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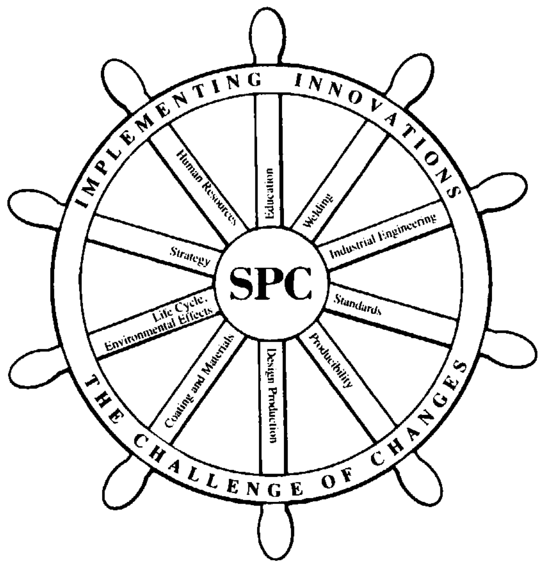

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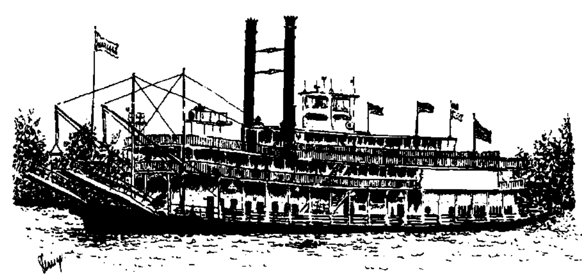

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Photogrammetry and Multi-Headed Theodolite Systems as Complementary Tools

No. 7A-2

Eric L. Boyer, Visitor and Peter L. Sparacino, Visitor, Philadelphia Naval Shipyard

ABSTRACT

Foundations for wet accumulator bottles (WABs) are large, complex structures that require fabrication in accordance with exacting dimensional tolerances. WABs are those tanks that store steam for the launching of aircraft off aircraft carriers. The traditional process for fabrication and installation of WAB foundations is a high risk venture not only from cost and scheduling perspectives, but also from a geometrical perspective. The WAB foundations consist of two units, each with four structural members and two padeyes that require fabrication and installation with respect to an imaginary WAB centerline. Through the complimentary use of photogrammetry and a multi-headed electronic theodolite system, the foundations can be fabricated in the shop to the correct shipboard geometry, and installed within tolerances, and within cost and schedule. With all of the fabrication completed in the controlled environment of the shop, all structural, fabrication, and installation problems can be alleviated before the actual shipboard installation. This paper explains the methods and techniques for using photogrammetry and a multi- headed electronic theodolite system as complimentary tools. It explains the practicality of collecting dimensional data from the existing ship structure using photogrammetry, and using a multi-headed electronic theodolite system to assist in the fabrication of the WAB foundations.

BACKGROUND

The efficiency of an aircraft carrier depends upon the speed of its aircraft launching operations. Therefore, a compact and efficient device for getting all aircraft into the air within a short time is needed. This requirement is met by the modern carrier catapult. The catapult permits controlled application of a predetermined amount of power at any desired instant. Through the controlled power of the catapult, the aircraft on the catapult is safely accelerated from a standstill to flying speed within the limited space available on the flight deck of a carrier.

During the 1950's, the British investigation of steam as the source of power for catapults attracted the interest of the U.S. Navy. The principle component of the steam catapult is a cylinder/piston assembly - two power cylinders and two pistons per catapult. The spear-tipped pistons, which in the launching operation are forced at high speed through the cylinders by steam pressure, are the assemblies that, along with the aircraft's engine thrust, actually propel the aircraft down the flight deck. Power to drive the pistons and the aircraft load comes from expanding steam piped to the catapult from the main boilers of the ship. This steam is placed under pressure in large tanks - called accumulators or receivers - located under the launching catapult on the hangar deck. From the receivers, the steam is transferred at the moment of launch into the power cylinders. Steam pressure acts directly on the piston and propels the piston/shuttle assembly through the cylinders, thereby launching the aircraft.

As part of the Service Life Extension Program (SLEP) for aircraft carriers, the obsolete aircraft catapult dry receivers were replaced by new wet accumulators. The replacement required the removal of eight vertical steam receivers, four each from #l and #2 catapults (catapults #3 and #4 were overhauled in a similar fashion). The dry receivers extended vertically from the main deck to below the flight deck, under both #l and X2 aircraft catapults. After removal of the dry receivers, an intermediate deck was installed between the 01 and 02 levels, under each catapult. With the installation of the decks completed, the WAB foundation assemblies were installed, followed by the WAB installations.

