers. It is also during the planning conferences that the Fleet operators plan the experiment's execution, including details such as flight windows, ship operational areas, and network configurations.

The process also includes all the required steps to obtain the permission and logistical support to install a system on a ship or at a shore installation. The steps are not different from those required to install a system on a ship or shore site outside of the FLEX process. However, the condensed nature of the FLEX process is very chal-

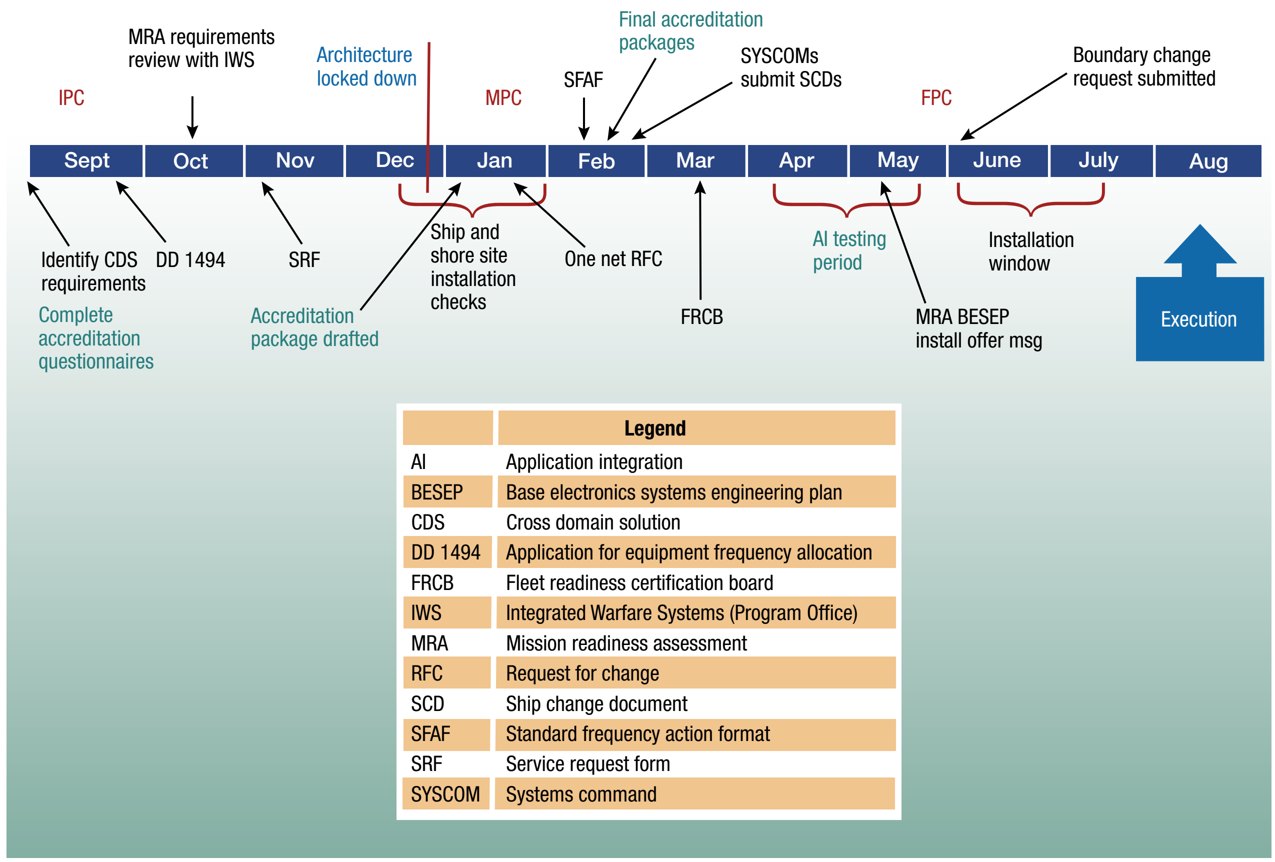

Figure 2. Typical milestone requirements and time line for participation in FLEX. The chart illustrates the full-year process and the many steps necessary to achieve a shipboard or shore site accreditation. (Modified with permission from R. Smithberger, Trident Warrior 16 accreditation presentation slide, May 2016.)

