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THE NATIONAL -- SHIPBUILDING RESEARCH PROGRAM

Photogrammetry in Shipbuilding

U.S. Department of Commerce
Maritime Administration

in cooperation with
Todd Shipyards Corporation

Transportation
Research Institute

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FOREWORD

This is one of the many projects managed and cost shared by Todd Shipyards Corporation as part of the National Shipbuilding Research Program. The Program is a cooperative effort between the Maritime Administration's Office of Advanced Ship Development and the U.S. shipbuilding industry. The objective, described by the Ship Production Committee of the Society of Naval Architects and Marine Engineers, emphasizes productivity.

The suggestion to investigate the effectiveness of photogrammetry in U.S. shipbuilding was submitted by Mr. Robert W. Schaffran, of the Maritime Administration, who obtained the idea from foreign literature. Mr. Thomas P. Primavera of the U.S. Army Topographic Command contributed the necessary indoctrination in photogrammetric theory and processes which was the basis for preparing the research specification.

As conventional photogrammetry was applied mostly in topographical work in 1974, the American Society of Photogrammetry advised of only six prospects having actual, or possibly applicable, experiences in industrial applications. Proposals from the six were evaluated by photogrammetric authorities from the University of California and the University of Washington. The research work was assigned to:

john f. kenefick Photogrammetric Consultant, Inc.
Indianapolis, Florida

Mr. L. D. Chirillo, Todd Shipyards Corporation, Seattle Division, was the Program Manager.

Special appreciation is expressed for the extraordinary assistance, accompanied by indispensable access to real ship design and building projects, furnished by:

- Sun Shipbuilding & Dry Dock Company
- General Dynamics, Quincy Shipbuilding Division
- Avondale Shipyards, Inc.
- J. J. Henry Company, Inc., Moorestown, N.J.

Appreciation is expressed to the following for their constructive criticism of the manual in its draft form: Mr. S. A. Mahler of Newport News, Va., a shipbuilding consultant; Mr. G. A. Uberti, National Steel & Shipbuilding Co., Mr. R. C. Moore, Newport News Shipbuilding; and Mr. P. E. Jaquith, Bath Iron Works.

EXECUTIVE SUMMARY

Photogrammetry is the art, science and technology which includes obtaining reliable information about physical objects by measuring and interpreting photographic images. The process began about 135 years ago and has its principal application in aerial surveying for compiling topographic maps. But, land-based or non-topographic applications, nearly as old, are now becoming more numerous because of rapidly occurring technical developments.

Presently, a number of organizations throughout the world productively employ photogrammetry, on a more or less regular basis, in architectural, biomedical and industrial areas. Within the latter there are shipbuilding applications for the measurement of hull sections, propellers in various stages of fabrication, cargo tanks, etc. Already, and as a result of initial work on this project, a U.S. shipbuilder has engaged a photogrammetric firm to prepare sounding tables for spherical LNG tanks.

Thus, this project has not been concerned with whether photogrammetry is a viable and sufficiently accurate measurement technique; it is ! Instead, the main objective has been to investigate the applicability of photogrammetry to dimensioning problems which frequently occur in shipbuilding. Particular emphasis has been placed upon applications which may have the greatest potential for improved productivity. Time and dollar costs involved for four photogrammetric demonstrations, in real shipbuilding situations, are well documented herein.

Uniquely, the photogrammetric researcher was required to obtain a sufficient understanding of shipbuilding processes to insure that this manual will be readily understood by shipbuilders. Further, his knowledge of shipbuilding permitted him to report objectively; both advantages and disadvantages are described. Information of immediate interest is in the first two chapters. Comprehensive appendices are provided for those shipbuilding functionaries who will have greater need for understanding photogrammetry.

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1. INTRODUCTION

1.1 *The Science of Photogrammetry*¹

Photogrammetry is a well established measurement science which is particularly applicable when any one or more of the following conditions is encountered:

- the object to be measured is large and relatively inaccessible for conventional measurements,
- the object is complex in detail or shape,
- a large amount of data is required,
- measurements at widely separated locations on the object must be precisely related to each other, and
- the object is in motion.

Because of its potential for handling such conditions, photogrammetry should be considered as being a complement to, rather than a substitute for, conventional methods of measurement. But, it has an important unique capability. Photographs for photogrammetric work are cheaply made permanent records that can be easily filed. They could serve in the future should a need arise to establish facts, such as for litigation, regarding as-built dimensions, tank sounding-tables, etc.

Basic methods of photogrammetry are analog, semi-analytical and fully analytical. Analog photogrammetry employs stereo pairs² of photographs which, when viewed simultaneously in a two-projector instrument called a stereo plotter, permit graphical mapping of the perceived three-dimensional optical model of the scene. Semi-analytical photogrammetry is practically identical except that discrete points in the optical model are digitized (X, Y, Z) and then subjected to computer processing for numerical and/or graphical presentation of results.

Fully analytical photogrammetry requires measurements of images of discrete points directly on the photographs from stereo pairs or on convergent photographs.² Subsequent numerical triangulation produces a digital model of the scene which can then be manipulated further to yield numerical and/or graphical results.

Because of the need to measure the optical model on the photographs directly, photogrammetry is not a real-time measurement system. Under ordinary conditions several hours to several days are required to produce results.

Accuracies of measuring by photogrammetry are well established. Analogue and semi-analytical methods can produce tolerances upwards of ± 1 part in 14,000 of the major dimension of the scene photographed. Analytical methods can be exploited to reach tolerances ranging as high as ± 1 part in 60,000.

1.2 *The Value of Measuring with Photogrammetry*

1.2.1 *Advantages*

- a. Complexity of shape or detail of the scene is not restrictive.
- b. Relative directions to all points of interest within the field of view of a camera are recorded instantaneously with a single opening of the shutter. (This is in contrast to time consuming measurement of horizontal and vertical angles with a transit or theodolite.)
- c. All data (photographs) can be obtained in a short period, thereby minimizing the effect of thermal induced or other changes within the scene upon the consistency of the final results.
- d. The amount of data to be extracted from the photographs does not pose severe time and cost limitations.
- e. The process is virtually noncontacting.
- f. Due to the short period of time required for taking the photographs, there is minimum interference with ongoing work. In some instances work may not be interrupted at all.
- g. Objects in motion can be accommodated with the use of two or more cameras having synchronized shutters.
- h. The orientation of attitude of the scene is of no consequence. Photographs can be taken from above, below or to the sides so long as there is room to stand off with the camera.
- i. With the fully analytical method of photogrammetry, the accuracy can be varied over a wide range to suit a particular need.
- j. The photographs constitute a permanent record and may be reused to check results or gather additional data.

¹A glossary of photogrammetric terms and a more detailed explanation of photogrammetry are provided in Appendices A & B respectively.

²Photographs for photogrammetric work are normally taken with a rigidly constructed camera(s) having a distortion free lens. Exposures may be taken on film, glass plates or both. When pictures are exposed with at least 50% overlap (common imagery) and with the camera axes nominally parallel, pairs of adjacent photographs are said to form stereo pairs. When the camera axes are steeply inclined to one another the photographs are said to be convergent.

- k. Photographs may be taken and archived for any potential need to produce data in the future. This applies to potential litigation as well as to pure technical requirements.

1.2.2 *Disadvantages*

- a. Results of photogrammetric measurements are not produced instantaneously. Depending on the difficulty of the task considered, the time required to produce final results may range from several hours as a minimum to several days. An extreme situation might involve several weeks.
- b. Useful photographs cannot be taken in rain, fog or snow.
- c. Measurements in very confined spaces are generally not practical due to the large number of photographs needed to cover the entire scene. Also, the depth of focus of the camera lens may not be able to accommodate varying distances to points within the scene.
- d. The first cost for an in-house capability ranges from \$50,000 to \$180,000 depending on the capability desired.¹
- e. Depending on the capability desired, a photogrammetrist or special training of a shipbuilder would be required for an in-house capability.

1.3 *A Search for Applications in Shipbuilding*

An extensive search of photogrammetric literature and a direct mail solicitation revealed considerable interest in applying photogrammetry in shipbuilding or in industries having similar industrial functions. A number of such articles and reports are described in Chapter 3. However, only three instances were found wherein photogrammetry is apparently applied as a routine matter. These are: development of sounding tables for LNG spheres, measurement of ships' propellers and checking of nodes, subassemblies and deck-stabbing guides of offshore drilling platforms.

Through direct interaction with several U.S. shipbuilders and a naval architect a separate list of possible applications of photogrammetry was compiled.² These possible applications were judged to be not feasible or unproductive, uncertain as to productivity, or likely to be

quite productive. They are so classified and described in Chapter 3.

Of the most promising applications four were actually demonstrated. These are comprehensively described in Chapter 2.

1.4 *Summary Opinions*

1.4.1 *Conclusions*

- a. Principal areas of application of photogrammetry are in the design and erection phases of shipbuilding, although, scattered applications exist in other areas.
- b. The fully analytical method of photogrammetry is by far the most versatile for handling a variety of measurement problems. For the most part these applications are concerned with dimensioning large steel units.
- c. Precise measurement of large steel units as three-dimensional entities provides a wealth of data which can be judiciously analyzed with an eye toward avoiding costly moves and/or lifts when corrective action may be required.
- d. Moreover, the fully analytical method applied to such units does not require the ground surveys for control nor extraordinary provisions for locating and framing the camera that have been reported³ for different methods and techniques.
- e. As a corollary, interference with ongoing Shipyard work is minimal.
- f. Equipment, software and procedures needed for routine application of fully analytical photogrammetry are state of the art and can be employed immediately by any shipyard on a subcontract basis or through implementation of an in-house capability.
- g. Analog photogrammetry is the second most useful method to shipbuilders.
- h. Analog photogrammetry can best be applied in design functions which require graphical output such as arrangement drawings or as-built drawings.

¹These considerations are treated in greater detail in Chapter 4.

²Several of these had variations on the principal application.

³See Appendix C, Part I, Articles C.1 and C.2

- i. Although hardware for analog photogrammetry is state of the art, procedures to be followed for different measurement problems require development and refinement.
Semi-analytical photogrammetry is the least applicable. However, it may be very useful for developing digital representations of machinery space models for use in automated design systems.
- k. Accuracies of measurements derived from a sound photogrammetric scheme are entirely compatible with shipyard needs.
- 1. The cost and turnaround time for photogrammetric surveys cannot generally be compared to present procedures since the photogrammetric method can accommodate relatively difficult situations and provide a large amount of data: i.e. photogrammetry should generally be considered as a supplement to, rather than a replacement for, current shipyard measurement procedures.
- f. However, more detailed study of the potential for analog photogrammetry as an aid to design of machinery spaces and development of as-built drawings is clearly warranted.

