Silent Hammer

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The Silent Hammer Limited Objective Experiment aimed to assess additional capabilities for a new class of submarines in fighting terrorism. What resulted was an excellent case study of a large-scale, operationally relevant test of integrated sensing and decision support concepts. This article discusses the Silent Hammer architecture, with a special focus on the Metadata Architecture fielded by Lincoln Laboratory, and describes the experimentation methodology developed to rigorously evaluate these capabilities in a realistic operational scenario. While the independent analysis conducted by Lincoln Laboratory provided the Navy with the knowledge it needed to evaluate the capability of the submarine class, it also increased understanding of the needs of the broader community to successfully obtain and process intelligence, surveillance, and reconnaissance information to support the decision process.

Integrated sensing and decision support (ISDS) seeks to understand how humans discover and use information in the decision process. Nowhere is this decision support process more critical than during military tactical operations. Traditional intelligence, surveillance, and reconnaissance (ISR) support often provides too much and perhaps irrelevant information or conversely too little, perhaps not timely information to operators and command staff during mission planning and execution. However, while experimentation in a modeling and simulation environment can suggest methods to improve decision support, evaluating the operational utility of ISDS tools to the warfighter requires experimentation with the systems architecture in a realistic and stressing environment. This presents a challenge: how does one design and execute an ISDS experiment within the constraints of large-scale military operations?

The Silent Hammer Limited Objective Experiment, run under the Sea Trial guidelines set by the Navy Warfare Development Command, successfully addressed this question. At the heart of the Silent Hammer experiment was a new, transitional class of submarine, designated SSGN for Ship, Submersible, Guided, Nuclear (see sidebar "The SSGN Platform," p. 248). The Navy is keenly interested in expanding the military utility of this platform, which has been designed for missions in the war on terror. While the SSGN carries an impressive cruise missile arsenal and can provide clandestine transport for Special Operations Forces in and out of rapidly emerging hot spots, it is currently limited in its ability to sense its operational environment. Furthermore, it does not carry personnel who can process ISR information, nor does it carry a command staff that can make tactical decisions based on new knowledge. Effectiveness in counterinsurgency operations, however, depends on the ability to rapidly identify, locate, and act against an elusive enemy. To this end, the Navy believed it would gain significant tactical advantage if many of the sensing and decision support functions were on board the SSGN, rather than distributed to other platforms or remote locations.

To experimentally test this hypothesis, the Naval Sea Systems Command commissioned Silent Hammer, and promptly brought on board Lincoln Laboratory as its independent analyst. This role was an outgrowth of the Laboratory's successful analysis on an earlier SSGN experiment, called Giant Shadow. Lincoln Laboratory was therefore centrally positioned to ensure Silent Hammer was designed and executed as a scientifically rigorous experiment. In large part because of the fully instrumented information architecture that the Laboratory provided, Silent Hammer generated a comprehensive collection of data to address seven diverse analysis questions of interest to the Navy.

Three of these questions were ISDS-centric:

- Can the SSGN serve as an effective sea base to perform mission planning?
- Can the capabilities in the SSGN command center support the embarked commander for the missions explored in Silent Hammer?
- Is the Metadata Architecture an effective tool for information dissemination management and/or information management?

While the resulting analysis to address these questions was directed at SSGN military utility, the results are relevant to the broader ISDS community. Silent Hammer allowed Lincoln Laboratory a deep look into how ISR information is used in the military decision-making process during a stressing and realistic operation, and yielded great insight into areas to improve decision support.

SSGN's Advanced Capabilities

The SSGN platforms will provide the Navy with a significant new tactical capability. They can conduct clandestine missions with Special Operations Forces (SOF) and provide tremendous firepower when needed. In such situations, the SSGN would receive mission orders from an off-board (and often far distant) commander and planning staff. However, military experience shows that tactical effectiveness can be degraded when the commander and his or her staff are not leading operations from an up-close vantage point.

To remedy this, the Navy is evaluating a more autonomous, advanced configuration for the SSGN, which it calls the SSGN-SOF Strike Group, or S3G. The S3G brings the "decision" element to the SSGN, which must then be integrated into an appropriate sensing and information exploitation environment. Knowledge extracted from timely, relevant ISR data must be made available to the embarked commander and staff. The SSGN must therefore have off-hull ISR assets under its control to collect information, sufficient communications bandwidth to receive the sensor data, and on-board analysts to process the incoming information. While the SSGN (often referred to by submariners as a "floating hotel" in contrast to the much smaller fast-attack submarines) has significant real estate to offer, the S3G configuration must combine command staff, analysts, SOF personnel and equipment, and ship's crew onto one submerged platform. It is important to note that command of the platform itself is maintained by the submarine captain. It is his responsibility to maintain ship's functions, and ensure ship and personnel safety while supporting the needs of the operations commander.

It is clear that the planning and execution of time-critical counterinsurgency missions will stress the S3G personnel and communications allocations. An enabling capability is therefore a network-centric information architecture to manage the dissemination and discovery of high-value ISR data products. This information management capability, instantiated in Silent Hammer as the Metadata Architecture, reduces communications bandwidth needs by initially transmitting to the command center only a thin representation of each data product. Such "metadata," which contains who/what/where/when/how information and perhaps a thumbnail representation, can be cataloged and made accessible to all personnel. Only those data products determined from their metadata to be relevant will be pulled to the SSGN. This selectivity will also reduce the amount of time wasted on processing information of negligible value.

Clearly, the Silent Hammer evaluation was centered on an improved integrated sensing and decision support capability for the SSGN. Therefore, results from Silent Hammer and Giant Shadow, a precursor experiment, have far-reaching relevance beyond that of the submarine force and the Navy.

Lessons from Giant Shadow

The first experiment conducted by the Navy to evaluate S3G military utility, called Giant Shadow, was conducted in January 2003 at the Atlantic Undersea Test and Evaluation Center in the Bahamas. Participants included the *USS Florida* (SSGN-728), the *USNS Mary Sears* (a surrogate for the SSGN command center), Naval Special Warfare Group Four, the Naval Air Systems Command "Hairy Buffalo" (a modified P-3C Orion aircraft), and other units and platforms to provide networked ISR.

Lincoln Laboratory personnel analyzed information flow in Giant Shadow between the various airborne ISR assets and the surrogate SSGN command center. One lesson learned was that the ability of the battle staff to efficiently use ISR data products was hindered by inefficiencies inherent in the design of the distributed information architecture. In particular, the analysis showed that the fielded 'push-based' dissemination architecture coupled with poor coordination between data providers and analysts resulted in the wrong information being