PLANNING

The initial plan called for the completion of a photogrammetric survey of dry receiver spaces #l and #2 aboard the USS Constellation (CV64) while at port in San Diego, during February of 1990. The photogrammetric survey was to consist of the interface points between the existing ship's structure and the new WAB foundations. The photogrammetric data was to be modeled using a computer aided manufacturing (CAM) system. The CAM model was to be downloaded to a computerized plate cutting machine, whereby the WAB foundations were to be cut to exactly match the ship's existing structure, within a tolerance of 0 cm (0 in.) to 0.5 cm (0.1875 in.), the required root opening of the weld. The initial plan would have allowed for a first-time fit of each WAB foundation. However, upon inspection of the two (2) dry receiver spaces while on shipcheck in San Diego, the spaces were found to be too congested with the existing dry receiver tanks and foundations. Clear lines of sight required for photogrammetry could not be established, and physical constraints were too severe. The initial plan would have insured that the photogrammetric survey and data reduction were completed before the start of the design of the WAB foundations. The WAB foundations could have been designed and fabricated using exact ship dimensions. Due to the inability of obtaining the photogrammetric data on shipcheck, it seemed the first-time installation could not be achieved.

A new scheme was developed whereby the photogrammetric survey was accomplished only after completion of both the removal of the existing dry receiver tanks and foundations, and the installation of the intermediate decking. This required that the photogrammetric survey be completed while the CV64 was in drydock at the Philadelphia Naval Shipyard in February of 1991, severely impacting the production schedule. All of the design and 25% of the fabrication and installation were to be completed by this date. To hold schedule; a fast-tracking approach was developed whereby an electronic theodolite system was employed to transfer the photogrammetric data to the fabricated WAB foundations as they became ready for assembly on the shop floor. This would allow for a final cut in the shop, and a first-time fit aboard the ship.

Under the new scheme, the design of the WAB foundations were completed using as-built plans and the ship's book of offsets. The design dimensions were modeled on a CAM system where 5 cm (2 in.) of excess was added to the foundation sections. The excess allowed room to lay the cut lines on the foundation sections using the electronic theodolite system. The CAM model was then downloaded to an electronic plate cutting machine. The plates were cut with the excess and delivered to the shop floor. During the same time span, the photogrammetric surveys of dry receiver spaces #l and X2 were accomplished, and the photogrammetric data was reduced to ship's coordinates. As WAB foundation sections were assembled on the shop floor, the photogrammetric data was transferred into a local coordinate system (a coordinate system generated from the imaginary bottle centerline) for each of the four (4) foundation sections. This assured that the foundation units were fabricated, and that the photogrammetric data was applied to the prefabricated units, concentric to one another, thus having the same "Y" and "Z" coordinates about the centerline of the WAB. When the first foundation section was assembled, the electronic theodolite system was used to align the two (2) horseshoe assemblies and the two (2) cradle assemblies with respect to the WAB centerline. Once aligned, the assemblies were tack welded in place, and the cut lines, as generated from the photogrammetric data, were transferred to the sections using the electronic theodolite system. As the cut lines were transferred to the first foundation section, the second foundation section was assembled. This general sequence was followed for all four (4) foundation sections. Finally, the foundation sections were cut to the exact ship's dimensions, production welded, delivered to the pier, and installed with a first-time 100% fit-up within the allotted schedule.

PHOTOGRAMMETRIC SURVEY

The modified wet accumulator spaces #l and #2 (formerly the dry receiver spaces #l and #2) are essentially rectangular shaped boxes (see Fig. 1). The bottom of each box consists of the new intermediate decks located between the 01 and 02 levels. The front and back sides are the frame 54 and frame 64 transverse structural bulkheads respectively. The two (2) sides are the outboard longitudinal bulkheads and the ship's shell, and the spaces are open to the flight deck level above.

In order to establish control lines and foundation interface lines for targeting the photogrammetric survey, a standard transit survey was performed on February 8 and 11, 1991 for wet accu- mulator spaces #l and #2 respectively. To locate the transit, the longitudinal and transverse centerlines of each wet accumulator space were determined. The intersection of the longitudinal and transverse centerlines created centerpoint which actually located the centerpoint of each WAB. The longitudinal and transverse centerlines were obtained from design dimensions. The transit was aligned and leveled over each space's centerpoint. To establish the control required by photogrammetry, a 24.5 m (80 ft.) waterline was established, and the WAB's vertical and transverse centerline points were located on the forward and aft bulkheads. Using the transit, the forward centerline point and the aft centerline point were connected by starting at the forward centerline point and extending the centerline down the forward bulkhead, aft on the new intermediate deck, and up the aft bulkhead to the aft centerline point. These two (2) control lines were required to assure vertical and horizontal control (see Fig. 2). Upon completion of the control lines, the interface lines between the new WAB foundations and the existing ship's structure were surveyed. Six (6) interface lines were surveyed in each space, three (3) for the forward foundation structure and three (3) for the aft foundation structure. The three (3) interface lines consisted of one (1) for the forward horseshoe assembly, one (1) for the two (2) cradle assemblies, and one (1) for the aft horseshoe assembly (see Fig. 3). Upon completion of the six (6) interface lines in each wet accumulator space, the transit survey was completed.

After centerpunching each surveyed line and snapping chalklines along the surveyed lines, the targeting began. The targeting sequence began February 12, 1991 and was completed February 15, 1991. The camera simulation revealed that the required target size was 0.75 cm (0.30 in.). The target type was adhesive-backed vinyl. The target numbering scheme was simple and unique. Each target was identified by a four (4) digit number. The first digit identified the wet accumulator space, (1) for wet accumulator space #l, and (2) for wet accumulator space #2. The second digit identified the various surveyed lines. A list of the second digit designators is shown below.