1.4.2 **Recommendations:**

- a. Shipyards should be made cognizant of the immediate capacity for fully analytical photogrammetry to accurately survey large steel units. This should not only be done through distribution of this report, but also through short personal presentations within shipbuilders' facilities.
- b. At the same time, possibilities for other applications of photogrammetry found through the literature search and developed by this study should also be presented.
- c. Should a shipbuilder elect to use photogrammetry for a series of alike ships, serious consideration should be given to a combined in-house/subcontract arrangement wherein the shipbuilder takes the photographs and a photogrammetrist performs the photogrammetric work.
- d. [f a shipyard elects to develop an in-house capability for photogrammetry, technical implementation should be directed by a photogrammetric consultant who should also be retained for on-call service for a period after start-up.
- e. Further investigation into applications of fully analytical or semi-analytical photogrammetry is not necessary.

2. DEMONSTRATED APPLICATIONS

This section presents details of how each demonstrated task was performed, results achieved, time and costs involved and suggestions relative to future work of similar nature.

In developing the photogrammetric approach to each demonstration particular care was taken to simplify the on-site work, even to the extent of complicating subsequent photogrammetric laboratory work. The philosophy underlying this tactic is simply that if photogrammetry is to be practical, in the intense drive for more productivity within a shipyard, it must create very little interference with ongoing work. It is also noteworthy that consistency has been maintained for all demonstrations by using the same basic equipment, procedures and computer programs. This is a desirable criterion if photogrammetry is to be a universal measurement tool within a shipyard.

2.1 Measurement of a Complete Midbody Section

At Sun Shipbuilding and Dry Dock Company, a "RO/RO" ship midbody was made available for the purpose of demonstrating a photogrammetric method for precise dimensioning of the entire unit. Dimensions of the midbody were about 92 feet in breadth, 90 feet in length and 60 feet in depth. Access for photography was only on the day prior to its scheduled launch. Launch preparations were not interrupted.

2.1.1 Preparation

As this was to be the photogrammetrist's first shipbuilding demonstration a visit to the yard was made to determine dimensioning requirements (type of data and accuracy). Also, the visit permitted observation of the physical conditions under which the work would be performed. With the knowledge thus acquired it was clear that the fully analytical photogrammetric method, using convergent photographs, should be used because of:

- the need to dimension the midbody as a single three-dimensional unit represented by discrete points,¹ and
- the moderately rigid tolerance that was required.

Subsequent to the visit, planning of the photogrammetric field procedures commenced. This effort involved selection of camera station locations, calculations to assure adequate depth of field for the camera, an error analysis to assure that required accuracies could be achieved and design of a target.

In advance of the date scheduled for photography Sun SB & DD prepared about 100 targets in accordance with a design specified by the photogrammetrist. Each consisted of a 3-inch square of 16-gauge galvanized sheet metal, painted flat black, upon which a 1-inch diameter white Dennison Pres-a-ply self-sticking label was attached.² Scribed cross hairs facilitated their placement to within $\pm 1/32$ inch of particular locations selected by both the shipyard and photogrammetrist. Figure 2-1 illustrates the target location scheme; note that most locations were strategically selected to facilitate determination of the as-built configuration of the midbody.³

Typically targets were attached with small but strong magnets.⁴ An exception was adopted for seven targets placed at widely separated main deck locations. Distances between several of these targets were to be taped for the purpose of providing scale references for the

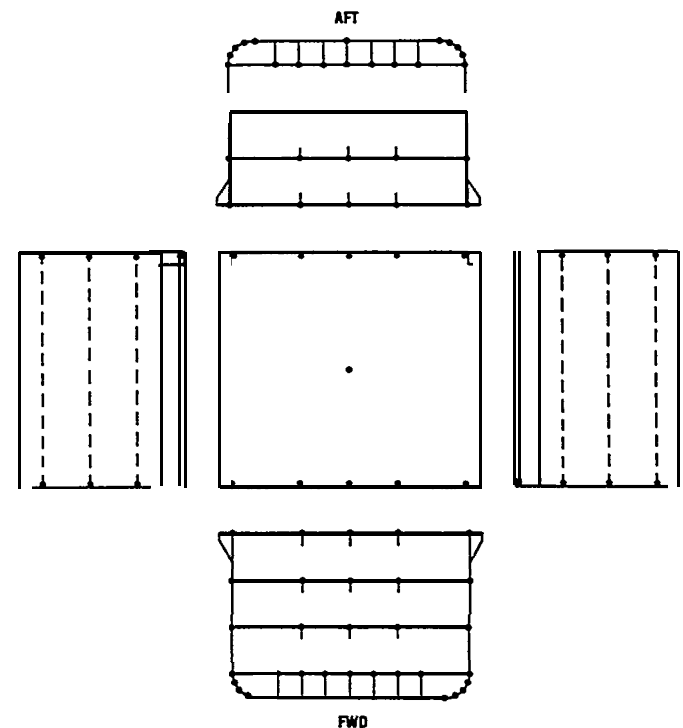


FIGURE 2-1: Blowout View of Midbody Showing Locations of Targets. The side shell targets were offset from the butts by 2 inches. They were used primarily to analyze squareness of the side shells. A few additional targets (not shown) were placed on the side shells and main deck to facilitate correlation of overlapping photographs. Taped distances between other targets (not shown) on main deck provided scale references for the photogrammetric solution.

¹This permits relating widely separated points such as those on the forward transverse section to those on the after transverse section.

²The design is fairly standard for this type work. Exact dimensions are governed by distances from planned locations of the camera stations to points within the scene photographed. The objective is to obtain very small (say 0.002 to 0.004 inch) but measurable images on the negatives.

³Targets were placed at the "molded surface" intersections of vertical and horizontal structural members. Others defined the inboard or "molded" side of the shell.

⁴These were of the type used by steel shop burners for fixing straightedges.

photogrammetric solution. Thus, Dennison Pres-a-ply labels were adhered directly to the deck to be certain that no movement would occur.

2.1.2 Photographic Procedures

A two-man photogrammetric team arrived on site in the early afternoon preceding the day scheduled for photography. During the next morning, when the shipbuilder's people were attaching targets, the photogrammetric team set up their very basic developing equipment for on site processing. Test exposures were taken and developed to verify camera settings.

Taking of final photographs commenced in the afternoon. The camera stations were occupied over a total period of about four hours. Had the cranes on this newly built shipway been complete and available, this time could have been reduced considerably. As it was, the overhead pictures were taken from a personnel carrier slung from a slow moving "cat" crane. Locations of the camera stations are illustrated in Figure 2-2.¹

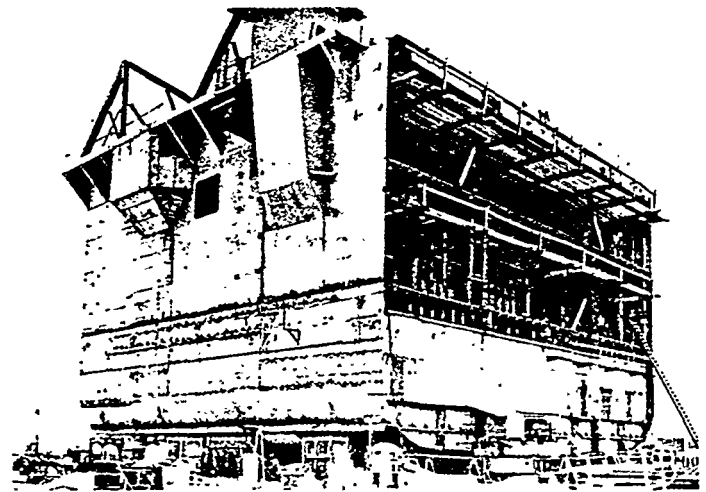


FIGURE 2-3: Typical Photograph of Midbody From Ground.

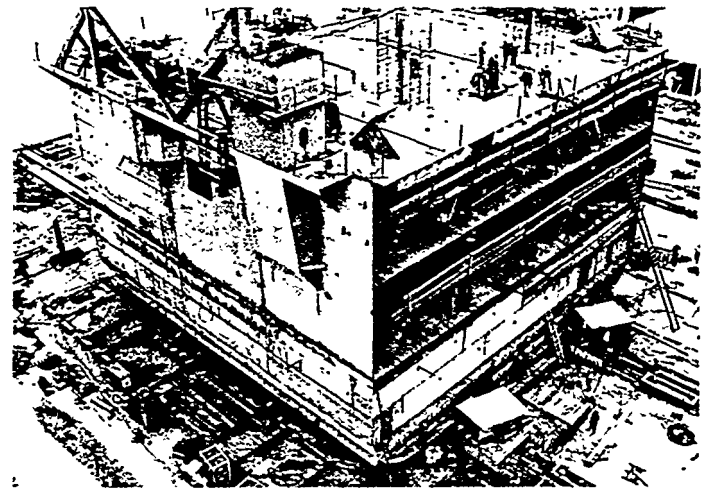


FIGURE 2-4: Typical Photograph of Midbody From Overhead.

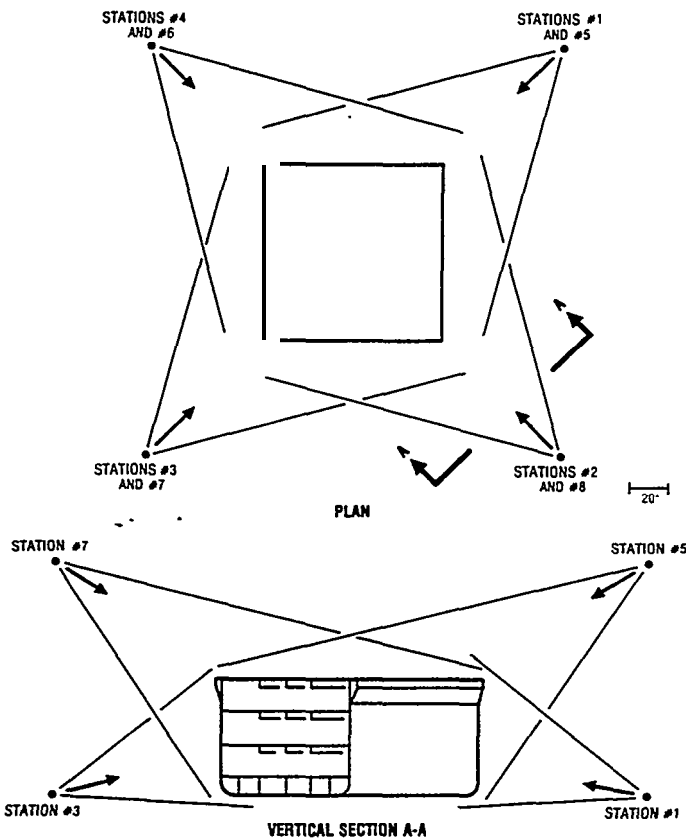


FIGURE 2-2: Locations From Which Photographs Were Taken of Midbody.