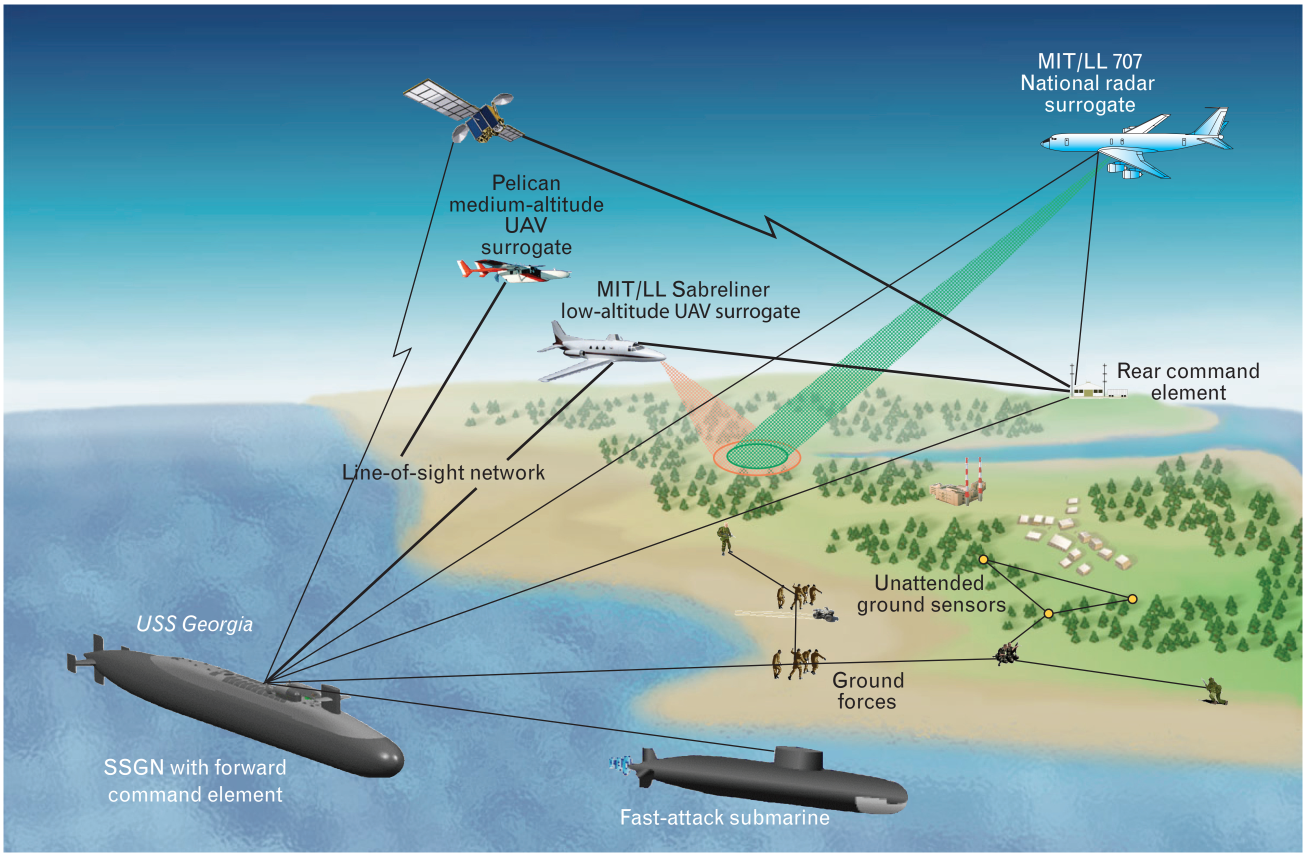


FIGURE 1. Silent Hammer architecture. Undersea, land, and air assets were brought together for Silent Hammer to emulate a potential operational deployment of the SSGN-SOF Strike Group. A variety of networks provided connectivity of these assets, including unmanned aerial vehicle (UAV) surrogates, allowing data and information to be shared during the exercise.

sent to the command center and the right information being held back. The providers, not the consumers, decided what information to transmit and when, which created a situation whereby analysts were overloaded with processing extraneous information, yet still had insufficient information for decision support.

The results of the Giant Shadow analysis significantly affected the design of the follow-on experiment, Silent Hammer—specifically, by prompting the implementation of a Metadata Architecture scheme to reduce the amount of irrelevant data transmitted to the SSGN. Furthermore, the Giant Shadow results helped identify measures of effectiveness and performance for Silent Hammer, especially regarding communications and information usage by operators. Other areas identified for improvement of experimentation methodology were increased experimental monitoring and control for understanding and reconstruction; increased realism and flexibility in experiment concept of operations to more rigorously emulate operational practice; and integration of analysis goals into experiment planning with participation of all major technology providers. These lessons were thoroughly and successfully incorporated into the design and execution of Silent Hammer.

Silent Hammer Overview

After the successes and limitations of Giant Shadow, a follow-on experiment, named Silent Hammer, was quickly commissioned. It was agreed upon that Silent Hammer would be an ambitious undertaking. Its goal was nothing less than a thorough, analysis-based evaluation of the S3G concept. Fielded assets and technologies would be realistic surrogates for desired S3G capabilities, and the scenario would accurately replicate a potential operational environment. This level of realism would ensure the relevance of the S3G evaluation based on the Silent Hammer analysis. The evaluation would then be presented to a Military Utility Assessment panel composed of senior Navy personnel from a wide range of commands, who would then adjudicate which prov-

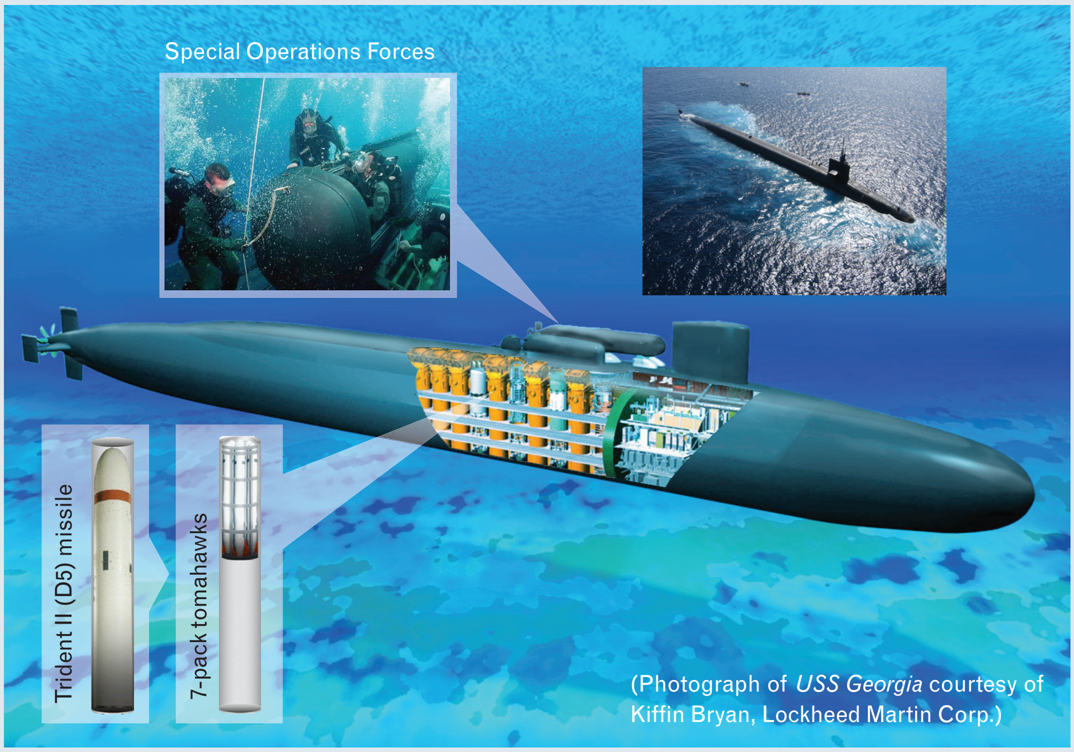
THE SSGN PLATFORM

Beginning in 1981, the U.S. Navy commissioned 18 nuclear ballistic missile submarines (SSBN) as part of its strategic-defense arsenal. These submarines were designed to clandestinely patrol the seas for months at a time, carrying as many as 24 nuclear-armed Trident missiles that could be launched at the Soviet Union or other threat nation.

With the ending of the Cold War and the shift toward counterinsurgency operations, the Department of Defense repurposed four SSBNs that had been selected for decommissioning as guided missile submarines, or SSGNs. Because seven conventionally armed land attack cruise missiles fit into one missile tube, each SSGN will carry an arsenal of up to 154 cruise missiles. In addition, two missile tubes are being converted to support Navy SEAL or other Special Operations Forces (SOF) missions. The ship also provides accommodations and support for more than 66 SOF personnel and their equipment for up to 90 days.

The strengths the SSGN brings to the counterinsurgency fight are stealth and endurance coupled with a large payload capacity. It can remain on station and at depth for months, limited only by the food it can carry for its 154 crew members and other embarked personnel. It provides a clandestine platform for staging SOF operations in emerging conflict areas. And when required, the SSGN can deliver tremendous firepower. In the future, some of the missile tube payload capacity of the SSGN may be dedicated to off-board intelligence, surveillance, and reconnaissance (ISR) assets, as well as other weapons systems.

The SSGN conversion process began in 2002, at a cost of approximately $400 million per ship. Two SSGNs, the *USS Ohio* and *USS Florida,* returned to service in 2006. The other two, the *USS Michigan* and *USS Georgia*, are to follow in 2007 and 2008.



(Photograph of *USS Georgia* courtesy of Kiffin Bryan, Lockheed Martin Corp.)

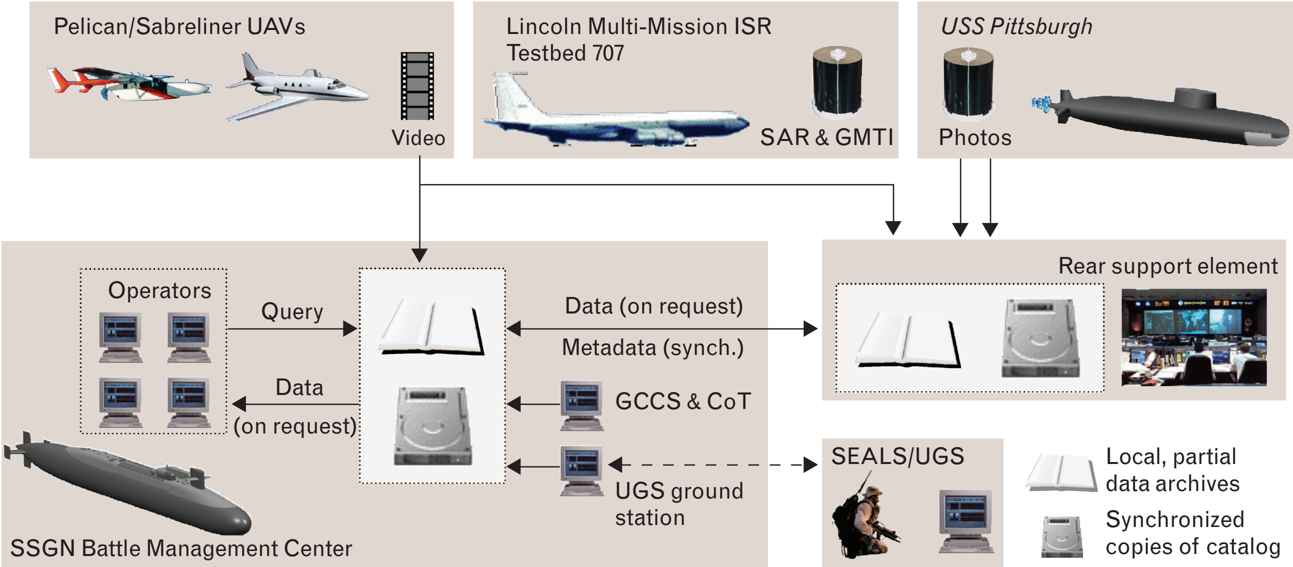


FIGURE 2. The Metadata Architecture allowed data produced during Silent Hammer, such as from unattended ground sensors (UGS), the Global Command and Control System (GCCS), and Cursor on Target (CoT), to be archived at local nodes, but commonly represented across all nodes through the use of metadata catalogues. This allowed users to search all data products, but request only the full download of only the most relevant products, reducing the need for communications bandwidth.