XlXX	Forward WAB foundation, forward horseshoe assembly;
X2XX	Forward WAB foundation, center cradle assemblies;
X3XX	Forward WAB foundation, aft horseshoe assembly;
X4XX	Aft WAB foundation, forward horseshoe assembly;
X5XX	Aft WAB foundation, center cradle assemblies;
X6XX	Aft WAB foundation, aft horseshoe assembly;
X7XX	WAB transverse centerline;
X8XX	24.5 m (80 ft.) waterline; and
X9XX	Fill-in targets.

The final two (2) digits were simply sequential designators (sequential from 01 to n). This numbering sequence may seem cumbersome and excessively detailed, however it proved to be most useful throughout the remainder of the project. The target numbering scheme proved to be most helpful in data review and in production assembly sequences which took place over a month after the actual photogrammetric surveys.

The targets were spaced in two (2) distinct patterns. The control line targets, those targets that defined the longitudinal WAB centerline and the waterline, *were* spaced approximately every 0.60 m (2 ft.) to 0.90 m (3 ft.). The interface line targets, those targets that defined the interface points between the new foundations and the existing ship's structure, were spaced approximately every 0.30 m (1 ft.). In addition, where butt lines existed and where dips and bulges existed in the bulkheads and decks, more frequent targeting was used to better define these abnormalities. Frequent targeting was important because the existing contour lines of the ship were transferred onto the prefabricated WAB sections in the shop. The key to this entire effort was to assure a first-time fit aboard the ship.

After the target numbering and placement was completed, the photogrammetric survey began. On February 16, 1991 the photogrammetric survey of wet accumulator space #2 was completed. Wet accumulator space #l was completed on February 17, 1991. The exact contours of the bulkheads and decks, along targeted interface lines, were required. To obtain this contour data, a convergent *survey* was accomplished. Due to the rectangular shape of each space, a P31 Super Wide Angle glass plate film camera was chosen to accomplish the photogrammetric survey. This type camera was chosen for its high accuracy and its wide range of coverage. The survey used twenty (20) camera stations in a two (2) tiered scheme in each wet accumulator space (see Fig. 4). The first tier stations were low shots (approximately 1.5 m (4 ft.) above the new intermediate deck) angled up. The remaining stations were high shots (approximately 2.5 m (8 ft.) above the new intermediate deck) angled down. The camera station placement and aiming angles assured both excellent