All exposures were secured with a Wild P31 camera² and glass plates coated with a panchromatic emulsion. The camera was simply moved from one station to the next as the work progressed. Figures 2-3 and 2-4 are enlargements made from two of the glass plates actually used in the photogrammetric work.

2.1.3 Laboratory Measurements

Upon receipt of the plates at the photogrammetrist's facility, they were examined with an ordinary magnifying glass to locate target images. Each image was circled on the "glass" side of each plate. A few of these locations were also numbered according to a previously devised numbering scheme which assured that each target would always have the same number regardless of which plate

¹Figure 2-2 shows only those frames ultimately used. Four additional frames were taken from the ground viewing each "side" of the midbody straight on.

²Illustrated in Appendix B, Figure B-2.

- g. Best-fit circles were computed for targets on turns-of-the-bilge to determine how closely the turns conformed to true circles. See Figure 2-9.

2.1.5 Evaluation of Results

Sun SB & DD analyzed the data derived from the computations described in paragraph 2.1.4 and reported that:¹

“This program provided the following information that is difficult or impossible for us to obtain on our own:

- (1) The tank top formed a flat plane within $\pm 1/4$ ".
- (2) The centerlines of all decks and keel, fore and aft, are lined up within $\pm 1/4$ ".
- (3) The fwd cut was even to within $\pm 5/16$ " and the shape of this end was correct (unskewed) to within $\pm 9/16$ " on the diagonal.
- (4) The aft cut was parallel to fwd cut to within $\pm 1/4$ " and the shape of this end was correct to within $\pm 9/32$ " on the diagonal.
- (5) The stbd side was square to within $9/32$ " on the diagonal.
- (6) The port side was square to within $1/8$ " on the diagonal.

The program also provided deck heights and half-breadths which we routinely measure ourselves.”

The tolerance of locating a target photogrammetrically was firmly estimated to be ± 0.08 inch in any direction and the tolerance of any distance between two targets was estimated to be ± 0.11 inch. Typical accuracies were expected to be even better than this, about ± 0.04 and ± 0.06 inch respectively. There were, however, several significant differences (the worst being $1 3/4$ inches) between photogrammetrically determined distances and earlier taped distances.

The reasons for some of these discrepancies were ultimately discovered, but others were not. Evidence, which included a subsequent semi-independent check using a photograph not used in the original photogrammetric reduction, indicated that the differences were not attributable to photogrammetric error. As the midbody was launched two days after the pictures were taken, it was not possible to check the taped data.

One logical but unproven theory for the unexplained discrepancies is simply that the targets may not have been exactly at the same points between which distances were taped. It is known that the distances were taped three days before the targets were set and that some movement of targets did occur during the course of the photography

(see paragraph 2.1.7.). Consequently, the next two demonstration tasks were purposely designed to incorporate valid independent checks on the photogrammetric results.

2.1.6 Time and Cost Analysis

Costs for the photogrammetric work as well as for shipyard support were closely monitored. In Table 2.1 efforts of the photogrammetrist are presented in terms of man hours and dollars so as to reflect a production situation wherein a shipyard contracts for a total photogrammetric service. The shipyard's effort is in Table 2-2.

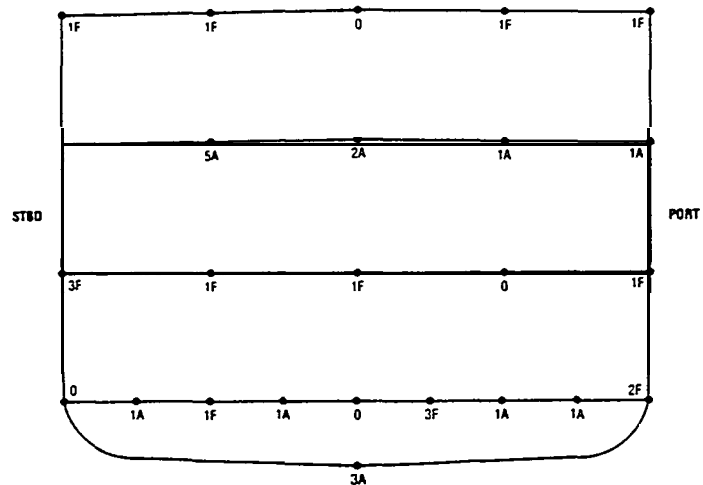


FIGURE 2-7 Deviation of Forward Transverse Section of Midbody from Best-Fit Plane. 'A' and 'F' respectively denote whether the butt is aft or forward of the best-fit plane. Numbers are distances in 16ths of an inch.

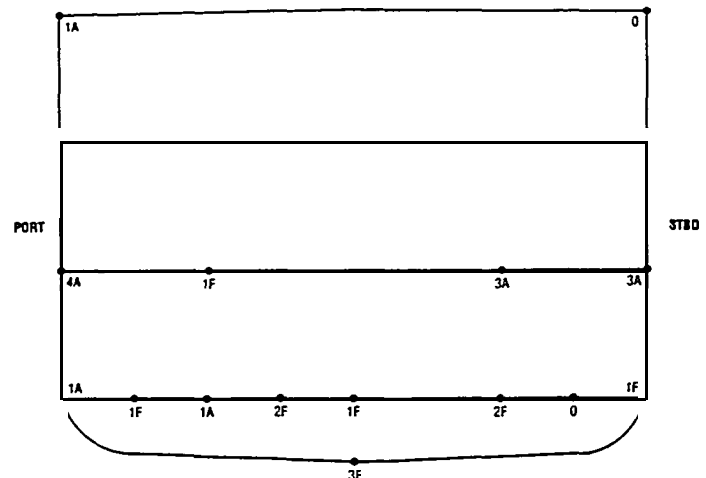


FIGURE 2-8: Deviation of After Transverse Section of Midbody from the Plane Parallel to the Plane Best Fit to the Forward Transverse Section. "A" and "F" respectively denote whether the butt is aft or forward of the best fit plane. Numbers are distances in 16ths of an inch.

¹Quoted from an unsolicited Sun SB & DD memorandum.

The breakdowns given in Tables 2-1 and 2-2 show that the shipyard was responsible for fabrication and attachment of the targets. This could have been accomplished by the photogrammetrist.¹ Most importantly the selection of target locations was based upon mutual decisions.

2.1.7 Suggestions Relative to Future Work

Original planning of this demonstration task was done under the assumption that work on the midbody would be completed before the photographic effort commenced. Thus it was felt that the magnets would be well suited for attaching and removing the targets. However, some work was in progress while the pictures were being taken and a

number of the targets were disturbed. The magnets were also less than ideal for positioning on beveled edges. The following is recommended:

- If shipyard work is in progress, use self-adhesive targets directly on flat surfaces. Irregular or beveled surfaces should be covered with a square of 16-gauge sheet metal tack-welded in place.
- If shipyard work is not in progress, magnets may be used even for some irregular surfaces provided the targets are held squarely. Flat-faced clips, Figure 2-10, can be used to square off a beveled edge.

TABLE 2-1: Photogrammetrist's Man Hours and Cost for Dimensioning the Midbody²

1. Labor	Man Burdened “ Hours	Rate ³	Cost
a. Project planning and 44 coordination including visit to shipyard (1 man)	19	\$	836
b. Prepare and ship 35 equipment and round trip travel (2 men)	12		420
c. On-site preparation 46 and photography (2 men)	12		552
d. Prepare photographic 12 plates (1 man)	12		144
e. Measure plates (sub- — contracted)	—	—	562
f. Data processing and 61 reporting (1 man)	19		1.159
Total Labor			\$3.673
2. Expenses			
a. Transportation and per diem (initial visit and on-site work)		\$	934
b. Materials (photographic plates, etc.)			114
c. Computer			6 3 0
d. Miscellaneous (air freight, etc.)			128
Total Expenses			\$1,806
			\$5,479
Profit @ 15%		\$	822
TOTAL			\$6,301

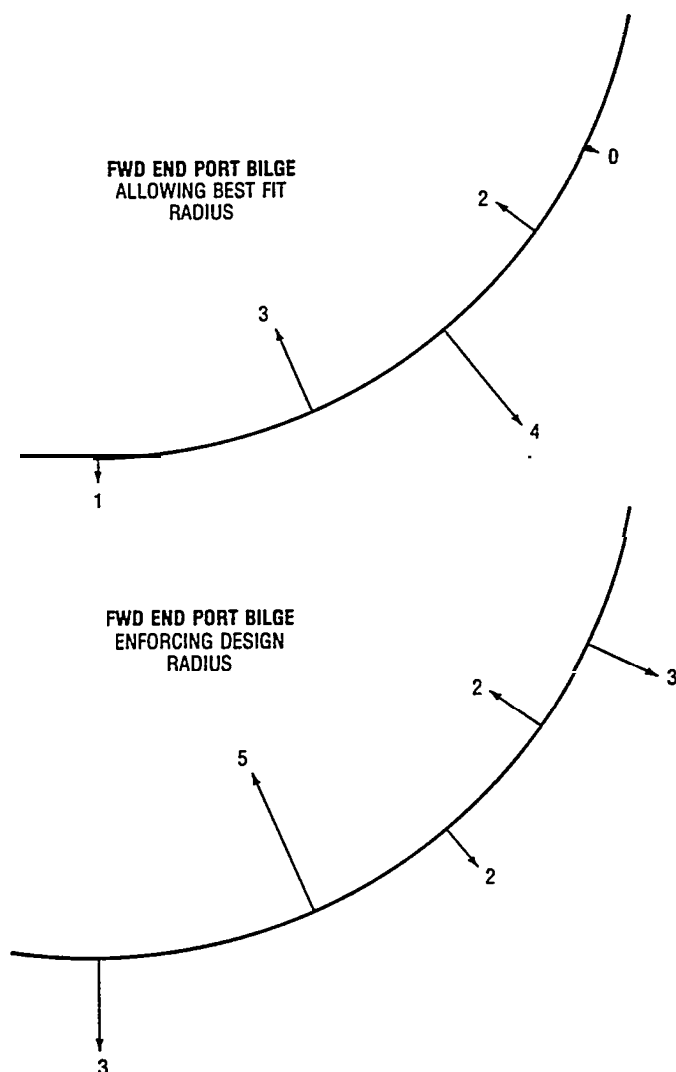


FIGURE 2-9: Examples of Best-Fit Circles to Turn of Bilge. In the upper diagram the best-fit circle was allowed to seek its own radius whereas in the lower diagram the design radius was enforced. Arrows depict directions to steel surface (built to the molded surface) from the best-fit circle. Numbers are distances in 16ths of an inch.