en capabilities to recommend for procurement for the SSGN. About eighteen months of planning went into Silent Hammer, with approximately 1100 personnel from 62 organizations—including fleet units and teams of industry and academic naval researchers—taking part.

Silent Hammer was executed during 4 to 13 October 2004 on and around San Clemente Island off the coast of San Diego. At the center of Silent Hammer was the *USS Georgia* (SSGN-729). Improving upon Giant Shadow, a prototype advanced capability command center called the Battle Management Center (BMC) was stood up on board the *USS Georgia*. In charge of counterinsurgency operations was an embarked Joint Task Force (JTF) forward command element. The JTF commander, an Air Force brigadier general, and his staff, combined with Special Operations Forces units, led to the desired high level of operational realism needed for evaluation of the S3G military utility.

Supporting operations was a distributed network of ISR assets. Two manned aircraft, the Naval Postgraduate School's Pelican and Lincoln Laboratory's Sabreliner, acted as surrogates for unmanned aerial vehicles (UAV) carrying electro-optical sensors. A third aircraft, Lincoln Laboratory's Boeing 707, carried the Lincoln Multi-Mission ISR Testbed (LiMIT), which provided synthetic-aperture-radar and ground-moving-target indicator capabilities. Unattended ground sensors provided eyes-on-the-ground situational awareness. Finally, an additional submarine provided electro-optical images of maritime vessels taken through its periscope. All ISR information was made available through a Metadata Architecture (described below) both to the forward command element and support staff based in the Battle Management Center and to a land-based rear command element and support staff.

The Silent Hammer communications architecture included military voice radios, satellite communications voice and data channels, and a commercial wireless network to emulate both the SSGN planned High Data Rate antenna (a 256-kilobit-per-second satellite link) and a proposed line-of-sight data link to the UAV surrogates. Figure 1 provides an overview of the assets deployed during Silent Hammer.

Metadata Architecture

The limited bandwidth of the SSGN and the limited number of ISR analysts in the Battle Management Center placed a premium on the efficiency of information management. Drawing from Department of Defense guidance for the Global Information Grid [1], the Navy's FORCEnet initiative [2], and industry experts from

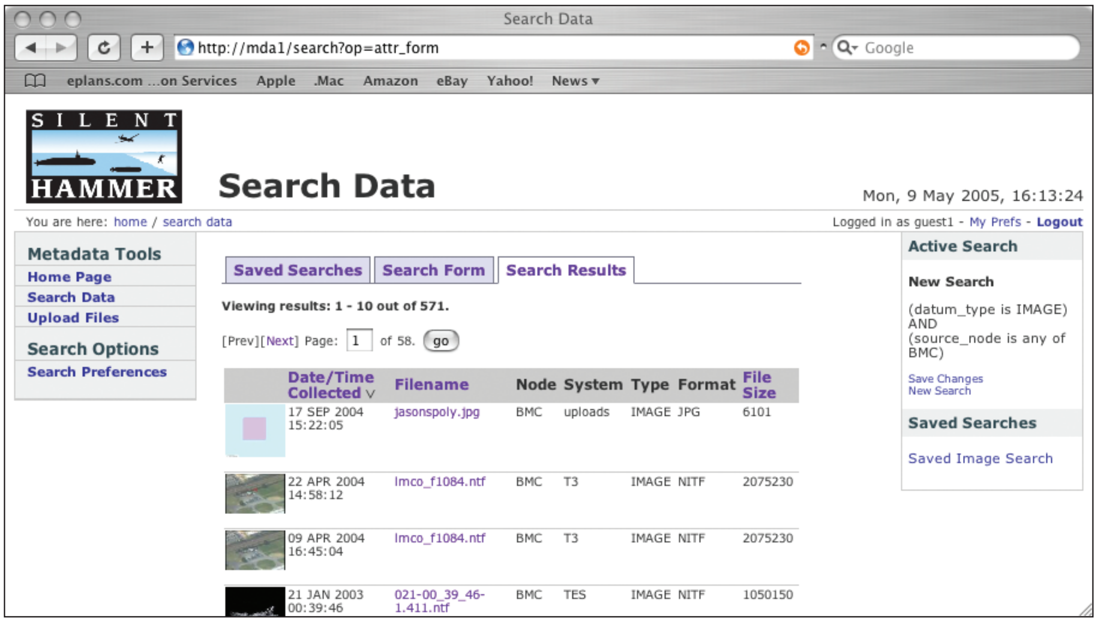


FIGURE 3. Example of metadata search results. Each listed result presents a thumbnail image and other identifying information, allowing the user to quickly find the products most relevant to the task at hand.

Northrop Grumman Electronic Systems, Lincoln Laboratory designed and built the Silent Hammer Metadata Architecture (Figure 2) to archive ISR data products across a distributed network of multiple archives and to provide tools for users to readily discover and efficiently disseminate the highest-value products.

Personnel in the Battle Management Center on board the SSGN and the land-based rear support element each had responsibilities to collect and archive particular ISR products into their copy of the metadata catalog. The Battle Management Center had primary responsibility for collecting video and single-frame images from the Pelican UAV surrogate, and photographs from unattended ground sensors. It also archived imagery from National ISR assets collected prior to Silent Hammer and chat logs generated during operations. The rear support element collected images from the Sabreliner UAV surrogate and LiMIT. Both sites collected exploitation products, notably the PowerPoint briefs generated.

For each ISR product, a metadata entry was installed into the local catalog. This entry consisted of a standard set of information, including times associated with data production and installation in the catalog, the latitude/longitude location of the image, sensor type, data source, filename, and small thumbnail images. Then every 30 seconds the two catalogs would be synchronized and new metadata shared so that each site would have an identical copy of a common catalog. This collaboration ensured that both sites had awareness of all information without having to download the entire data volume.

By using a Web-based interface, operators could then search the metadata catalog for relevant ISR products by specifying values of one or more metadata fields, or by focusing the search to a particular geographic location via a simple map interface. ISR products that satisfied the search constraints were presented as a list of thumbnails and key metadata values (Figure 3). Though small (less than 64 × 64 pixels), the thumbnail images were adequate to judge image quality and could be used to disregard images that contained only cloud cover or open ocean. Next, the operator could select a promising ISR product and display it at a mid-level resolution (less than 800 × 800 pixels). If the product still appeared to have value to the operator, he or she could finally request the original, full-sized image. If located at the remote site, the original image would be downloaded and stored in the local cache, obviating the need to retransmit if another operator requested the same product.

Use of a Web-based portal allowed all communications traffic to be transmitted with standard protocols. Integration was simplified by using commercial products for the database and web services. Metadata Archi-

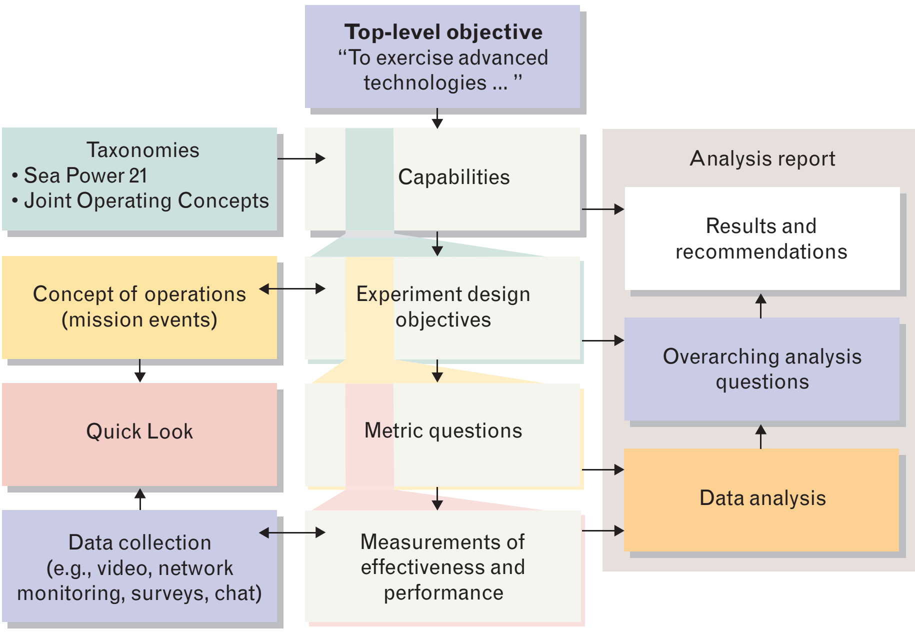


FIGURE 4. The Silent Hammer evaluation strategy. Decomposing the evaluation into the appropriate objectives and metrics kept the resulting analysis focused on answering questions of key concern to the differing communities of interest.

tecture software existed only on the metadata servers and not on client machines, simplifying the security authorization procedures for software on classified systems.