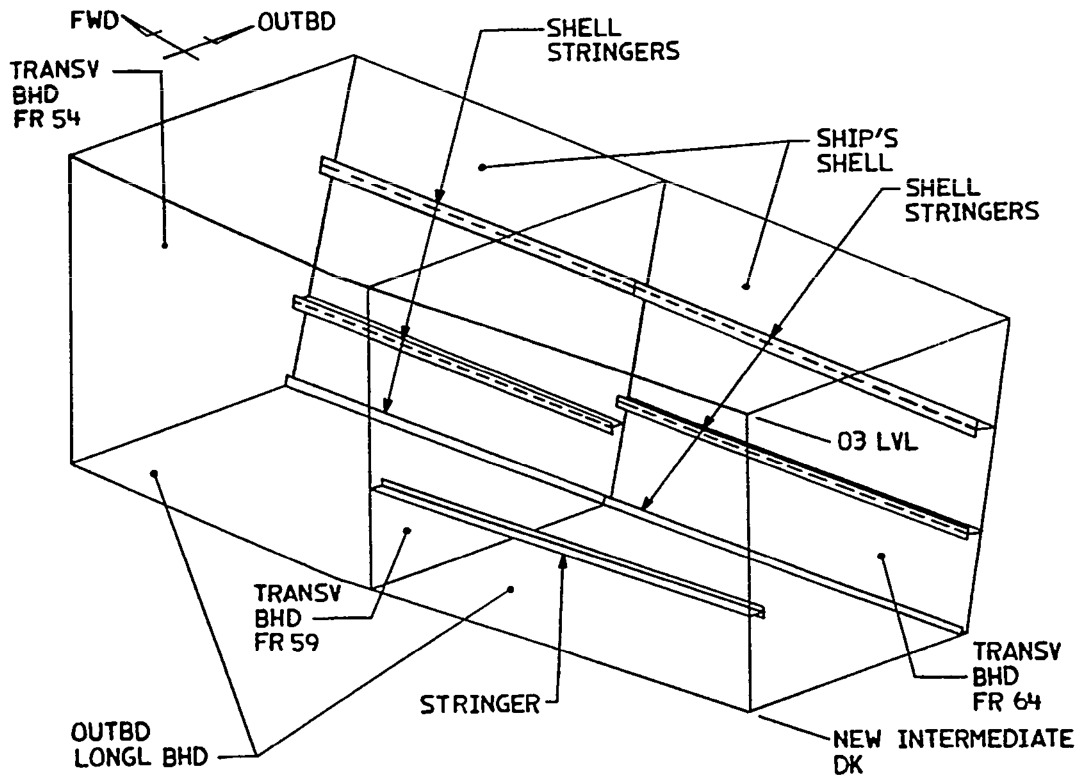

Fig. 1 WAB Compartment Configuration

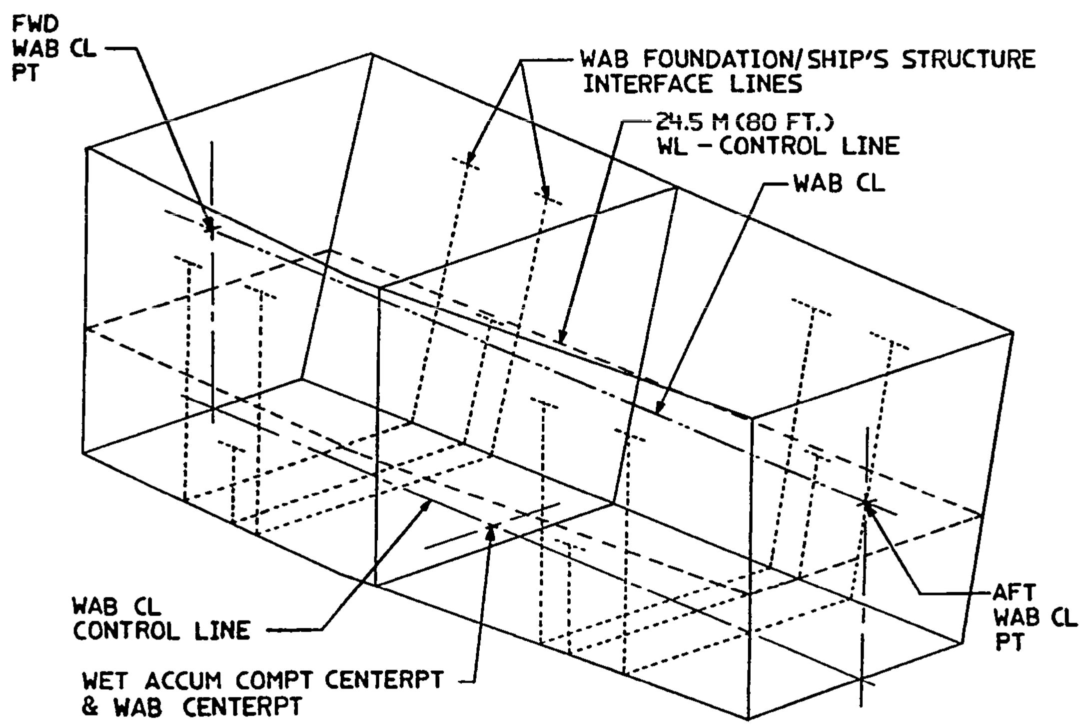

Fig. 2 Control/Interface Lines

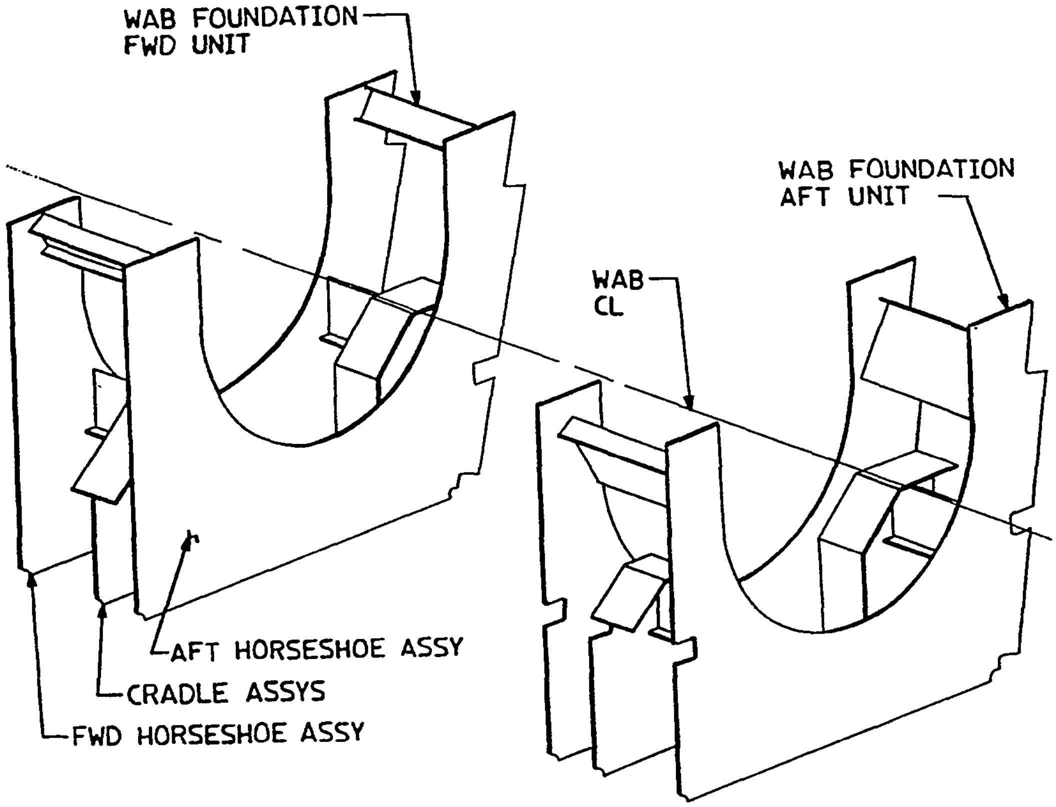

Fig. 3 WAB Foundation Configuration

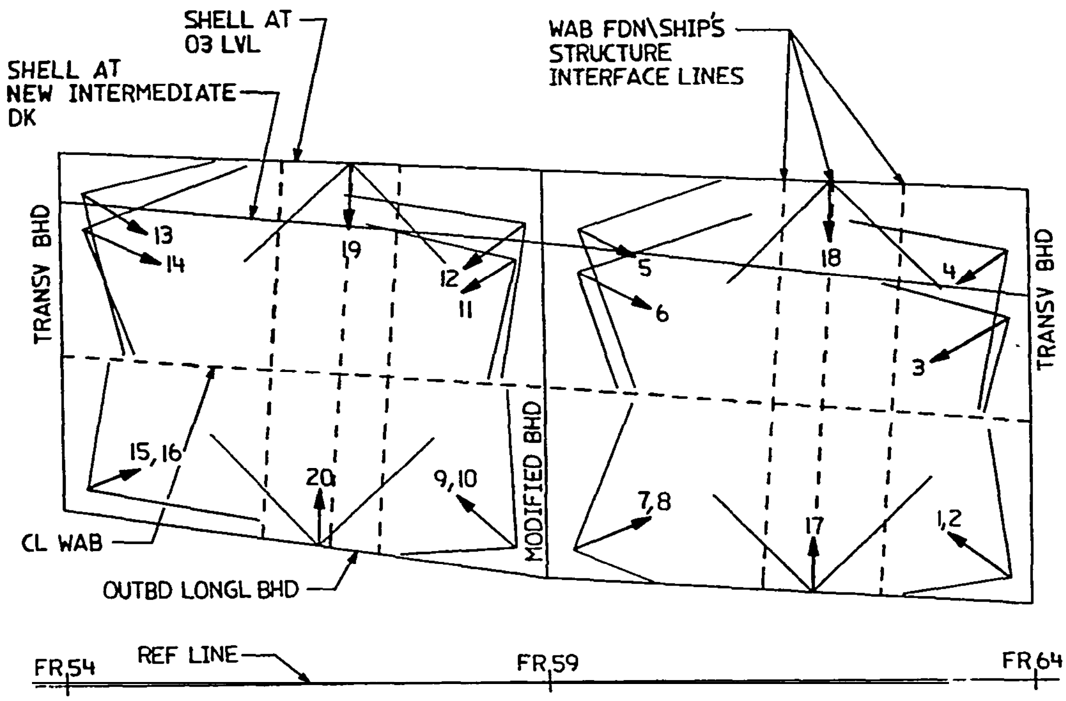

Fig. 4 Camera Plan

geometry for triangulation of the targets and complete coverage of all the targeted lines. The final step in the photogrammetric survey process was to generate scale. Scale was taken by measuring the two (2) most distant targets on longitudinal WAB centerline. The targets were measured using a 15.5 m (50 ft.) steel tape with a 45 kg (10 lb.) pull. The length was measured three (3) times to assure that an accurate scale was used later in the photogrammetric triangulation.

Upon completion of the photogrammetric survey, the glass plate negatives were developed at a nearby site to assure clarity of target images and total coverage of all the targeted interface lines (see Fig. 5). In addition, point sketches were drawn of each wet accumulator space. The point sketches served as "road maps" used as references with respect to the ensuing multi-headed electronic theodolite surveys. As questions arose during the theodolite surveys, the point sketches were used to identify targets and to identify what was actually targeted well after the photogrammetric survey was completed. The SLEP schedule called for the sandblasting of each wet accumulator space immediately after the photogrammetric surveys were completed. As a result, all interface lines and the centerpunch