¹Oftentimes the most productive arrangement is for the photogrammetrist to supply the targets and for the client to attach them.

²Where travel is involved, a Florida based photogrammetric firm working in Sun SB & DD is assumed.

³Rates vary among firms.

TABLE 2-2: *Shipbuilder's Effort in Support of Dimensioning the Midbody*

1. Labor

<u>Task</u>	<u>Man Hours</u>
a. Fabricate targets	6
b. Attach targets	12
c. Target maintenance	8
d. Assistance in personnel carrier for overhead photographs	8
e. Crane operator	4
TOTAL	38 manhours

2. Miscellaneous

a. Target materials	\$ 2
b. Crane	4 hrs.

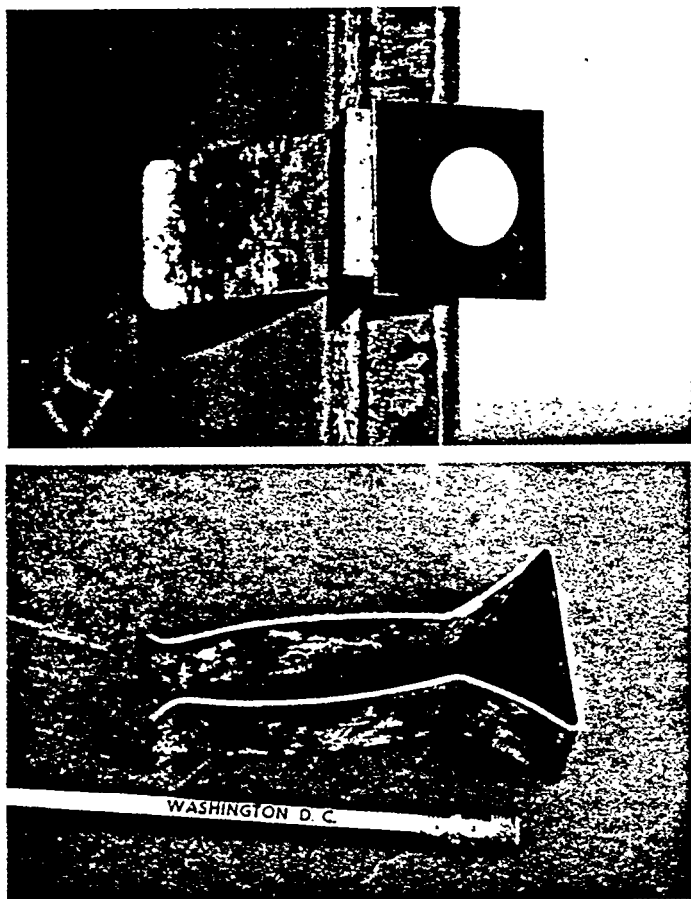


FIG URE2-10: Flat-faced Ctip For Squaring Off Beveled Edges.

2.2 *Measurement of a Hold Receiving a Spherical LNG Tank*³

This demonstration was conducted at the Quincy Shipbuilding Division of the General Dynamics Corporation where a series of eight LNG tankers were being constructed. The method of containment utilized the Moss-Rosenberg spherical tank design. For this particular demonstration the shipyard primarily desired to check the circularity of the 120-foot diameter cylindrical steel support skirt which is to receive the first LNG tank. This structure must mate with a cylindrical aluminum support skirt which is attached to the equatorial ring of the spherical tank. As will be seen, additional data were also developed from the same photographs.

2.2.1 *Preparation*

A visit to the shipyard was conducted to determine dimensioning requirements and to observe the hold so as to become familiar with the physical conditions under which the work would be performed. Because of the need for precise dimensions in all directions and to relate points on the weather deck opening some 30 feet above the top of the cylinded to the cylinder itself, the fully analytical method of photogrammetry using convergent photographs was chosen for executing the task. Subsequent to this initial visit to the shipyard, planning of photogrammetric field procedures commenced. This planning effort was as described for the midbody in paragraph 2.1.1.

An obvious photographic plan would have been to take pictures from above the weather deck looking down into the hold so as to see the entire top end of the cylinder. To do this, however, would have required the use of the shipyard's 1,200-ton crane. Since the photogrammetrist did not wish to disrupt any shipbuilding work in progress, an alternate photographic scheme which did not require the crane was devised. Although this alternative involved a greater photogrammetric effort, the trade-off was favorable because there was no interference with ongoing shipyard work.

In advance of the scheduled date for photography GD Quincy fabricated about 150 targets in accordance with a design specified by the photogrammetrist. Each target was a 1 1/2-inch square cut from a 16-gauge aluminum sheet, one side of which was painted flat black. A 3/4 inch diameter white Dennison Pres-a-ply label was adhered to the painted side and a double sided pressure sensitive adhesive material was attached to the unpainted side.

The target location scheme is illustrated in Figure

¹ Because targets were being disturbed by ongoing work, continuous checking of the target locations was required. Also see paragraph 2.1.7.

² Except for the self adhesive bull's-eyes, targets were made from scrap.

³ Also, see subparagraph 3.2.3c.

⁴ Hereinafter the word "cytinder" is substituted for "cylindrical steel support skirt. "

2-11. GD Quincy attached 96 targets to the top of the cylinder on its inner surface, 28 on the sloping bulkheads at the bottom of the hold, 8 on the longitudinal and transverse bulkheads and 22 on the edges of the weather deck opening. Targets placed on the top of the cylinder were intended primarily to represent its shape. But, they were also aligned with webs of vertical stiffeners, on the cylinder's outer surface, so that arc distances between the stiffeners could be determined.

Targets on the sloping bulkheads were to be used in two ways. Distances were to be taped between four pairs of targets for the purpose of providing scale references necessary for the photogrammetric solution. Taped distances between other selected pairs of targets were to be used as a check on the accuracy of the photogrammetric work. As it was wise to have redundant references, distances were also taped between the four pairs of targets on the vertical bulkheads.

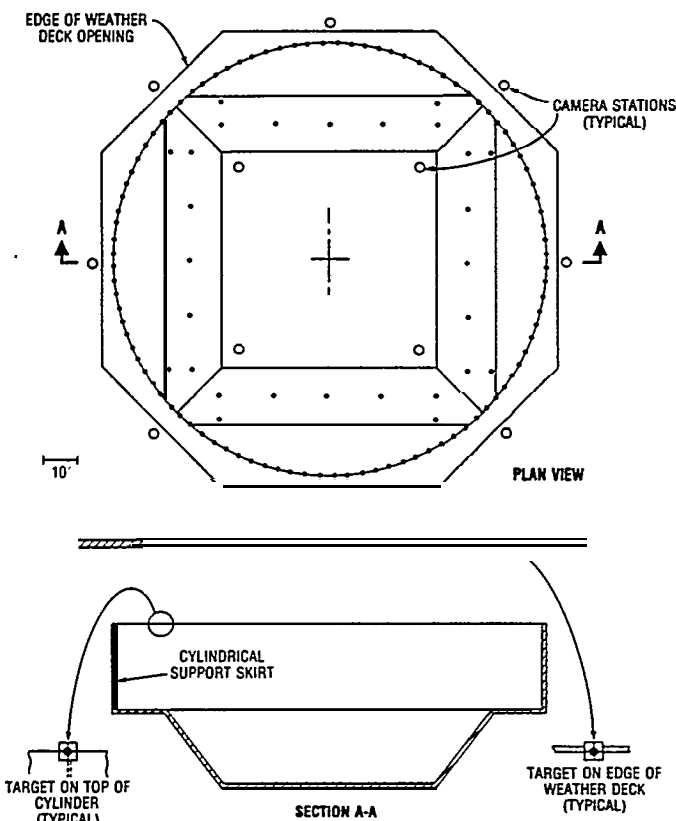


FIGURE 2-11: Locations of Targets and Camera Stations in an LNG Spherical Tank Hold. Targets aligned with the cylinder's inside top edge are also aligned with the webs of the outside vertical stiffeners. The longitudinal and transverse bulkheads, and the eight targets located on them, are not shown. See Figure 2-15 for locations of targets on the edge of the weather deck opening.

Targets on edges of the weather deck opening in combination with those on top of the cylinder were for determining whether their respective planes were skewed. In addition, the weather deck targets were to be referenced to the axis of the as-built cylinder to determine the distances between the axis of the cylinder and the edges of the weather deck opening.

All but the weather deck targets were attached only by means of the adhesive on the backs of the targets. Flat-faced clips, Figure 2-10, were used on the edges of the weather deck opening. Targets were then adhered to the faces of the clips such that target centers were aligned with the bottom surface of the weather deck, i.e., the as-built surface which corresponded with the design molded surface.

2.2.2 Photographic Procedures

Basic developing equipment was set upon site in the dark room used for the shipyard's X-ray exposures. Test exposures were immediately processed to verify appropriate camera settings. Final photographs were taken both from the weather deck and from the bottom of the hold. Eight photographs from the weather deck were "looking" down and across the hold whereas four photographs from the bottom of the hold viewed across and out of the hold. Figure 2-11 illustrates the arrangement of the camera stations. A total of 60 minutes was required to secure all 12 photographs once the targets were in place.¹ All photographs were exposed on glass plates coated with a pan chromatic emulsion. Figures 2-12 and 2-13 were made from two of the glass plates which were actually used in the photogrammetric solution.

2.2.3 Laboratory Measurements and Data Processing

Preparation and measurement of the photographic plates proceeded exactly as described for the midbody in paragraph 2.1.3. Photogrammetric computations were as described in paragraph 2.1.4.

Once the photogrammetric computations had constructed the digital model of the cylinder and weather deck overhead, as represented by the targets, the following calculations were performed:

- a. A best-fit plane was passed through the top of the cylinder to determine how closely it conformed to a true plane. Actually, the top had not yet been trimmed but this computation was nonetheless performed to demonstrate the technique and also to establish a plane which could be related to the weather deck above. See Figure 2-14.

¹The photographic work proceeded quite rapidly since no shipyard work was in progress within the hold.