The Metadata Architecture monitored every action related to the metadata catalog, including installation, viewing, and downloading of ISR products. This information made it possible to reconstruct who was using what information and when—and thus to determine which images were most useful to each operator, which images were most useful during particular mission phases, and how long it took to generate and exploit information.

Data Collection and Analysis

The SSGN-SOF Strike Group evaluation required the Silent Hammer architecture to be stressed in a well thought out and controlled manner, and the appropriate data collected to capture the response. It was therefore necessary to create a representative military environment and execute an insurgency scenario designed to replicate potential future threats. Data collected on the action of the warfighters, coupled with measurements of system performance, could then be evaluated to determine S3G operational effectiveness.

The challenge was to design and execute a valuable and valid experiment within real-world limitations of resources and without interfering with Navy operations. Lincoln Laboratory, under the guidance of the Navy Warfare Development Command, led the creation of the Silent Hammer Data Collection and Analysis Plan. Because of the ambitious scope of the evaluation, an experiment design formalism was developed to keep the analysis anchored to the operational capabilities under exploration. This successful formalism was met with widespread interest throughout the Navy, and has been adopted by the Laboratory's Integrated Sensing and Decision Support group for new systems evaluation efforts.

The overall evaluation strategy (Figure 4) began with the top-level objective from the experiment proposal, which aligned with Navy doctrine outlined in the Chief of Naval Operations' "Sea Power 21" taxonomy [3]. This strategy ensured that the advanced capabilities under investigation for the SSGN filled identified capability gaps, ensuring the relevance of the experimentation effort to the Navy.

Experiment design must be in alignment with Navy concept of operations. In other words, the system being evaluated had to operate in a realistic test scenario. Therefore, ISDS-relevant experiment design objectives for Silent Hammer included the collection of timely ISR data relevant to the maintenance of situational awareness over land and sea, and the rapid generation of actionable information from off-board sensors.

Each experiment design objective is then decomposed into a series of metric questions. For example, to evaluate ISR data collection, we needed in part to answer the following question: Is the method of data off-load from the collection platform timely enough to accomplish the sensor objective? Phrasing metrics as a question aids the analyst, as the answer immediately translates into a defensible result when backed by the relevant measures of performance and measures of effectiveness. A measure of performance yields a quantifiable measurement of how well a component of the system performed, while

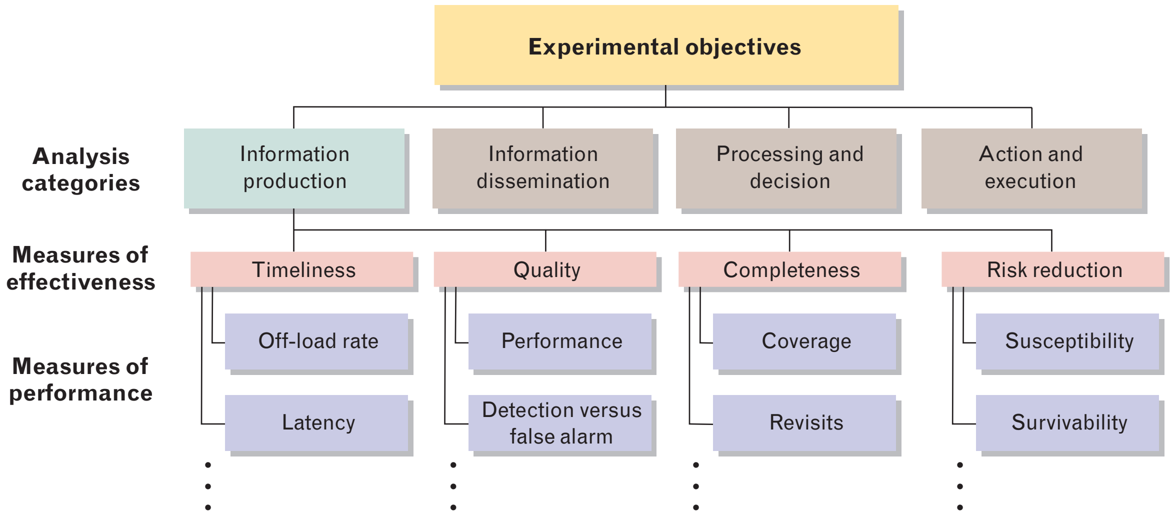


FIGURE 5. Metric decomposition hierarchy. Thirty-six measures of effectiveness and 83 measures of performance were defined for the Silent Hammer analysis plan, necessitating the development of a formalism to connect relevant metrics to each of the experiment design objectives.

a measure of effectiveness relates system performance to operational effectiveness. Therefore, multiple measures of performance can feed into a single measure of effectiveness. The expert input of the warfighters using the system must be included when evaluating measures of effectiveness in an operational context.

In all, 36 measures of effectiveness and 83 measures of performance were defined in the Silent Hammer analysis plan. Maintaining control of this metric decomposition necessitated the development of the hierarchy illustrated in Figure 5. The metric analysis was grouped into four functional categories: information production, information dissemination, processing and decision, and action and execution. Metrics were further subdivided by four attributes: timeliness, quality, completeness, and reduction of risk. The last attribute ensured that during the attempt to improve system effectiveness, additional risk was not incurred to the SSGN and the personnel supporting the mission.

With the metrics clearly described, the data necessary to support the analysis of these metrics could be determined. Figure 6 provides an overview of the data collection plan. All sensor data were archived through the Metadata Architecture, along with platform telemetry information, primarily in support of information production metrics. Network connectivity and traffic records were collected in support of information dissemination metrics. Processing and decision metrics were supported by collecting metadata catalog usage data and by archiving the exploitation products generated by Battle Management Center personnel (which were left in a shared directory structure).

In addition, all personnel would be required to log their actions, and to complete a survey at the end of each shift. This survey provided the warfighter input so vital for evaluating effectiveness. Finally, observers from Lincoln Laboratory and the Navy were on hand in the Battle Management Center to record the actions of the battle staff and Special Operations Forces during missions ashore (action and execution metrics). Successful execution of this data collection plan during Silent Hammer yielded a rich and complete data set to support the analysis.

Executing the Silent Hammer Scenario

A realistic War on Terror scenario was conducted over a ten day period (4 through 13 October 2004) on and around San Clemente Island, approximately 65 km off the coast of southern California. The scenario included surveillance and reconnaissance missions, direct action missions on land and sea, and simulated Tactical Tomahawk cruise missile strike missions. A terrorist “Red Team” composed of personnel from the *USS Georgia* and the U.S. Navy Reserves was tasked to role-play insurgent activity at various sites on San Clemente Island and aboard the ship *USS Acoustic Explorer*. Activity was scripted in advance of execution by the Experiment Control Group, who ensured that the S3G “Blue

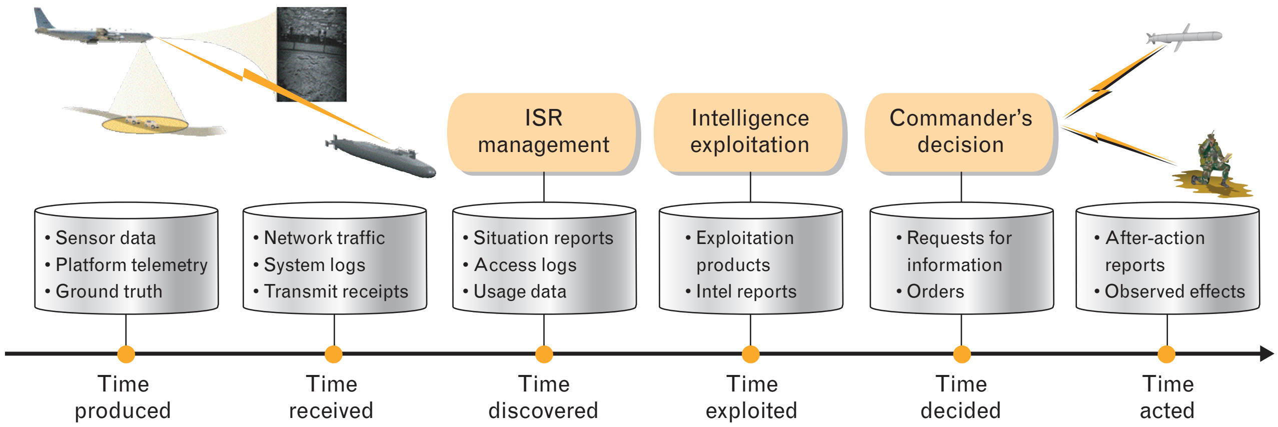


FIGURE 6. Silent Hammer data collection framework. A complete archiving of all data, information, and knowledge products generated during Silent Hammer was undertaken to support the S3G evaluation. This rich data set, which also captured artifacts of the decision process, provided insight into the use of intelligence, reconnaissance, and surveillance (ISR) information during a realistic military operation.