marks defining these lines would have been obliterated. The interface lines were preserved by taping over the centerpunch marks that defined each interface line. All production personnel were notified that the taped centerpunch marks were to be avoided. Without the existence of the initial centerpunch marks, the WAB foundations could not have been landed on the surveyed lines.

MULTI-HEADED ELECTRONIC THEODOLITE SURVEY

During a three week period extending from February 22 to March 11, 1991, the photogrammetric data reduction and analysis was completed. The photogrammetric contractor reduced the data from the glass plate negatives and forwarded it to the shipyard in a predetermined format. The photogrammetric data was first reduced to ship's coordinates. ship's coordinates are those coordinates measured from the ship's origin. The ship's origin designates the forward perpendicular as 0 on the "X" axis, the ship's centerline as 0 on the "Y" axis, and the ship's baseline as 0 on the "Z" axis. Once the ship's coordinates for each target were generated, the coordinates were then transferred into four (4) separate and distinct local coordinate systems, one for each of the four (4) WAB foundation units. The local coordinate systems were composed of those coordinates measured from the WAB centerlines. The WAB centerline origin designates the WAB centerpoint as 0 on the "X" axis, 0 on the "Y" axis, and 0 on the "Z" axis. Once the photogrammetric data was translated to the local coordinate systems for each foundation unit, the theodolite surveys began.