- b. A best-fit plane was passed through targets on the weather deck but with the condition that it be parallel to the best-fit plane through the top end of the cylinder. This calculation was designed to reveal skewing between the two planes. See Figure 2-15.
- c. A best-fit circle was passed through targets on the top of the cylinder. This computation was designed to establish the 'out of roundness' of the cylinder as well as its best-fit inside radius. See Figure 2-16.
- d. As a by-product of step "c" above the center of the best-fit circle was determined and projected upward, perpendicular to the plane best fit to the top of the cylinder. Its intersection with the paral-

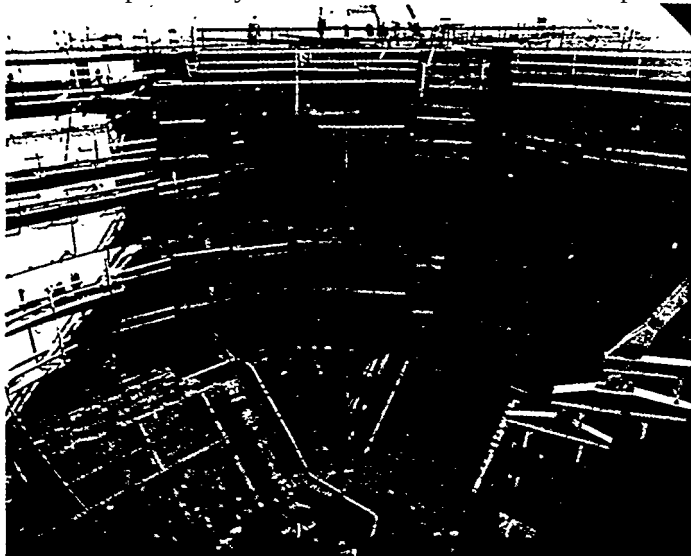


FIGURE 2-12: Typical Photograph From Weather Deck of Hold for a Spherical LNG Tank.

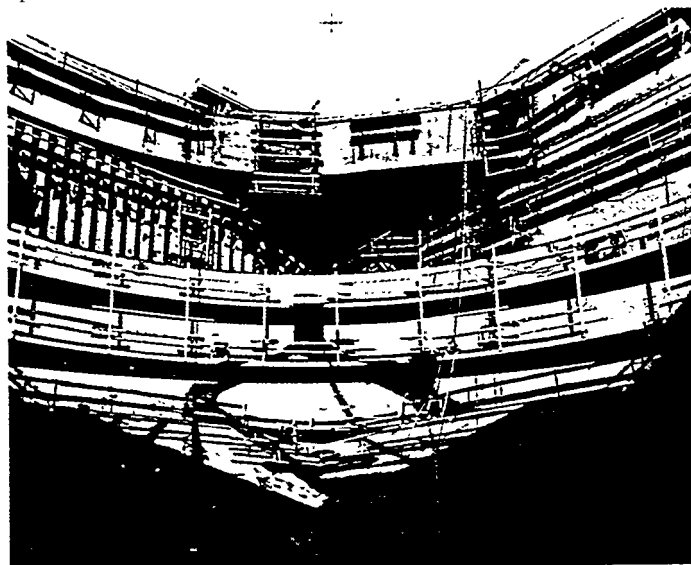


FIGURE 2-13: Typical Photograph From Tank Top of Hold for a Spherical LNG Tank.

lel plane best fit to the weather deck allows accurate prediction of clearances between the spherical tank, during its installation, and the weather deck opening.

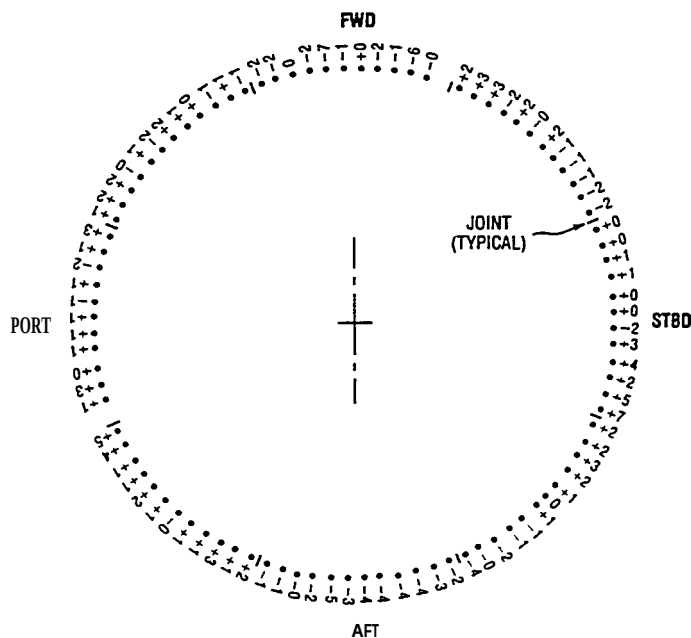


FIGURE 2-14: Deviation of Top of Cylinder From the Best-Fit Plane. Values are in 16ths of an inch. Plus means steel is above the best-fit plane. Some systematic "highs and lows" are evident: excess stock had not been trimmed before pictures were taken.

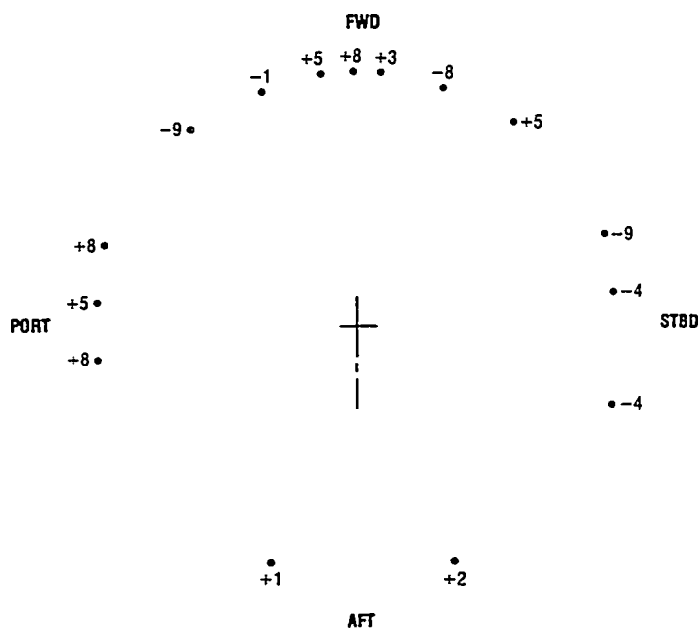


FIGURE 2-15: Deviation of Weather Deck From Plane Parallel to Plane Best Fit to Top of Cylinder. Values are in 16ths of an inch. Plus means the bottom surface of the deck is above the plane. No systematic skewing relative to the top of the cylinder is evident. Large gaps in distribution of data resulted from targets being obscured by staging.

- e. Finally, arc distances between targets on top of the inner surface of the cylinder were computed. These were used to calculate distances between the vertical stiffeners on the outside of the cylinder.¹

2.2.4 Evaluation of Results

Certain distances obtained from the photogrammetric calculations were forwarded to GD Quincy. The shipyard then taped five of the same distances for comparison;² all were about 45 feet in length. The average difference between the two sets of distances was $\frac{1}{16}$ inch and the maximum difference was $\frac{1}{16}$ inch. This agreement is considered to be exceptionally good because:

- a. The estimated tolerance of a target's position as determined by photogrammetry was ± 0.10 inch with a typical expected error of ± 0.05 inch. The corresponding estimated tolerance for a distance between two targets was ± 0.14 inch with a typical expected error of ± 0.07 inch.
- b. Taped distances were determined by summation of segments with the total lengths recorded to the nearest $\frac{1}{16}$ inch. Ordinary shipyard procedure was used in taping the distances.

- c. The distances were taped about 10 days after the photographs were taken and the surveyors taping the distances had no knowledge of the photogrammetric results.
- d. The differences between photogrammetric and taped distances encompass errors in both measurement processes.

The shipyard's analysis of the entire photogrammetric product generated a letter which stated "... very complete information in a concise manner with excellent accuracy. We are most pleased with the photogrammetric technique. . ."

2.2.5 Time and Cost Analysis

Very close accounting was kept of man hours and costs involved in dimensioning the hold. Man hours and costs for the photogrammetrist's effort, as presented in Table 2-3, have been adjusted to reflect a production situation wherein a shipyard subcontracts for the service. The shipyard's effort in terms of man hours is given in Table 2-4.

Of the four photogrammetric demonstrations conducted for this project, this demonstration was the only one which was executed as if it were indeed a production situation. Preparation of the photographic plates, measuring of the plates, and data processing were completed to the point that initial results could be telephoned to the shipyard starting on the eighth calendar day after taking the photographs. A complete letter report including tabulations of data, sketches and a narrative were forwarded to sketches and a narrative were forwarded to the shipyard on the 12th calendar day. This is considered to be a typical turnaround for a project of this magnitude when working on a one shift per day basis. Two and even three shifts could be employed to speed the process.

2.2.6 Suggestions Relative to Future Work

As indicated in Figure 2-15 a number of targets on the edge of the weather deck opening could not be triangulated because their images failed to appear on two or more photographs. This was the result of obstructions to view caused by staging. For more complete data, staging in front of the targets could have been temporarily removed. An alternate possibility would be to offset the targets, in elevation, by known amounts.

2.3 Measurement of a Transverse Bow-Section

At GD Quincy an LNG tanker hull was made available to demonstrate photogrammetric dimensioning of a transverse section having high degrees of curvature. The section measured was about 135 feet in breadth by 82 feet in height and was to receive a 900-ton bow erection unit.

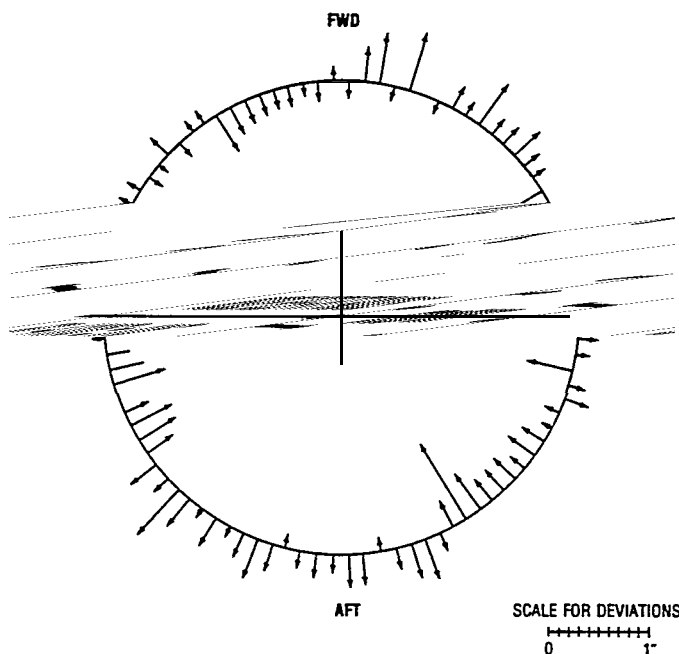


FIGURE 2-16: Deviation of Top, Inside Edge of Cylinder From Best-Fit Circle. Systematic deviations are evident but the root-mean-square departure from a true circle is only $\frac{1}{4}$ inch and the steel is within design tolerances. Vector data were also provided to the shipbuilder in tabular form.