Team" members did not have *a priori* knowledge of the unfolding scenario. The Experiment Control Group monitored all Red and Blue Team activities, and provided simulated higher command instructions and intelligence reports to keep the scenario on track.

The submarine *USS Georgia* arrived on station on 4 October with the embarked JTF forward command element and special operation forces units. Immediately, the staff entered the "find" phase of operations—the gathering of ISR information necessary for situational awareness. This phase included sending SOF units to the island for the "eyes on" surveillance of activity necessary to satisfy the rules of engagement, and to reconnoiter the site for the pending ground assault. All ISR information was made available to the operators on board the SSGN, who used it to pinpoint the threat locations. These locations were then neutralized by (simulated) cruise missile strikes.

ISR Data Collection

Figure 7 shows samples of data produced by the Lincoln Laboratory ISR assets flown during Silent Hammer. LiMIT generated synthetic aperture radar imagery with one-meter resolution, and also produced surface moving-target indicators (SMTI) of vehicle traffic on San Clemente Island. The UAV-surrrogate Sabreliner produced high-resolution electro-optical images and lower-resolution video. Other ISR data sources included video from the Pelican surrogate UAV, unattended ground sensor imagery, and archival data from National assets.

Table 1 summarizes the numbers of ISR images produced, cataloged, viewed, downloaded, mensurated, and ultimately used in a report. Note that both Pelican and LiMIT produced far more images than were cataloged. In the case of Pelican, this discrepancy arose because images were over-sampled—a practice that resulted in largely redundant, consecutive images. Consequently, only every sixth image was saved to the metadata catalog. With LiMIT, the amount of time needed to process each image for cataloging was about 15 to 20 minutes with the hardware available. Because of a lack of time, only about 20% of images (those which were thought to have the most value) were cataloged during the experiment.

The number of images viewed indicates a tally of images that were displayed at the mid-level resolution. The entry for number of images downloaded at full resolution was a subset of these viewed images. The term "images mensurated" refers to those which were used for obtaining coordinates for targeting. "Images reported" refers to any image product that was incorporated in a report—specifically, a PowerPoint file. Note that the number of "images reported" sometimes exceeded the number of "full-res images downloaded." This is because in some cases, the user was satisfied with the mid-level resolution image and did not request the full resolution for download. In other cases, reports contained images that were never installed in the metadata catalog and had been acquired by other means, most notably as e-mail attachments.

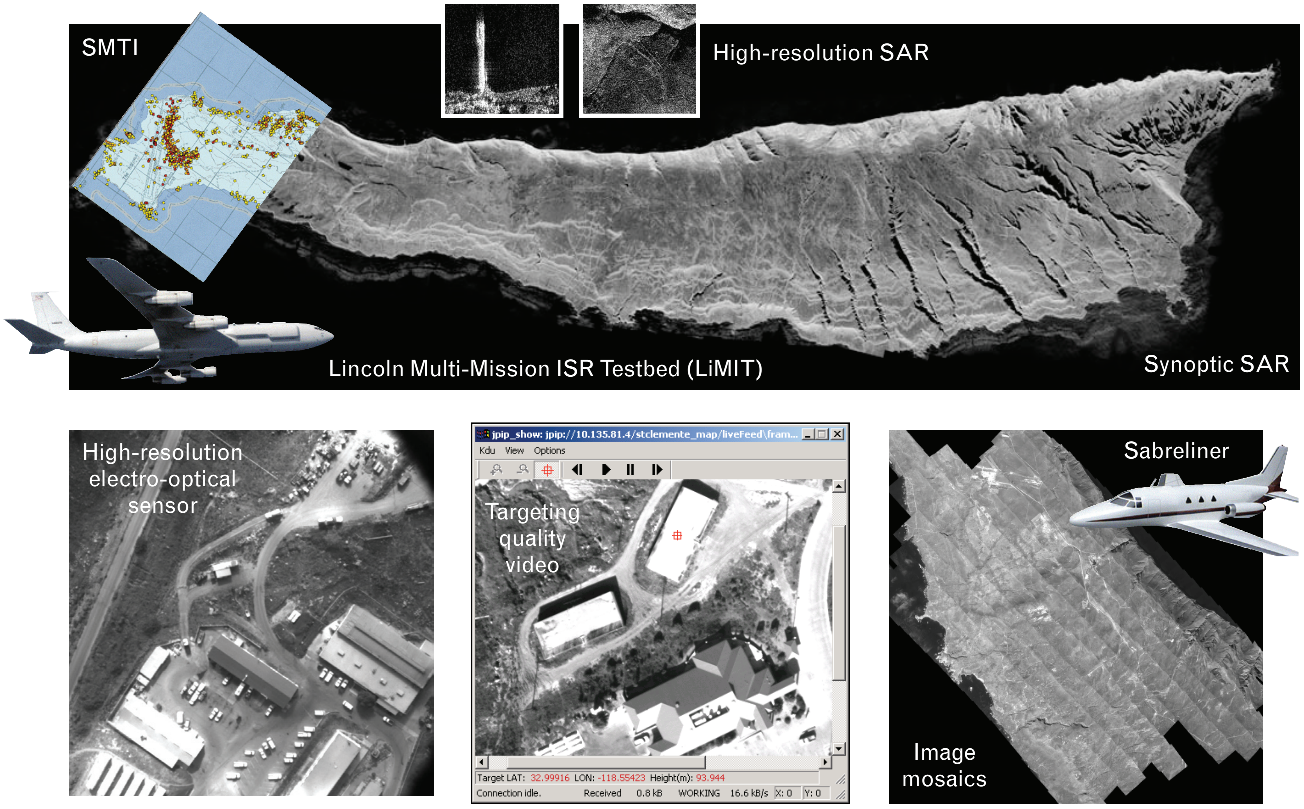


FIGURE 7. Lincoln Laboratory's support for intelligence, surveillance, and reconnaissance (ISR). Top images show data products from the LiMIT platform, with both synthetic aperture radar (SAR) and surface moving-target indicator (SMTI) modalities. The bottom images show electro-optical data products from the Sabreliner platform.

A total of 8.5 gigabytes of data were accumulated in the metadata catalog during Silent Hammer. In addition to the numbers shown in Table 1, about 100 photographs from various sources were archived, as well as 17,070 chat entries and 2994 exploitation products (including PowerPoint files and annotated images).

Applying Information to Mission Goals

The War on Terror scenario conducted in Silent Hammer tested the SSGN's ability to receive, manage, and exploit near-real-time ISR data in support of mission planning and the embarked commander. Over the ten-day period, the Battle Management Center's battle staff provided command and control for surveillance and reconnaissance missions, direct action missions, and simulated Tactical Tomahawk strike missions. These missions resulted in the capture of key insurgent personnel and the destruction of target sites. The use of ISR data was crucial to the operation's success.

Figure 8 shows typical ISR coverage for one day during the experiment, with the sensor footprints (the coverage of individual images) denoted as polygons. The data for these airborne collections and other ISR sources were accessible to operators in the Battle Management Center via the metadata catalog. Video from UAVs and imagery from unattended ground sensors were transmitted directly to the Battle Management Center for immediate viewing and exploitation by operators. Some important images and intelligence reports were sent through e-mail, while other intelligence updates were passed along through chat messages.