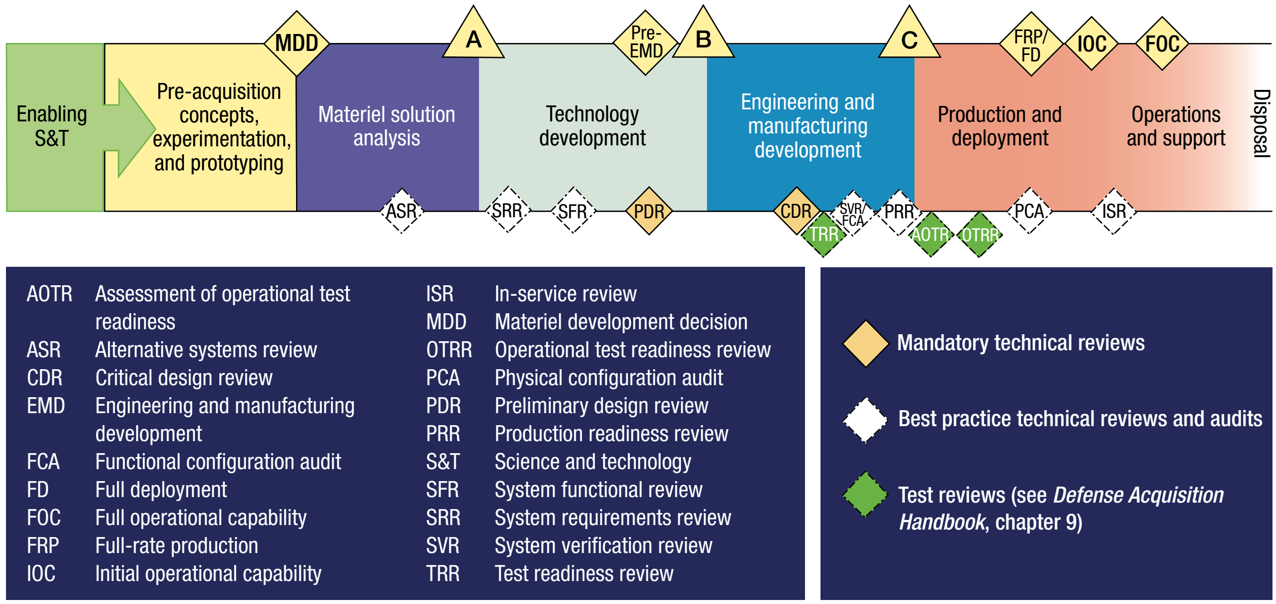

Figure 3. The weapon system development life cycle is a blueprint for development of weapon systems. (Reproduced from Ref. 2, chapter 4.)

lenging. It is highly likely that the system being installed will require additional testing to ensure its compatibility with shipboard networks; this testing must be accounted for in the schedule.

Tomahawk Flight Test Experimentation

The TWS Program Office has used another event that can be attached to a Fleet experiment or can stand on its own. During the Tomahawk Flight Test (TFT), an existing part of the TWS, Tomahawk missiles fly on a test range, allowing the team to verify and validate changes in the missile, weapons control system, launch platform, and mission planning system, including hardware or software updates. After the primary test objectives for the flight test have been met, a new capability can be demonstrated as a rider to the test (but it cannot interfere with the test). An advantage of the TFT is that it is a well-defined process that is controlled totally by the program office. Additionally, the costs of the flight test (missile, test range, testing, chase planes, firing unit, data collection, etc.) are all paid for by the program that requires the flight test.