¹Targets on the top of the cylinder were purposely aligned with stiffener webs for this purpose; see Figure 2-11.

²Distances between targets on the sloping bulkheads were selected for comparison since these targets were the most accessible to the surveyors for taping.

TABLE 2-3: *Photogrammetrist's Man Hours and Costs for Dimensioning a Hold to Receive a Spherical LNG Tank¹*

1. Labor			
	<i>Man</i>	<i>Burdened</i>	
	<i>Hours</i>	<i>Rate²</i>	<i>Cost</i>
a. Initial visit to shipyard (1 man)	24	19	\$ 456
b. Project planning (1 man)	13	19	247
c. Prepare and ship equipment and round trip travel (2 men)	36	12	432
d. On-site preparation and photography (2 men)	32	12	384
e. Prepare photographic plates (1 man)	8	12	96
f. Measure plates (subcontracted)	—	—	351
g. Data processing and reporting (1 man)	48	19	912
Total Labor			\$2,878
2. Expenses			
a. Transportation and per diem (initial visit and on-site work)			\$1,074
b. Materials (photographic plates, etc.)			104
c. Computer-			730
d. Miscellaneous (air freight, etc.)			103
TOTAL EXPENSES			\$2,011
			\$4,889
PRoFIT@ 15%			733
TOTAL			\$5,622

2.3.1 Preparation

Prior to undertaking this demonstration a visit to the shipyard was conducted to determine dimensioning requirements and to become familiar with the physical conditions under which the work would be performed. Ideally the objectives should have been to determine the shape of the shell plating, conformance of the section to a true plane, and its degree of perpendicularity. As the master butt was not yet neat cut, the objective was limited to determining accurate half breadths and elevations of selected points on the shell; i.e. the as built shape of the shell plating.

Photogrammetric planning following the shipyard visit encompassed the same considerations as described for the midbody in paragraph 2.1.1. Technically, this demonstration could have been handled by either semi-analytical or fully analytical photogrammetry. The fully analytical method was selected primarily because it could be more readily executed with equipment in hand. However, the fully analytical method did offer greater accuracy (admittedly not essential) and greater freedom in taking the photographs. This latter flexibility was welcomed because the ship was in a building dock with only 68 feet between the transverse section to be measured and the dock gate. This restricted the vantage points from

TABLE 2-4: *Shipbuilder's Effort in Support of Dimensioning a Hold to Receive a Spherical LNG Tank*

1. Labor

<i>Task</i>	<i>Man Hours</i>
a. Fabricate targets ³ (including flat-faced clips)	12
b. Paint targets	2
c. Carpenters - to extend staging and attach targets	7
d. Surveyors -	
(1) accompany. photogrammetric team ⁴	11
(2) measure distances ⁵	24
TOTAL	56man hours

2. Miscellaneous

a. Target materials	\$10(est.)
---------------------------	------------

¹Where travel is involved, a Florida based photogrammetric firm working at CD Quincy is assumed.

²Rates vary among firms.

³This is partially a non-recurring cost since the flat-faced clips may be reused.

⁴An observer was required for security reasons due to use of a camera within a shipyard where Navy work was in progress.

⁵This does not include check distances since these would not normally be taken in a production situation.

which pictures could be taken. In fact, the only logical vantage points (save for the use of a crane or specially erected staging) were across the top of the dock gate. From there it was more convenient to expose a series of highly overlapping nominally oriented photographs instead of a regularly arranged group of stereo pairs.

In advance of the date scheduled for photography GD Quincy fabricated about 75 targets similar to those used in the LNG tank hold (see Section 2.2.1) except that the diameter of the bull's-eye was reduced to 1/2 inch. Figure 2-17 illustrates the targetting scheme wherein about one half the targets defined the shell plating. Flat-faced clips, Figure 2-10, were fixed to the plating and each target was then adhered to the face of a clip such that the center of the target was aligned as near as possible with the "molded" edge of the shell. The remaining targets were adhered to the transverse bulkhead in a well distributed pattern in order to provide additional common points

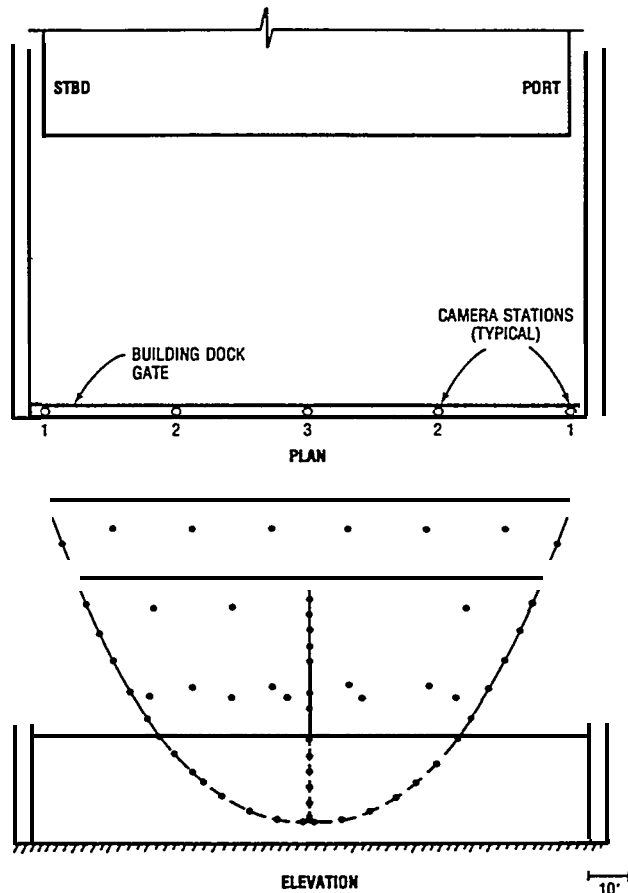


FIGURE 2-17: Locations of Targets and Camera Stations for Survey of Transverse Bow Section. Targets on bulkhead served only to provide additional points for correlation of overlapping photographs. Numbers below camera stations indicate number of exposures taken; each exposure viewed somewhat different portions of the section.

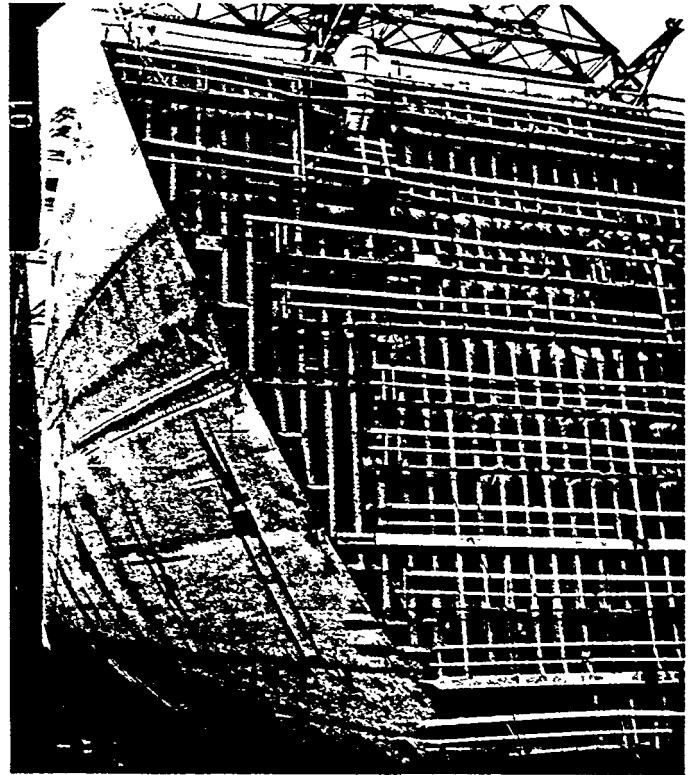


FIGURE 2-18: Typical Photograph of the Transverse Bow Section.

among the overlapping photographs. A number of these targets were also aligned with the bulkhead centerline as a reference for subsequent calculation of half breadths. One target was located at the intersection of the bulkhead centerline and the 1-foot waterline to provide a reference for computing elevations.

Shipyards surveyors taped several distances between pairs of targets. Some were provided to the photogrammetrist for use as scale references in the photogrammetric calculations while the remainder were withheld to check the photogrammetric results.

2.3.2 Photographic Procedures

Photographs were taken from the top of the dock gate as shown in Figure 2-17. The total elapsed time for obtaining all 9 exposures was 59 minutes. All were exposed on glass plates with the same camera¹ used for the midbody and cylinder surveys. Similarly, on-site processing was performed to assure satisfactory exposures. Figure 2-18, made from one of the photographs, illustrates the degree of curvature of the shell plating.

2.3.3 Laboratory Measurements and Data Processing

Preparation and measurement of the photographic plates proceeded exactly as described for the midbody in

¹A Wild P31 camera as illustrated in Appendix B, Figure B-2.

paragraph 2.1.3. Photogrammetric computations were as described in paragraph 2.1.4. Because of the high overlap of the pictures some individual targets appeared on as many as seven frames and, therefore, were triangulated by as many optical rays.

Upon completion of the photogrammetric computations the digital model of the transverse section was translated and rotated into the ship's coordinate system according to the following conditions:

- a. **The target on the centerline plane at the 1-foot waterline was assumed errorless with an offset and elevation of exactly 0.0 and 1.0 feet, respectively.**
- b. **All other targets on the centerline plane were constrained to have zero offsets in a best-fit sense. That is, the actual offsets were not exactly zero, but small and balanced in a $\pm$ sense.**
- c. **Targets on the edge of the shell plating were to have zero values in the fore-aft direction, again in a best-fit sense.**¹

2.3.4 Evaluation of Results

Photogrammetrically derived coordinates of the targeted points defined the shape of the shell. To compare this as-built shape to the design, it was first necessary for the shipyard to obtain offsets and elevations for a fictitious reference frame since the master butt was located between frames. Then the differences between "as built" and "design" were obtained as follows:

- a. Offsets determined by photogrammetry were corrected because the actual steel at each target was actually forward or aft of the adopted design reference frame (relative fore and aft positions of the targets were known from the photogrammetric solution).
- b. Portions of the reference frame thought to most closely correspond to the actual steel measured were plotted at a very large scale (about 3:1 relative to the ship) in the vicinity of each target.
- c. Photogrammetrically determined locations of the targets (but corrected as described in "a" above) were superimposed upon the plots.
- d. The perpendicular distance between the as-built location of each target and the design molded hull was simply scaled with a ruler. Figure 2-19 depicts the overall differences found. (Their magnitudes were confirmed by the shipfitters when mating the bow unit.)