One impediment to measuring the usage of ISR data in Silent Hammer was the variety of ways in which data were disseminated. The metadata catalog was invaluable in tracking data usage history and pedigree within the Battle Management Center, because it recorded and time-stamped every user query and download from the archive. For a complete understanding of ISR data usage in the Battle Management Center, however, it was also important to look at the shared directories, e-mail

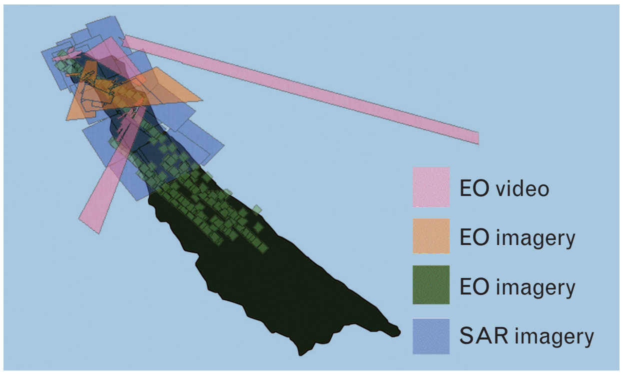


FIGURE 8. Example of ISR sensor coverage. Polygons denote sensor image footprints from representative ISR data collections from electro-optical (EO) sensors and synthetic aperture radars (SAR).

archives, chat archives, and logs kept by the operators themselves. A forensic examination of the files left in shared directories—in particular their creation and modification dates—revealed clear cases of products being downloaded from the catalog and annotated by one operator, and then copied and incorporated into the reports of another operator. Archived e-mail messages with attachments were excellent records of ISR product dissemination. Operators' log entries (sometimes including embedded links to files) often provided good records of how information was gleaned from ISR products or received from other operators.

A look at three different examples of ISR usage in the Battle Management Center—based on the experiences of the intelligence (intel) operator, the personnel recovery officer, and the cruise missile strike cell—helps illuminate what was going on during Silent Hammer. The intel operator was a hub of ISR information. Responsible for building and maintaining situation awareness, this officer processed and disseminated high-value ISR products to other operators and the command staff. Intel logs, which the operator was instructed to keep for analysis purposes, show that during a typical shift, the operator looked at the latest UAV video feed, ground sensor images, intel reports, and periscope imagery. He then decided what products had the highest importance, and redistributed them to various operators by e-mail, by chat, or on paper. He exploited imagery products by making text and graphic annotations in PowerPoint or within the image file itself. Sometimes correlations or identifications came from assembling multiple images in PowerPoint. At other times, exploited products were provided to the intel operator by the ground sensor operator or by supporting off-board intel operators.

The personnel recovery officer, who was responsible for the safety of Special Operations Forces during missions, was a constant consumer of ISR information. His interactions with other staff were focused on collecting the up-to-date information that was necessary to reduce risk to personnel during missions. Mission plans were extensive PowerPoint briefings containing a variety of exploited ISR products and intel reports, along with maps, sketches, and screen shots from other tools. The personnel recovery officer used imagery from UAVs and unattended ground sensors to identify terrorist activities. Having access to the latest ISR data was critical to the personnel recovery officer. In one case, a single UAV image led to a simple but critical modification of a plan to apprehend a terrorist leader just hours before the mission began.

The cruise missile strike cell searched the ISR data in the Battle Management Center for a few select pieces of information it needed to precisely target sites and optimize flight plans. Target survey packages provided at the start of the experiment contained crude maps and ground-level imagery for five targets, but were insufficient for cruise missile targeting because they lacked accurate geo-spatial coordinates. Over eight days, the

Table 1. Number of Data Products Collected during Silent Hammer

	Pelican	*Sabreliner*	*UGS*	*LiMIT*	*National*	*TOTAL*
Images produced	15,625	3890	747	950	539	>21,751
Images cataloged	2729	2134	747	147	539	6296
Images viewed by operators	174	54	68	46	19	361
Full-res images downloaded	14	4	0	10	17	45
Images mensurated	0	0	0	3	3	6
Images reported	16	0	5	1	4	26

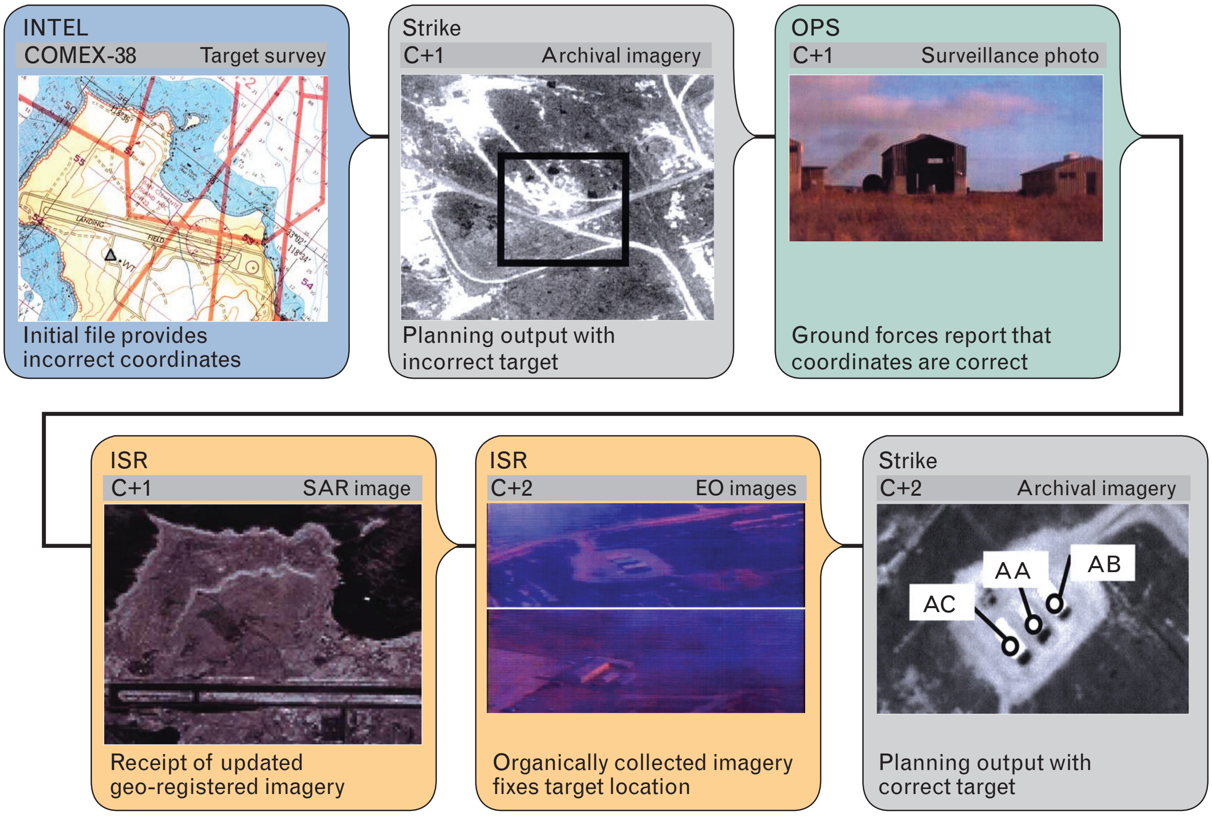


FIGURE 9. Targeting work flow for the Weapons of Mass Effect (WME) facility. This series of images shows the process by which actionable intelligence was developed by strike planners against one ground target. Incorrect initial information gave way to a correct, precise geo-location of the target over the course of days, as new ISR products became available.

strike cell gradually assembled the ISR data products needed to accurately mensurate target coordinates.

Figure 9 shows the ISR puzzle pieces used to fix the location of one target, the Weapons of Mass Effect (WME) facility. As shown in the upper left corner, the coordinates provided by the initial survey were incorrect, which misled the strike cell to a similar-looking set of structures in the wrong target area. The correct target area was identified by using first-hand information provided by Special Operations Forces, who were unable to pass the coordinates back to the Battle Management Center. Geo-registered synthetic aperture radar imagery was then used to supplement the outdated imagery. UAV imagery helped discriminate and identify the target area, despite its lack of geo-location information. Ultimately, detective work by the strike-cell and other operators yielded satisfactory aimpoint mensuration for the WME facility and other targets struck in Silent Hammer.

Part of the success of the Battle Management Center was that it provided a collaborative work environment for mission planning. Locating the strike cell inside the SSGN rather than off-hull provided an opportunity for a variety of useful interactions, as illustrated in Figure 10. The Joint Operations Center Chief of Staff, responsible for coordinating and directing the work of other command staff members in the Battle Management Center, appreciated the opportunity to conduct drills with the strike-cell coordinators and question them directly about cruise missile employment. At the same time, the strike-cell coordinators were able to fine-tune the commander's intentions through face-to-face meetings. In addition to receiving data products from the intel operator, the strike cell was able to speak directly to embarked Special Operations Forces to help identify targets correctly.