The particular theodolite system used was the Cubic Precision, Analytical Industrial Measuring System, version II (AIMS II). The AIMS II system consisted of two (2) theodolite heads interfaced with a personal computer containing the measurement software and routines.

The theodolite plan called for the theodolite surveys of each foundation section to be accomplished on each WAB foundation unit as it was assembled on the shop floor. As the first WAB foundation unit was assembled, the theodolite system was used to align the two (2) horseshoe sections and the two (2) cradle sections with respect to an imaginary WAB centerline (see Fig. 3). After the four (4) foundation pieces were aligned in accordance with the design specifications, the separate pieces were tack welded together.

The cut lines were then laid out by transferring the localized photogrammetric coordinates to the theodolite system in a point by point fashion (see Fig. 6). The photogrammetric coordinates were transferred to each WAB foundation unit with four (4) separate theodolite setups. A typical theodolite setup involved several distinct steps. First, the two (2) theodolite heads were placed so as to maximize their coverage of the WAB foundation unit, while maintaining a geometric configuration required by the theodolite system triangulation software. The theodolite placement was followed by the theodolite leveling sequence, which is a theodolite system software routine that defines both the location of each theodolite head relative to one another, and the scale which is determined by measuring a highly accurate scale bar. After the leveling sequence was completed, the transfer of photogrammetric coordinates to the foundation units was performed. Because of the complex configuration of the foundation units, not all the photogrammetric coordinates were transferred with the initial setup. Before the initial setup was broken down, several pass points were located and measured in the vicinity of the WAB foundation unit. At least three (3) of these pass points had to be visible from both theodolite heads at each of the three (3) ensuing setups. Once the theodolite placement, leveling, and scaling was completed for a subsequent setup, three (3) pass points were measured. Once the pass points were