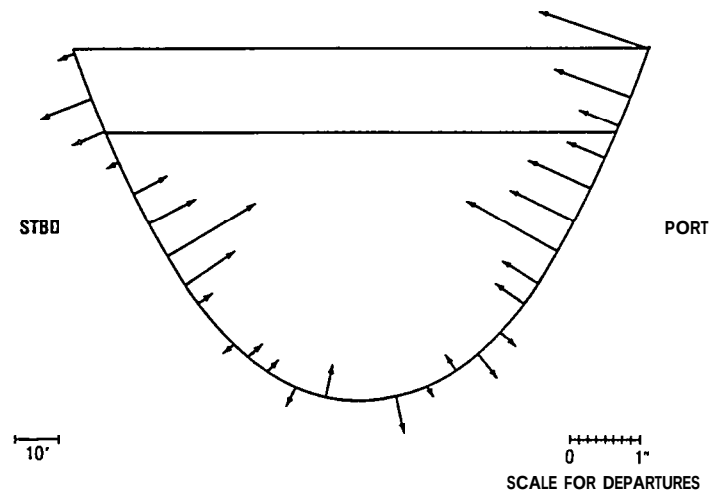


FIGURE 2-19: Deviation of Shell Plating of Transverse Bow Section. The design transverse section, corresponding to location of the master butt, is the reference illustrated. Each vector is perpendicular to the reference and depicts the direction to the steel surface built to the molded surface.

by only the shipyard on the day during which the photographs were taken.

A total of five distances ranging from roughly 24 feet to 56 feet were compared. The average difference between the two sets of data was $\frac{2}{16}$ inch with the maximum difference being $\frac{5}{16}$ inch.² The estimated tolerance of the photogrammetrically determined position of any target was ± 0.08 inch. And, the corresponding tolerance for a distance between any two targets was ± 0.1 inch. Typical expected errors were about one half these figures.

Taped distances were measured in segments and summed to the nearest $\frac{1}{16}$ inch to obtain total distances. Thus, combined photogrammetric and taping errors contribute to the differences reported.

2.3.5 Time and Cost Analysis

An accounting of the photogrammetrist's man hours and costs for this demonstration is presented in Table 2-5. As in previous analyses the figures have been adjusted slightly to reflect a production situation wherein a shipyard subcontracts for a photogrammetric survey. The

¹This was done even though the section had not been trimmed. Any small resultant error in being perpendicular to the ship's centerline would have insignificant effect on computed offsets and no effect on computed elevations.

²The average difference of $\frac{2}{16}$ inch is reasonable but the maximum difference of $\frac{5}{16}$ inch seems too large to be attributable to ordinary measuring errors. It is probably invalid because this difference applied to a distance which was actually a segment of a longer distance which checked within $\frac{1}{16}$ inch.

TABLE 2-5: *Photogrammetrist's Man Hours and Costs for Dimensioning the Transverse Bow-Section*¹

1. Labor

	<i>Man Burdened</i>		
	<i>Hours</i>	<i>Rate²</i>	<i>cost</i>
a. Initial visit to shipyard (1 man)	24	19	\$456
b. Project planning (1 man)	16	19	304
c. Prepare and ship equipment and round trip travel (2 men)	36	12	432
d. On-site preparation and photography (2 men)	22	12	264
e. Prepare photographic plates (1 man)	4	12	48
f. Measure plates (subcontracted)	—	—	189
g. Data processing and reporting (1 man)	41	19	779
Total Labor			\$2,472

2. Expenses

a. Transportation and per diem (initial visit and on-site work)	\$1,074
b. Materials (photographic plates, etc.)	62
c. Computer	271
d. Miscellaneous (air freight, etc.)	103
Total Expenses	\$1,510
	\$3,982
Profit @ 15%	\$ 597
TOTAL	\$4,579

shipyard's effort was essentially the same as for the survey of the cylinder (Table 2-4) with the exception of about five fewer man hours.

2.4 Piping Drawings from a Machinery Space Model

To demonstrate a photogrammetric method for lifting precise dimensional data from a design model,³ a machinery space model being constructed by Sun Shipbuilding and Dry Dock Company was made available to the project. All piping in the model was color coded and portrayed true to scale ($\frac{3}{4}'' = 1'$) rather than by the wire and disc method. Only side views of the model were used since a plexiglas deck prevented taking useful photographs from overhead. Accordingly, it was only possible to prepare elevation drawings.⁴ Nonetheless, the photogrammetric method was amply demonstrated.

2.4.1 Preparation

Very little preparation of the machinery space model was required prior to the taking of photographs. Within the model room the starboard half of the model was rolled against a wall such that the centerline of the model was parallel to the wall. An ordinary wooden ruler was used to measure the distance of the centerline from the wall so as to establish the parallel condition. About 20 high-contrast targets were applied to the wall to provide contrasting points about the model. A target simply consisted of a Dennison circular white Pres-a-ply self-sticking label upon which a small black dot was rubbed on from a transfer sheet. The latter were of the type used by secretaries for standard symbols and notations. These targets served two basic functions. First, the targets provided contrasting points, on an otherwise featureless surface,⁵ which facilitated orientation of one photograph to the other. This is a step which had to be performed before photogrammetric measurements of the model could be taken. Second, the contrasting points defined the plane upon which the elevation drawing was projected.

The final preparation was simply to attach a strip of balsa wood along the longitudinal direction of the main deck of the model, the length of the strip being about the length of the portion of the model measured. An ordinary round-headed tack was placed at each end of the strip and the distance between the centers of the tacks was measured with a steel tape for the purpose of providing scale to the photogrammetric analysis. For a check, a distance was also measured between two of the targets attached to the wall.

¹Where travel is involved, a Florida based photogrammetric firm working at GD Quincy is assumed.

²Rates vary among firms.

³Subparagraph 3.2.1a discusses the concept of producing arrangement drawings from design models.

⁴It is possible to develop some plan detail without overhead photographs but with full scale pipes the process is complicated. Also, the accuracy is considerably reduced.

⁵In order to "see" through the entire width of the model it is necessary for the lens to have a corresponding depth of field. To achieve the required depth of field the camera is necessarily at a distance removed from the model such that a sizeable portion of the wall is photographed along with the machinery space model.

2.4.2 Photographic Procedures

A series of photographs was taken with a single camera from the locations illustrated in Figure 2-20. After turning the model around, a similar series of photographs were exposed to aid mapping of detail from its other side. Although a rather large number of photographs were exposed, only six of these were ultimately used. The purpose in taking more photographs than absolutely necessary was simply to supplement, with slightly different views, those few photographs which would be used for most of the mapping.

All exposures were taken on glass plates coated with a

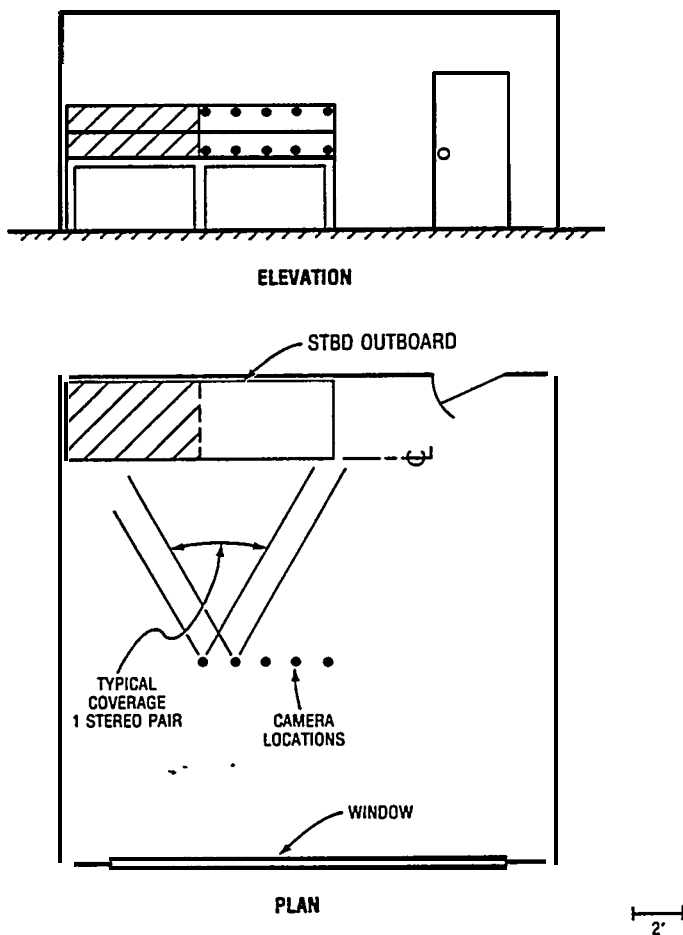


FIGURE 2-20: Locations From Which Photographs Were Taken of Machinery Space Model. Photographs were also taken of the outboard side. The shaded portion of model was ignored for this demonstration.

panchromatic emulsion using a Wild P31 camera. ¹No special illumination was used. Ambient light through the windows plus overhead fluorescent lights provided adequate, but not absolutely ideal illumination. All photographic plates were developed on site using very basic developing equipment and procedures. Figure 2-21 was made from a typical photograph. To expedite identification of the color coded pipes as rendered in black and white, color snapshots were also taken for reference by the stereo plotter operator. ²

2.4.3 Mapping Procedures

One pair of photographs, corresponding to a view from inboard looking outboard, was placed in a stereo plotter for viewing and mapping of the optical model ³ according to the following:

- One photograph was oriented to the other so as to create the optical model.
- The scale of the optical model was adjusted until the measured distance between the heads of the tacks was equal to the known distance as converted to the desired scale of the drawing. To be compatible with design drawings of the machinery space model a scale of $\frac{3}{8}'' = 1'$ was selected.
- The optical model was rotated until all targets on the wall were at the same depth as measured in the stereo plotter.
- Straight-line details, such as edges of decks and bulkheads, were traced. A mechanical linkage from the stereo plotter to the plotting table caused a pencil to draw at the correct scale. The lines were smoothed and inked by hand.
- Next, edges and detail of fixed machinery were traced. Again, the penciled lines were smoothed and inked by hand.
- Because of the complexity of the piping only one pipe was traced at a time, with the operator referring to the color snapshots as necessary. As piping drawings typically show centerlines of pipes, the actual procedure was to pencil an "eyeball" best-fit straight line through each traced edge of a pipe and then take the average of these two lines

¹The camera is illustrated in Appendix B, Figure B-2.

²The mapping work was subcontracted to Henderson Aerial Surveys, Inc. of Columbus, Ohio. A Wild Autograph A10 stereo plotter was used; see Appendix B, Figure B-7. The subcontractor had never seen the actual machinery space model nor was he provided with any of its design drawings. Materials provided consisted only of a sample arrangement drawing from another ship, photographic plates, color snapshots and sketches showing the camera stations relative to the machinery space model. Approximately 2½ hours of verbal instruction was also provided.