Finally, the personnel recovery officer worked directly with the strike-cell operators to develop target folders and a strike briefing. Much of this collaboration during targeting and execution relied upon real-time commu-

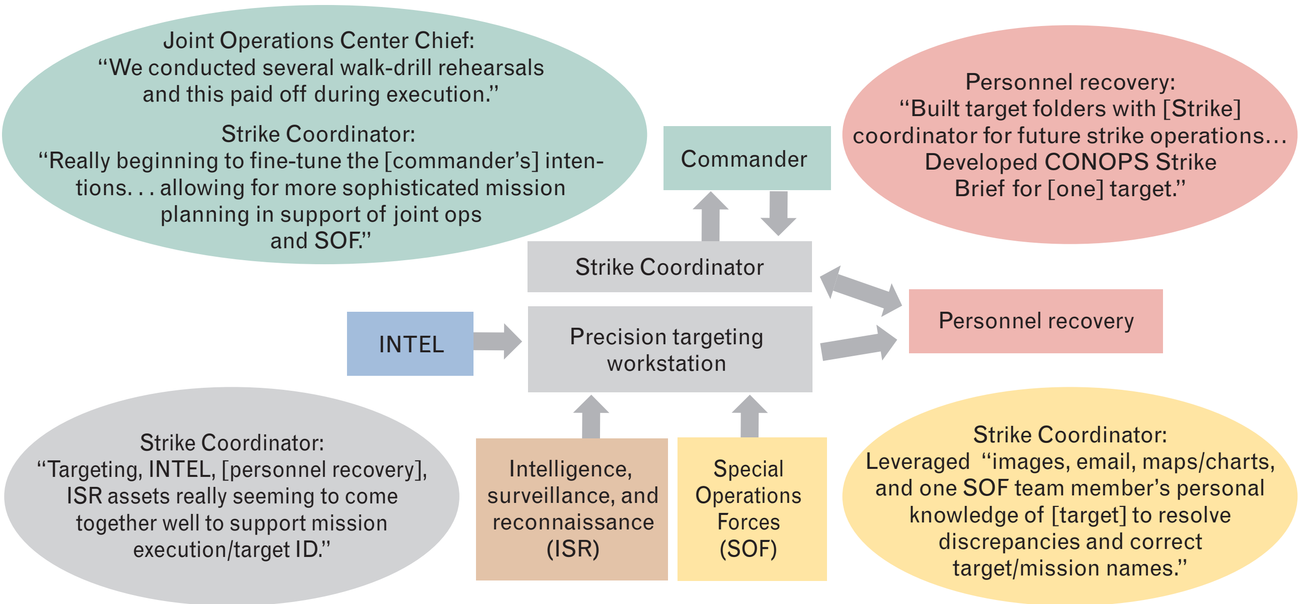


FIGURE 10. Human collaboration in the Battle Management Center (BMC). This diagram shows the interactions of strike-cell members with other personnel in the BMC, with quotes that highlight the value of face-to-face collaboration during the planning of military operations. This level and ease of collaboration for time-critical mission planning is difficult to achieve if personnel are spread between sites and must rely on chat, e-mail, or file-sharing tools.

nication, nonverbal cues, or impromptu meetings. This level and ease of collaboration would have been difficult, if not impossible, using conventional chat, e-mail, or file-sharing tools between separate sites.

In summary, the quantity and quality of the available ISR data in the Battle Management Center was sufficient to support mission objectives in Silent Hammer. All targets were found and imaged by at least one sensor, and the rules of engagement were satisfied. Operator products show that target images were exploited and included in reports. Finally, operator surveys indicated that the metadata catalog was sufficiently complete to support their ISR data needs.

Perhaps most surprising to the submarine force was that the ISR intensive operations during Silent Hammer could be conducted while keeping to the 256 kb/sec bandwidth allocated for the SSGN High Data Rate antenna. Use of a surrogate antenna during Silent Hammer enabled bandwidth to exceed 256 kb/sec, and no bandwidth management scheme was in place. However, the Laboratory's analysis determined that bandwidth usage averaged below 256 kb/sec during a peak period in operations (Figure 11). Furthermore, spikes above 256 kb/sec could have been alleviated through simple management schemes. Much of the credit for conserving bandwidth went to the Metadata Architecture.

Table 2. Volume of Data Accumulated and Downloaded

Total data accumulated	10.9 GB
Volume of metadata generated	0.06 GB
Volume of data downloaded	1.58 GB
Percent of data downloaded	15%

ISDS-Relevant Analysis

Conservation of Resources

One motivation for constructing a fully instrumented Metadata Architecture was to determine whether a concise metadata catalog could indeed conserve limited communications and operator resources. As shown in Table 2, the combined volume of archived data products that accumulated at the Battle Management Center and at the rear support site was 10.9 gigabytes. In the absence of a metadata catalog, providing access to operators at both sites to the entire volume of data would have required transmitting the entire 10.9 gigabytes. In contrast, the total volume of data that was actually downloaded from one site to another was 1.58 giga-

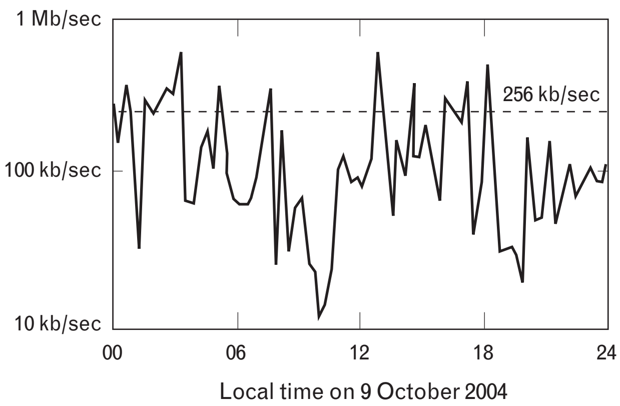


FIGURE 11. Measured SSGN bandwidth utilization during peak operations. Much to the surprise of the submarine force and due in large part to the Metadata Architecture, Silent Hammer ISR intensive operations averaged below the 256 kb/sec allocated bandwidth of the SSGN High Data Rate antenna. Spikes above 256 kb/sec could have been alleviated through simple bandwidth management schemes.

bytes, or 15% of all available data. The 85% reduction had been accomplished at a cost of exchanging only 0.06 gigabytes of metadata.

At 256 kb/sec, it would take a total of about 14 hours to download the 1.58 gigabytes of data to the SSGN. This is a dramatic improvement over the 95 hours it would have taken to download all 10.9 gigabytes of data. Furthermore, if data had been collected continuously, the amount of data would have been ten times greater and would have taken nearly a thousand hours to download. Clearly, some kind of information management mechanism like the Metadata Architecture will be necessary for the Battle Management Center to support an ISR role.

The other limited resource was the number of operators available to look at image data. Without information management, operators might have needed to display and examine all 6296 images in order to find the few images that were tactically useful. In contrast, searches on the basis of location, time, and image type immediately eliminated more than half of the images from consideration: only 3029 out of 6296 images appeared as small thumbnails in the search results page. Of these 3029 small thumbnails, only 361 were subsequently viewed at the large thumbnail resolution, or 6% of the images in the metadata catalog.

Without search capabilities, and assuming that it takes fifteen seconds to load an image for viewing and to scan its content, scanning the 6296 images would have taken about 26 hours of operator time. If image collections had been continuous, the amount of resulting image data would have been ten times larger. In this case, the two Battle Management Center staff members responsible for extracting information from new ISR data would each have had to screen images for more than twelve hours every day of the exercise. The statistics for image use are summarized in Table 3.

Operator Acceptance

Operators were generally receptive to the concept of metadata as a means of archiving and accessing ISR data products. Several operators commented that they appreciated having a single, unified interface for quickly browsing ISR data. Survey questions answered by eight Battle Management Center operators indicated that the metadata catalog was very helpful (five out of eight) or helpful (two out of eight). They also indicated that the metadata catalog was easy (four out of eight) or very easy (two out of eight) to use.

Responses to a separate set of survey questions, shown in Figure 12, indicated that the concept of a metadata catalog was useful and valuable to operators. Negative responses were mostly associated with timeliness and quality and least with value and completeness.

The response to the metadata catalog was not uniformly positive, however. In fact, some staff members refused to use the metadata catalog and relied on other means for acquiring images. This negativity appears to be due in part to a lack of training. Personnel assigned to a Battle Management position just one week before the commencement of Silent Hammer provided less favorable survey responses, often commenting on their lack of training. This reaction is in marked contrast to the positive responses of the strike-cell personnel, who were experienced users of ISR data and who had the time to sit in on training sessions.

Table 3. Image Use Statistics

Images cataloged	6296
Thumbnails viewed by operators	3029
Images viewed by operators	361
Images downloaded	45
Percent of images viewed	6%

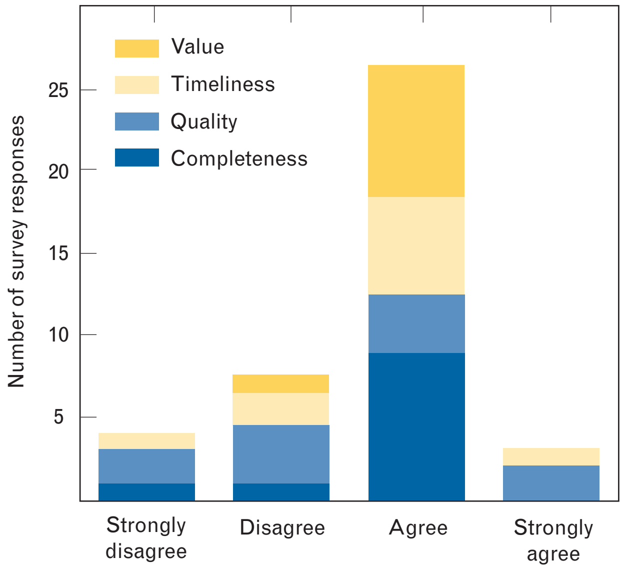


FIGURE 12. User survey responses regarding the Metadata Architecture were mainly positive. Personnel were asked throughout Silent Hammer if the Metadata Architecture provided sufficient value, timeliness, and quality.