SYSTEMS ENGINEERING FOR FLEX

Systems engineering is defined as "a methodical and disciplined approach for the specification, design, development, realization, technical management, operations, and retirement of a system."[2] As with all DoD acquisition programs, the systems engineering process is well defined and appropriately used to introduce capabilities to the Fleet. Figure 3 illustrates the weapon system development life cycle as defined in the *Defense Acquisition Guidebook*.[2]

In this life cycle, the experimentation and prototyping is in the pre-materiel development decision phase. However, over the past 10 years, the experimentation for Tomahawk has taken place in the operations and support phase in an almost continuous yearly cycle. Recently, the TWS Program Office has been funded to provide new capabilities to Tomahawk, and experimentation will be leveraged to inform systems engineering. The life cycle for Tomahawk experimentation can also be defined as a similar subset of the larger weapon system development life cycle. The experimentation cycle is a system life cycle because in most cases a system is developed, deployed, and operated in conjunction with other systems for the experiment. This experiment life cycle is not as long or as complicated as the weapon system development life cycle, and its stages are more like those in the International Council on Systems Engineering (INCOSE) generic life cycle shown in Fig. 4. The generic life cycle model can be adapted to the FLEX life cycle by replacing the utilization/support stage with

Figure 4. INCOSE generic development life cycle. This is a basic systems engineering life cycle for system development.[3]

Figure 5. FLEX life cycle. The generic systems engineering life cycle can be adapted for system development in FLEX.

experimentation. The retirement stage can be replaced by the analysis and reporting phase (Fig. 5).

The system developed in the experimentation life cycle has many of the systems engineering products that any system would have, such as high-level operational views, system views, data flows, and network architectures. Not only are systems engineering products important for defining and understanding the experimental system, but some products can also be used to help build a system that can transition to a PoR.

In the experimentation construct, the analysis and reporting phase may be the most important because it is in this phase that the results of the experiment are analyzed and distributed to the stakeholders. The analysis can help to define gaps in the concept that may need to be closed or mitigated. Analysis can also identify that a path or technology is not worth pursuing, enabling resources to be spent on initiatives that promise a better return on investment.

The following sections describe what happens in each stage of the experimentation life cycle for TWS FLEX.

Concept Stage

The overarching guide for developing experiment concepts from year to year is a multiyear experimentation campaign plan. The FLEX campaign plan should relate high-level Fleet needs to near-term experiment concepts.

The FLEX guidance (Commanders FLEX Guidance) is promulgated annually by U.S. Fleet Forces Command Commander Pacific Fleet.[4] It provides experimentation and prioritization guidance based on a review of Fleet needs such as those described in the Commander, Fleet Forces Command Warfare Integrated Priorities Capabilities List (IPCL), Urgent Operational Needs Statements (UONS), and Combatant Commander Integrated Priority Lists (IPL).[4]

During the concept stage, the operational view provides a high-level conceptual view of the experiment. It may be necessary to provide operational views of the planned operational implementation and of the experiment to distinguish between what is possible in an experiment and what could be implemented as an operational system. For instance, the experimental architecture may include a laboratory node that may not be part of an operational capability. NWDC reviews the experiment and accepts it as part of the Navy's experimentation plan or rejects it. Often, a plan is approved and the development phase starts without knowledge of how the experimentation effort will be funded. This is the yearly experimentation dilemma—to participate in an experiment that is 12 to 18 months in the future, planning has to begin as early as possible, before the funding is in place.

High-level objectives for the experiment are also created in this phase. It is important that the objectives relate closely to Fleet needs. It is also important that the objectives are attainable with the team and resources available (e.g., number of ships, type of environment, and aircraft availability). The outline of the experiment plan is created from the objectives. The experiment plan, which will be used as the script for execution of the experiment, includes the data collection plan, which is paramount for the data collection and analysis effort.

Development Stage

In the development phase, the concept is fleshed out. Because Tomahawk is a weapon system, this process involves identifying all actors in the weapons kill chain (find, fix, track, target, engage, and assess, or F2T2EA) from sensor to weapon. Often, experiment partners (other organizations with similar interests) are necessary to fulfill functions such as providing target data during the experiment. For instance, a sensor aircraft may be necessary to provide target position information, and a vendor may be necessary to provide a weapon simulation. Additional partners may include a ship's crew or personnel at a command and control (C2) node. Some partners can provide services, such as aircraft flight hours, simulation hours, or laboratory time, at no cost to the individual experiment.

At this point, experiment architecture is created based on the experiment objectives. The experiment "system" is created on paper from the experiment objectives. This now includes context diagrams, system views, and network diagrams.