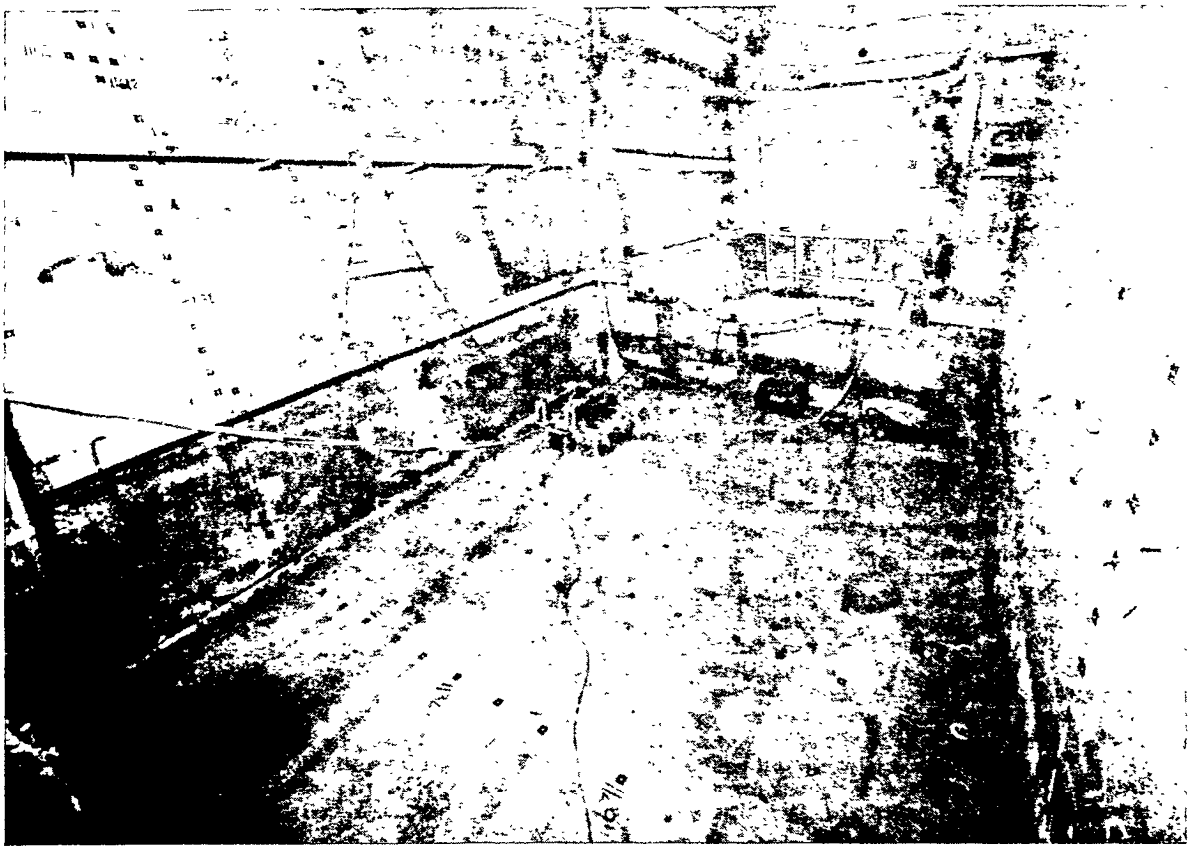

Fig. 5 Typical Photogrammetric Glass Plate Negative

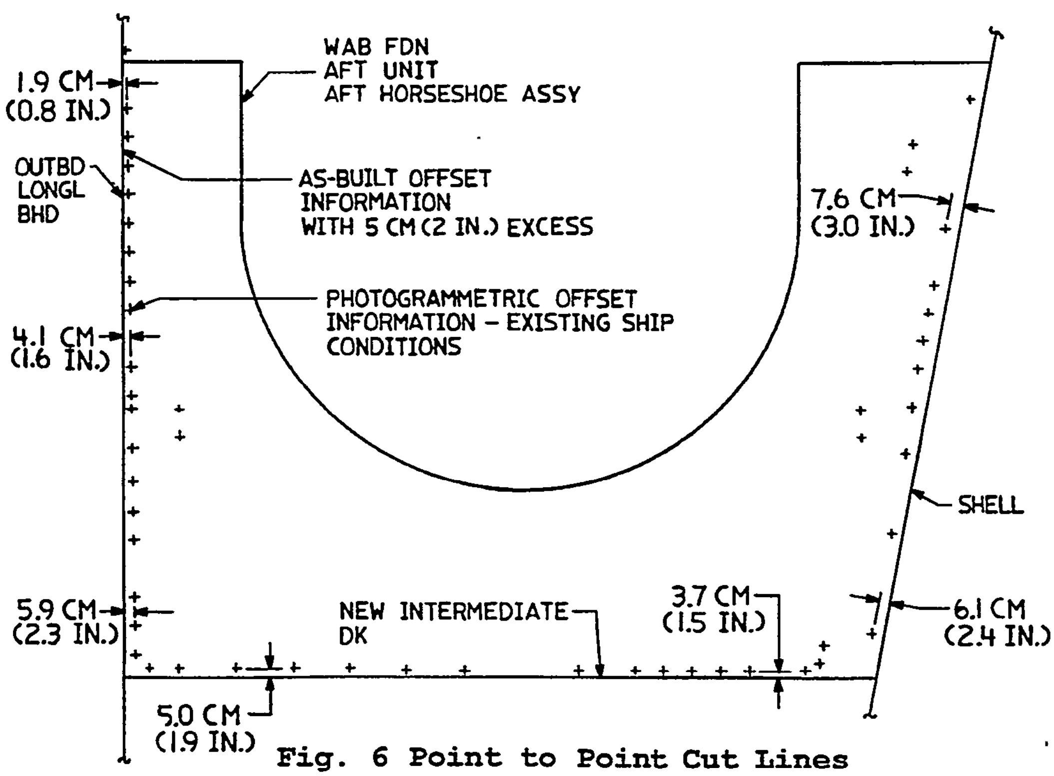

Fig. 6 Point to Point Cut Lines

measured, the initial values for those pass points were manually entered into the theodolite system's tripoint routine. Subsequently, the new setup was transferred into the original coordinate system as established by the initial setup. After the original coordinate system was re-established, further transfer of the photogrammetric coordinates to the foundation units was performed. Of the four (4) theodolite setups, the first setup allowed for the transfer of the points to the first horseshoe section. The second and third setups allowed for the transfer of the points to the two cradle sections, and the fourth setup allowed for the transfer of the points to the second horseshoe section.

Once all the points were transferred to a foundation unit, the transferred points were centerpunched, and scribe lines were constructed to connect each transferred point. The scribe lines and the data points defined the exact contour of the ship's structure laid out on the WAB foundation unit (see Fig. 7). All structural beam interferences, all deviations in the decks and bulkheads, and all alignment data were now "mapped" onto each unit.

In addition to mapping out the cut lines, the padeye locations and alignments for each foundation unit were determined by the theodolite system. The padeyes, which span between the horseshoe sections of each WAB foundation hold the steel straps that actually support the WAB. These padeyes, by design specifications, were to be located at 60° (+- 1°) from the horizontal. With the theodolite system angle between planes routine, the padeyes were located within tolerance.

At the culmination of the theodolite survey of the first WAB foundation unit, that unit was production welded, and the contour lines were cut. While the production welding and cutting was accomplished on the first unit, the theodolite survey was accomplished on the second WAB foundation unit. At the same time, the third WAB foundation unit was assembled on the shop floor, and the fourth WAB foundation unit was in its final stages of prefabrication. This fast-tracking technique was used throughout the theodolite survey. All of the theodolite surveys took place between March 12 and April 3, 1991 at the Philadelphia Naval Shipyard.