Data Awareness

The Metadata Architecture provided easy and efficient access to ISR data products. An examination of how operators used the Metadata Architecture, however, revealed that efficient access did not guarantee timely discovery of important ISR products. There were several tactically useful ISR products that were never found, found only with prompting, or found too late to contribute to mission success.

One factor is that the operators were never told about some image sources. For example, 51 photographs from the periscope of the *USS Pittsburgh* were included in the metadata catalog—yet none of the operators ever looked for or viewed these images through the metadata catalog. Instead, some of the operators received the images by e-mail directly from the *Pittsburgh*. The rest of the Battle Management Center staff became aware of the images when they first appeared in shift-change briefings.

A second factor was the latency between image collection on the sensor and installation in the metadata catalog. LiMIT synthetic aperture radar images required between 15 and 20 minutes to process and were passed from unclassified to classified networks by burning CDs and manually uploading the data. Except for a few high-priority images, most LiMIT images were installed one or two days after the sensor was flown (median time was around 24 hours). Similarly, Sabreliner images were manually installed in the metadata catalog from CDs. Because operators were never told when images were installed, they did not know when to look for them. Worse, they might look for images right after a data collection, not find them, and come away believing that there was no useful data there.

A third possible factor was the initial presentation of image data to the operators. For example, Sabreliner video was displayed in real time in the Battle Management Center. Because of bandwidth limitations and technical problems during the first few days, the video resolution was initially not sufficient to discriminate targets on the ground. Unknown to the operators, however, high-resolution single frames were also being extracted from the data feed and (sometimes many hours later) installed in the metadata catalog.

Because the installation of Sabreliner images in the metadata catalog was delayed and because the video resolution that operators initially saw was not representative of the quality of the high-resolution single frames, operators developed a strong negative bias toward Sabreliner images. Strike-cell operators completely ignored the archive of Sabreliner images, which contained good images of several of the planned targets (see images of the WME facility and the Global System for Mobile Communications base station in Figure 13), and relied solely on Pelican images for target verification. On multiple occasions, Battle Management Center operators were prompted by the rear support element to look at new Sabreliner images of targets. Consistently, the operators replied that the images either did not exist (when they did) or were of poor and unusable quality (when they were not). The bias was so strong that one of the experiment observers told an operator precisely where to look for a high-resolution Sabreliner image of the Acoustic Explorer (labeled AX in Figure 13), and the operator insisted that such an image didn't exist—even though a small thumbnail of the image was in front of him at that moment on his display.

In contrast, Pelican images were installed in the metadata catalog within minutes after the Pelican video was viewed in the Battle Management Center. Operators watching the video data could turn to the metadata catalog and immediately access the single-frame still images; median time from image archiving to discovery in the metadata catalog was two hours, as opposed to around 24 hours for LiMIT and Sabreliner. In short, the operators were immediately aware of the number, quality, and relevance of Pelican images in the metadata catalog. Not surprisingly, the Pelican sensor was one of the most popular image sources, even though it did not necessarily have the highest quality. This experience underscores the point that access to information, no matter how efficient or complete, does not guarantee discovery.

Other Lessons Learned

The Silent Hammer experiment showed several other important factors that affect the usefulness of metadata in this kind of operation. We summarize these lessons below.

Synchronize

The metadata catalogs in the Battle Management Center and the rear support site were synchronized every 30 seconds. Each site queried the other, requesting any metadata items that had been installed since the last synchronization. In fact, synchronization accounted for 74% of the 354,000 metadata actions logged. Despite the large number of synchronization-related actions, the process did not seriously tax SSGN bandwidth. However, with an increasing number of sites querying all other sites, network synchronization traffic will increase nearly exponentially. Specifically, the order complexity is $\mathbf{O}(N * (N-1))$, where N is the number of sites. In other words, this method of catalog synchronization does not scale to a large number of site—100 sites would require 9900 queries to be transferred every interval. An alternative strategy for maintaining distributed databases will be needed.

Standardize

Some systems producing ISR data used UTC (Zulu time), while others used local time. Time strings had great variety: e.g., "2005-06-30," "30 June 2005," "06/30/05," "050630," "30-Jun-05." Geo-coordinates were equally varied with some sources stating latitude and longitude in degrees, minutes, and fractions of minutes; others in degrees, minutes, seconds, and fractions of seconds. Some formats used delimiters such as hyphens or colons, while other formats relied on fixed field lengths to structure the metadata. Particularly frustrating was one legacy source of metadata that occasionally dropped placeholder 0's in fixed formats, making latitudes and longitudes difficult to interpret. As a result, software development was difficult and numerous bugs had to be fixed in the field. Standardization of time and geo-coordinates in metadata would alleviate these problems.

Package Metadata with Data

Some metadata were located in files separate from the data files. For instance, the telemetry information arrived in a separate stream from the video data to which the telemetry referred. During collection, the data and metadata were easily dissociated because of the different processing speeds for the two streams. This dissociation resulted in errors in time and location that grew larger over a data collection flight. Data collections, processing, and archiving would be greatly simplified if metadata were embedded within and concurrent with the data file.

Edit and Repair Metadata

The Silent Hammer Metadata Architecture provided no means of editing metadata entries. This restriction simplified software associated with installing and synchronizing data products. However, during Silent Hammer there were numerous times when data products were delivered with errors in metadata fields or when ISR products were inadvertently duplicated. The only way to fix these errors was to enter the database through a back door and perform a series of manual Structured Query Language update commands, an error-prone and unforgiving activity with potentially catastrophic consequences. Because synchronization handled only new and not changed items, each database fix required a complete re-synchronization of metadata. Providing a means and protocol for editing metadata entries in future systems is recommended.

Reconsider Metadata for Small Data Products

For large images, metadata provides a huge savings in the volume of information that needs to be exchanged between collaborating sites. However, for a data product that has a small volume, such as a single line of chat or a single track update record, the metadata can paradoxically be much larger than the original data product. Further thought is needed to make the inclusion of such data records more concise and efficient.

Closure

Lincoln Laboratory's central role as Naval Sea Systems Command's independent analyst for the Silent Ham-

FIGURE 13. Easy and efficient access to ISR data products during the Silent Hammer experiment did not guarantee the discovery of high-value products by operators. These tactically useful Sabreliner images of the ship Acoustic Explorer (AX), the Weapons of Mass Effect (WME) Facility, and the Global System for Mobile Communications (GSM) base station were not discovered—mainly because of the strong negative bias developed by personnel as to the value of this ISR feed. The image of the AX was found by the analyst only after repeated prodding by one of the experiment's observers. Once "discovered," the image provided crucial time-critical information for mission planning.

mer experiment, coupled with our role in providing the Metadata Architecture, allowed us to look into how ISR information is used in the military decision-making process during realistic operations. We could then fold this knowledge into our broader evaluation of the advanced capabilities proposed for the SSGN. Most significantly, our evaluation produced results and recommendations for the Navy that were recognized as being backed by scientific methodology and thorough measurement.

Four months after Silent Hammer execution, the Lincoln Laboratory analysis team presented the S3G evaluation results to the largest Military Utility Assessment panel ever stood up by the Navy, about 40 senior Navy personnel from a wide range of commands. The Silent Hammer analysis was deemed to be sufficient and complete to support their assessment, and the panel then adjudicated which proven capabilities to recommend for procurement for the SSGN. They assessed that the advanced Battle Management Center would be a significant tactical enhancement for the SSGN and recommended it be acquired for all four SSGNs. Furthermore, they recommended that there be not just an SSGN implementation, but a Navy-wide implementation, of a metadata architecture. It was clear to them, as it is to us, that an information management scheme is an enabling technology for military tactical operations communities and other communities who rely on ISR information to support the decision process.

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REFERENCES

1. Global Information Grid (GIG), Capstone Requirements Document (CRD), JROCM 134-01, 30 Aug. 2001, www.tricare.osd.mil/jmis/download/EA-Ref/GIGCapstoneRequirementsDoc30AUG01.pdf.
2. R.W. Mayo and J. Nathman, "ForceNet: Turning Information into Power," *U.S. Nav. Inst. Proc.* **129** (2), 2003, pp. 32–41.
3. V. Clark, "Sea Power 21: Projecting Decisive Joint Capabilities," *U.S. Nav. Inst. Proc.* **128** (10), 2002, pp. 42–46.

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