In almost all FLEX scenarios (other than just purely data gathering), some type of information assurance certification is required. A network connection to a laboratory will require information assurance certifications. If the FLEX includes a ship or deployment of hardware, software, or both, the process is more complex and expensive. At a minimum, this process includes the following:

- Information assurance
- SHIPMAIN process for permission to install equipment on a ship
- Application integration process to ensure that an installed system works well with the ship's network

Throughout the process, subject-matter experts review the architecture, and product teams are briefed. Each one of these processes could involve additional reviews and additional testing. Additional testing always impacts cost and schedule.

As the experiment's objectives are refined and the time frame available for testing in the experiment becomes clear, the objectives are mapped to the time frames allocated for execution of the exercise. These time frames are based on asset availability and coordination of multiple experiments, which may leave a relatively small amount of time for testing compared to the overall exercise period. For instance, if the experiment relies on an aircraft for its sensor or as a communications relay, the execution window for experimentation will be limited to the on-station times allocated to that aircraft.

Production Stage

During the production phase, the hardware, software, and network connections that will be installed at a facility or on a ship are placed in their final experimentation configuration. Hardware and software should be locked down in their final configuration as early as possible, mainly because of information assurance considerations but also so that the team can verify and test all the interfaces and connections. A step-by-step process or script of the experiment execution is devised for the experiment plan. These steps should be completed before the mid planning conference, as shown in Fig. 2.

During this phase, the team trains on and rehearses the experiment script, ideally with the actual equipment operators. Because of schedules, it may not be possible for Fleet operators to participate in rehearsals. In that case, it is important for the team to be in contact with the operators and to review expectations in detail.

It is extremely important to test as many network connections as possible during this phase to identify possible deficiencies in the network architecture. A Fleet exercise is a training exercise, and any experimentation cannot interfere with it. Also, a Fleet exercise can be affected by extreme weather, mechanical failure, or a reallocation of resources. During Trident Warrior 15, the destroyer targeted for ship installation was pulled from the exercise because of higher-level priorities. Through great teamwork, it was possible to move the installation to another ship. However, it is important to identify contingency plans for all aspects of experiment execution. For instance, instead of targeting only one ship for installation, it is possible to complete the required accreditation paperwork for two ships with no increase in effort.

Additionally, the final experiment script is integrated with the exercise schedule of events, usually during the final planning conference. This focuses the planning for all the available resources and helps identify the final logistical requirements. Equipment that needs to be installed must arrive on the ship or at the site with enough time to be checked in, set up, and tested. In addition, participants must know how to travel to the scene of the exercise, understanding any requirements for overseas travel (if applicable) and any other relevant logistics. It is just as important to include in planning how to uninstall and test to ensure that ship or site installations are returned to normal operation. Participants must understand the plan for returning both themselves and the equipment back to the place origin.

The experiment plan is completed, reviewed, and distributed during this stage. It is critical to ensure that Fleet participants have the ability to review and understand the experiment plan prior to its execution. The data collection and analysis plan is also completed in this stage. This plan details all the data that will be collected, including chat data, system data, observer notes, participant surveys, screenshots, and Global Positioning System (GPS) telemetry (if applicable). The data collection and analysis plan also explains who is responsible for collecting the data and how the data will be distributed for analysis.

Experiment Stage

In the experiment stage, the experiment test plan is executed during the exercise time frame. Once all personnel and equipment are in place at the beginning of the exercise, the experiment can be executed in the time frame allotted. Contingency planning done in the previous stage will help the team respond to unplanned changes in the exercise, such as equipment failures or weather. It is important to have execution options available because a Fleet exercise rarely goes as planned for the experimenters.

Upon completion of the experiment, the data must be collected and transferred from the experiment for postevent analysis. Equipment installed on a ship or at a naval facility must be uninstalled, and the original ship or shore configuration must be restored. The experiment team must ensure that the test equipment is inventoried and prepared for return.

Analysis and Reporting Stage

During the analysis and reporting phase, the data from the exercise are collated and analyzed. Preliminary data are reviewed and compared to experiment objectives to provide a quick-look report to experiment stakeholders. As the final data are distributed from the exercise to the applicable participants, they are analyzed and the final analysis report is prepared. Tomahawk experimentation has benefited from APL analysis tools such as the Maritime Process Instrumentation System (MPRINS). This tool takes the myriad chat, link, and target data produced in an exercise and generates an output on an identifiable time line. This output helps the team analyze processes, such as kill chain, that have responsiveness requirements. The final analysis report compares the experiment's results to its overall objectives. Areas that did not meet objectives can become foundational areas for future experimentation and may reveal concept gaps that will need to be addressed in future efforts for the PoR.