RESULTS

On May 7, 1991 the final assemblies were ready for installation aboard the CV64 in drydock at the Philadelphia Naval Shipyard. Each final assembly was approximately 4.5 m (15 ft.) wide from side to side, by 3.5 m (12 ft.) high from top to bottom, by 1.5 m (4 ft.) deep from front to back. Because of the

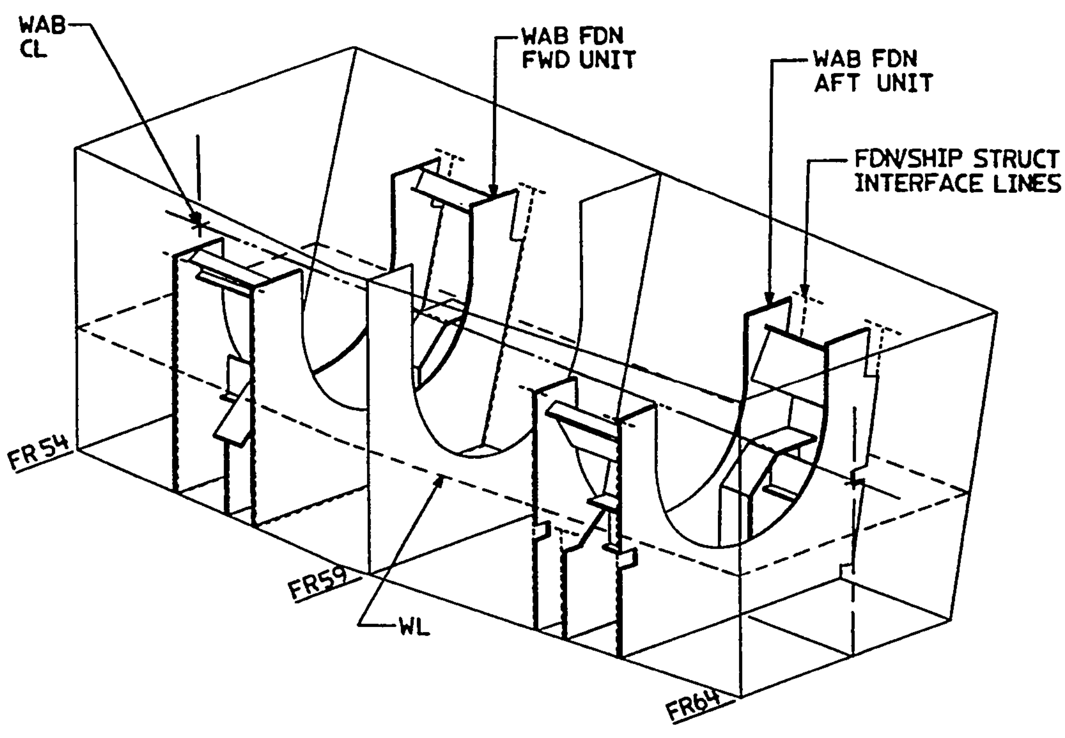

Fig.7 WAB Foundation Fit-up

size of each unit, careful handling and extensive maneuvering was required. Each entered the ship horizontally, and as it was lowered, was rotated into its final position. The resulting gaps between each unit and the inboard and outboard bulkheads was 0 cm (0 *in.) to* 0.5 cm (0.1875 in.). This gap was the actual tolerance allowed for the root opening as called for in the governing specifications. The fit-up was so consistent around the entire perimeter of each unit that production welding was initiated the following day.

The photogrammetric data made it possible to pick up discrepancies in the existing structure before the units were installed. This data revealed that the structural stiffeners located on the shell of the ship were skewed; when the as-built design drawings called for the stiffeners to be parallel to the ship's baseline. In addition, photogrammetric data identified discrepancies with respect to several stiffener sizes given by as-built drawings. Each unit assembly was modified prior to arrival on the waterfront to match the existing ship's conditions. This eliminated the need for costly and time consuming rework *on* the waterfront.

Finally, the theodolite system was used to lay out both the photogrammetric data on the unit for the final cut, and to serve in guiding the accurate final assembly of each unit. The padeyes that hold the strap from which the WAB is suspended were also set using the theodolite system. This angular dimension was critical in that it insured a 7.5 cm (3 in.) diameter pin, which secures the strap to the padeye, fit the first time without the need for rework in the field.

CONCLUSIONS

Including time spent for prefabrication of the units and preplanning for the photogrammetric/theodolite surveys, this project ran for approximately four (4) months. This time frame included several important steps:

(1) the planning and executing of the photogrammetric *survey;*

(2) the reduction of the photogrammetric data;

(3) the transformation of the photogrammetric data to the theodolite system;

(4) the laying out of the photogrammetric data with the theodolite system in the shop;

(5) the trimming of the excess from the WAB foundation units in the shop; and

(6) the installation aboard ship of the foundation units ready for production welding-

This project exhibits the following advantages of using advanced measurement technology in the shipbuilding industry.

(1) Photogrammetry and multi-headed electronic theodolite systems can be used effectively as complimentary systems.

(2) Scheduling impacts can be avoided with first-time fits.

(3) Performance figures on the CV64 as compared to previous SLEP overhauls for basically the same modification were significantly lower. This cost savings was attributed to the absence of rework.

(4) Flexibility and innovation *in* using these systems allows the ability to work around scheduling obstacles.

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(5) The elimination of rework allows for the ability to plan and maintain a close production schedule.

In summary, the success of this project has demonstrated the need to expand the use of advanced measurement technologies to their fullest extent in the shipbuilding and repair industry. These technologies allow first-time installations within tolerances, cost, and schedule.

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