TOMAHAWK EXPERIMENTATION

For over a decade, APL has been involved in many Tomahawk experimentation events that have produced tangible results toward the introduction of new technologies. APL has interfaced with the FLEX teams (the Fleet organizational construct for experimentation has changed several times over the years) and the TWS Program Office to help develop experimentation concepts and obtain experimentation funding. APL has led experimentation working groups, developed test plans as well as data collection and analysis plans, helped direct experiment execution, led the efforts on experiment analysis, and generated quick-look and final reports.

The Tomahawk experimentation campaign plans over the past decade focused mostly on the following three areas:

1. Third-party targeting
2. CONEMP for SUW Tomahawk
3. MTC (formerly synthetic guidance)

Third-Party Targeting

Tactical Tomahawk provided the new capability of in-flight communications, allowing exploration of targeting options. One of the first investigations involved third-party targeting. With this type of targeting, specially trained and certified tactical operators and Joint Terminal Attack Controller service members redirect the actions of combat aircraft to enable some targeting equipment to specify an aimpoint for destruction. That aimpoint is then sent to a Tactical Tomahawk missile in flight.

APL led efforts during Tomahawk test flights (formally referred to as Operational Test Launches, or OTLs) to demonstrate third-party targeting concepts. For example, OTL 437, in the fall of 2006, demonstrated that targeting information provided by Joint Terminal Attack Controller (JTAC) operators could be used to successfully redirect a Tomahawk in flight to a new target, as shown in Fig. 6. These OTL experiments were mostly data-gathering events. Although the events were static to ensure the safety of the flight tests, the results informed system and procedural changes in the Fleet.

Figure 6. This picture shows a target impact in OTL 437,[5] demonstrating that third-party targeting and in-flight redirection were viable.

CONEMP for SUW

During 2012, the Chief of Naval Operations directed the TWS Program Office to develop a Tomahawk version with a seeker capability for SUW. This effort was under a Rapid Development Capability (RDC), an acquisition vehicle that allows a capability to be quickly developed and inserted into the Fleet to meet Fleet needs. APL was asked to assist in this development and to help lead the working group responsible for the development of the CONEMP. The CONEMP is an acquisition document describing the operation of the proposed system. APL was instrumental in the processing of Fleet comments and completion of the document. As a risk mitigation, the TWS Program Office decided to validate the CONEMP in Trident Warrior 13. In other words, the sensor input, the network connections, and the steps necessary to create an SUW mission would be validated on a guided-missile destroyer and in a near-operational environment.

Although the RDC did not go forward at that time, important aspects of using a Tomahawk missile for the SUW mission were realized, including the following:

- A validated initial CONEMP from which system requirements have been derived, reducing risk for systems engineering work
- Identification of an Intelligence, Surveillance, and Reconnaissance (ISR) platform suitable for the SUW mission, including U.S. Air Force platforms
- A validated network pathway from the sensor to the Tactical Tomahawk Weapons Control System (TTWCS)

Although these products were not used in this edition, they served as lessons learned for the new Maritime Strike Tomahawk SUW capability.

Maritime Targeting Capability

Another effort, then known as synthetic guidance, was undertaken in 2014 to provide SUW capability to Tomahawk without any system changes. In this effort, now known as Maritime Targeting Capability (MTC) by the Navy, a third-party source sends target updates via a system that the Naval Air Weapons Center–Weapons Division developed, the Joint Network Enabled Weapon Mission Management Capability (JNEW MMC). JNEW MMC provided cross-functional domain (intelligence, surveillance, and reconnaissance–C2 node–weapon) network connectivity, as well as the ability to provide an in-flight Tomahawk with aimpoints that would describe an intercept course with a moving maritime target.

The Naval Air Weapons Center–Weapons Division developed and demonstrated this capability in a TFT on 27 January 2015 (see Fig. 7). The flight test demonstrated the ability of an unmodified Block IV Tomahawk to intercept a moving maritime target. APL led the complementary FLEX events.[6]

Later in the year, the project was selected as a Chief of Naval Operations Speed-to-Fleet initiative that would provide a baseline capability to the Fleet by 2019. During the same time, APL was leading a FLEX effort to examine how MTC would be employed in an operational environment. While the flight test demonstration of MTC used a developmental architecture to avoid system changes, the FLEX events began the transformation to an operational architecture as required by the Speed-to-Fleet initiative. These kinds of events give the team an understanding of the TTPs that would be required to employ this capability and how those required TTPs would translate into system-level requirements for synthetic guidance. Past and planned events include the following:

- Valiant Shield 14 (September 2014)
  - JNEW MMC located at Naval Air Weapons Station China Lake
  - Demonstrates the ability to guide simulated Tomahawk missiles to a target in an operational environment
  - Recommendations for operation from Navy SUW subject-matter expert
  - TTPs drafted by Navy SME
- Trident Warrior 15 (September 2015)
  - JNEW MMC placed aboard a guided-missile destroyer
  - More realistic Navy C2 structure directs trial engagements
  - Loose integration with an advanced sensor project demonstrates ability to improve kill chain
  - APL subject-matter expert on board guides ship's force through surface strike planning based on draft TTPs
- Valiant Shield 16 (September 2016)
  - MTC placed on two guided-missile destroyers
  - Near-operational architecture and improved software
  - Use of draft TTPs revised by the Surface and Mine Warfighting Development Center

These Fleet experiments result in operational feedback to the synthetic guidance development team from operators' experiences employing synthetic guidance in the operational environment. This feedback will help to improve the operational framework for Fleet employment.

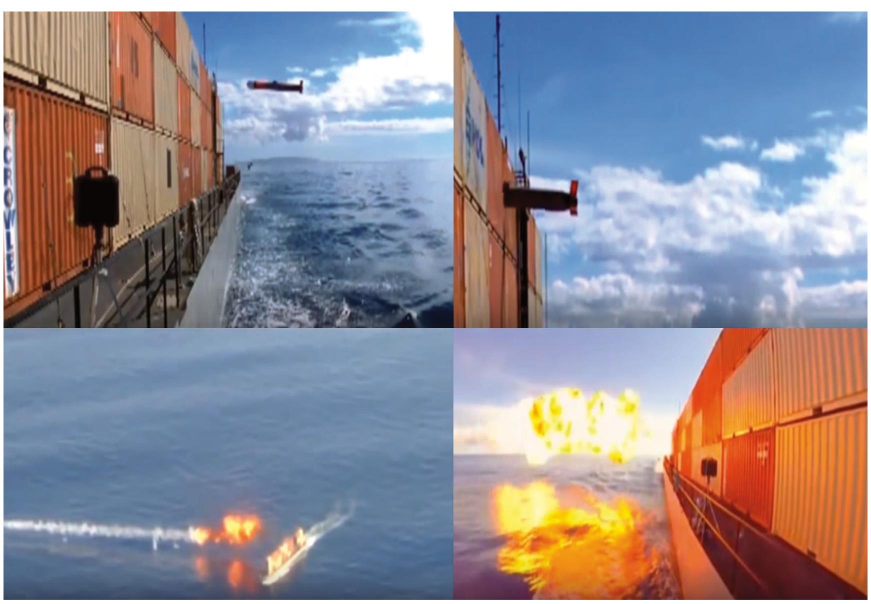

Figure 7. MTC (formerly synthetic guidance) flight test in January 2015.

CONCLUSION

The Navy's FLEX program is a fast and effective method for the TWS Program Office to demonstrate potential capabilities to the Fleet in the operational environment and to obtain important feedback about the process from stakeholders and the Fleet. Participation in FLEX events has resulted in materiel and nonmateriel (procedures) capability improvements for Tomahawk. Development of Fleet experiments for the TWS is analogous to the system development cycle and provides systems engineering products for future use in a transition process. FLEX will remain an important part of the process to identify and quickly deliver Tomahawk enhancements to the Fleet user. APL is an important part of this process, helping to create and execute Tomahawk FLEX and applying a systems engineering process to the experimentation life cycle.

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