³The stereo plotter reproduced the machinery space model as a phantomlike image through which accurate measuring and tracing devices were moved. Also, see Appendix B, paragraphs 2.3.2 and 2.4.1.

as representing the location of the centerline.¹ The centerline was then inked and the penciled edges erased so as to avoid confusion in plotting additional pipes.

- g. Additional pairs of photographs were inserted into the stereo plotter as necessary to complete all detail. Steps "a" through "c" were repeated for each new pair of photographs. Steps "d" through "f" were repeated for new detail only.

The mapping operation was performed by two persons. One operated the stereo plotter while the other simultaneously "heavyed up" detail being traced. That is, the second person served as a draftsman for the interpolation and drafting functions involved in steps "d" through "f" in the foregoing. Upon completion of the mapping work the original drawing was aligned on a digitizing table for measurement of distances between the centerlines of pipes and the deckheads or forward bulkhead.

Next, a check print was made and compared to the machinery space model. Annotations were made of missing detail, extraneous detail and names of machinery and distributive systems. Then, the photographic plates and the original drawing were reintroduced in the stereo plotter and required missing detail was recovered and mapped.

Figure 2-22 is a reproduction of the final drawing. At the suggestion of the shipbuilder, no drafting refinements have been added since they would provide no additional useful information.

2.4.4 Evaluation of Results

The drawing was checked both for content and for accuracy of dimensioned distances. Detail content was found to be very good. Some small diameter piping, such as used for the steam station against the forward bulkhead, could not be retrieved from the available photographs. In both instances it is likely that these details could have been mapped (at least to a great extent) had it been possible to obtain photographs from above the machinery space model. Nonetheless, it is anticipated that a small amount of manual finishing will always be required to complete a piping drawing prepared by photogrammetry.

Spot checks were made on the accuracy of the photogrammetrically prepared drawing by comparing 20 of its dimensioned distances to like distances on the shipbuilder's conventionally prepared drawings. Large differ-

ences were exceptions and were caused by known distortions in the model or by changes which had been made to the model, but not yet incorporated in the shipbuilder's drawings. The average difference between the photogrammetric and design dimensions was 1½ inch at the scale of the ship. The maximum difference was 2½ inch.

The reported differences reflect both photogrammetric error and error in the model itself since the model was built according to the shipbuilder's drawings. In design modeling, however, the model is the design and the error in arrangement drawings prepared by photogrammetry would be due strictly to photogrammetric error alone. In this particular demonstration the estimated tolerance of the photogrammetric error is ±1 inch at the scale of the ship and the estimated typical error is ±½ inch.

For dimensions derived from a machinery space model to be of value, it is generally agreed that a tolerance at the scale of the ship on the order of ±¼ inch to ±½ inch is required. Obviously a photogrammetric tolerance of ±1 inch is not adequate, but this demonstration was certainly not optimized for obtaining maximum accuracy. A tolerance of ±¼ inch is realistic for the photogrammetric method and has already been demonstrated by an investigation into design dimensioning from chemical plant models.² Suggestions for improving the process for machinery space models are given in paragraph 2.4.6.

2.4.5 Time and Cost Analysis

This particular demonstration is difficult to analyze in terms of time and other costs which might be experienced by a shipbuilder in a production situation. Several factors contribute to this uncertainty.

- a. The task was quite unlike any other undertaken by most photogrammetrists. Some inefficiency resulted from developing procedures as the work progressed.
- b. A plan view could not be obtained and only the steam systems within a portion of the model were mapped in the elevation view.
- c. The mapping work may have been more efficient had it been possible to prepare a plan view first. With only photographs from the sides of the model it was difficult to account for "hidden" pipes in common horizontal planes.
- d. Certain fixed costs apply regardless of how much of a model is mapped.

¹It should be mentioned that tracing edges of a pipe does not strictly produce its exact diameter to scale. This is because a photograph is a perspective view and optical rays through the lens tangent to a curved surface intercept a chord. Also, this interpolation process would not be necessary with a wire and disc representation of piping.

²See Appendix C, Part 1, Article B-2.

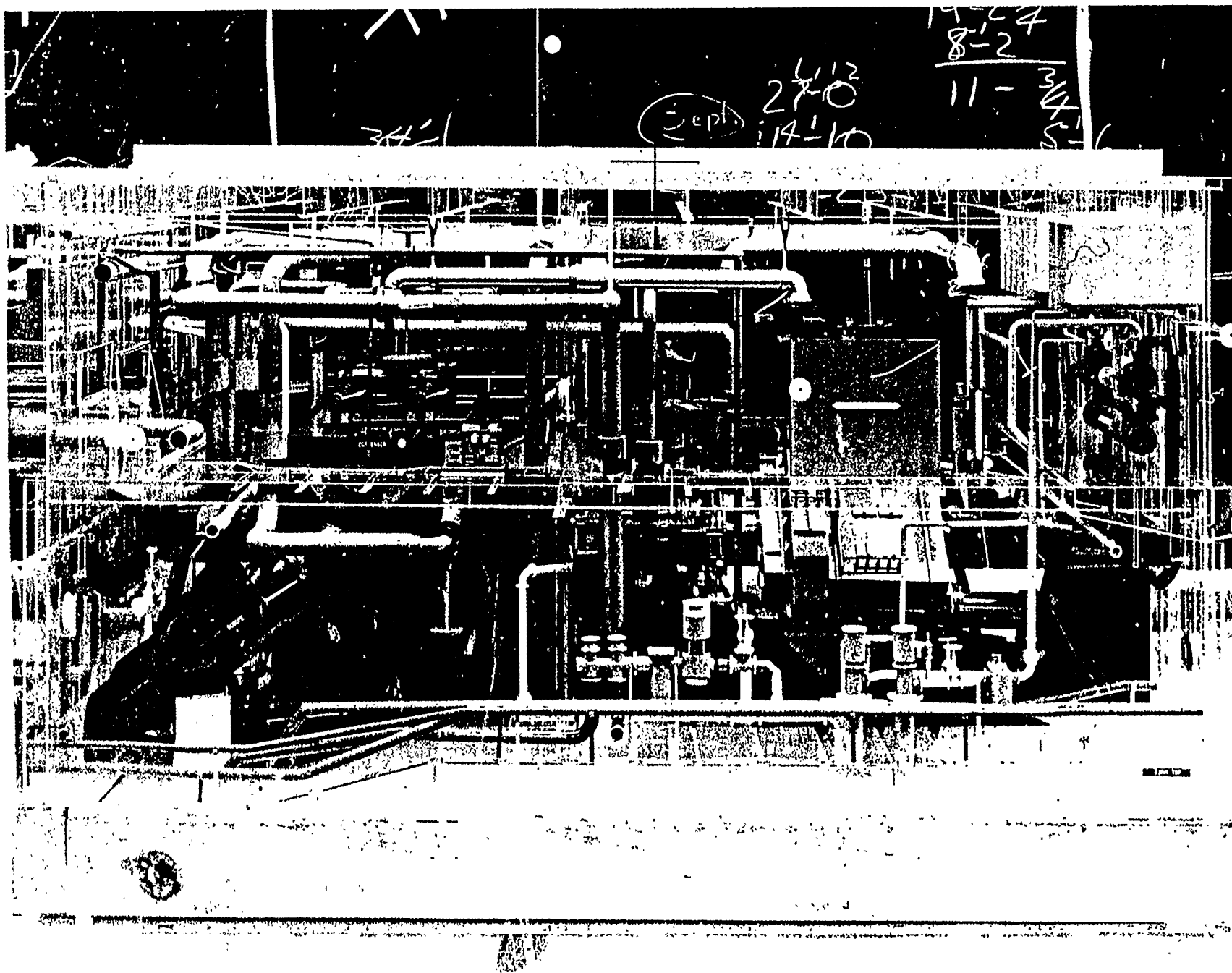


FIGURE 2-21: Photograph of Machinery Space Model Showing Extent of Model Mapped.

FIGURE 2-22: Elevation Drawing of Portion of Machinery Space Model. The original copy of this drawing was mapped at a scale of $\frac{3}{8}" = 1'$. All vertical distances are from the nearest overhead deck regardless of arrow direction. All horizontal distances are from frame 82. Drawing is directly from stereo plotter and not redrafted for aesthetic value. Only the steam systems are shown.

- e. Finally, the portion of the model chosen for demonstrating the photogrammetric method is considered to be the most complex. Therefore it probably represents the most difficult and expensive area to map.

Costs for preparing the elevation drawing shown in Figure 2-22 were adjusted as best as possible to reflect a production situation and are contained in Table 2-6. Using these adjusted costs as a basis, costs for a plan view were estimated and are also included.

2.4.6 Suggestions Relative to Future Work

Execution of this demonstration was undertaken with full knowledge that neither the available machinery space model nor the contemplated photogrammetric processes could be classified as being ideal. Moreover, it was also recognized that preparation of just a drawing of steam systems was merely touching upon the full potential for photogrammetric measurements as an adjunct to design modeling.¹ The intent in proceeding with this demonstration was to develop a basic example of the usefulness of photogrammetry for the design of piping systems. If a shipyard were to consider implementation of design modeling combined with photogrammetric dimensioning, the basic required improvements are:

- a. The model should be constructed with a view toward accessibility for photography. Preferably the model would be more modularized so that it could be disassembled at least in units bounded by transverse bulkheads. Also, separations at the centerline plane and the ability to separate upper and lower deck levels would be very helpful.
- b. The use of clear plexiglas for the sides, bulkheads and decks should be minimized to the greatest possible extent. Its light reflecting and refraction characteristics are disruptive.
- c. For greater measurement accuracy a wire and disc representation of piping systems should be used. This would also allow mapping to progress much more rapidly since a pipe could be mapped simply by identifying a few points along its path.

- d. More uniform lighting should be furnished, especially inside the model to minimize glare and shadows.
- e. Materials with dull finishes and flat coatings should be substituted for polished materials and glossy paints respectively, to further minimize glare.

TABLE 2-6: *Projected Man Hours and Costs for Plan and Elevation Piping Drawings*^{2,3}

	<i>Man</i>		
	<i>Hours</i>	<i>Rate⁴</i>	<i>Cost</i>
1. Labor			
a. Project planning and coordination including visit to shipyard (1 man)	38	\$19	\$ 722
b. Prepare and ship equipment and round trip travel (2 men)	33	12	396
c. On-site preparation and photography (2 men)	40	12	480
d. Mapping (2 men including stereo plotter)	87	30	2,610
Total Labor			\$4,208
2. Expenses			
a. Transportation and per diem (initial visit and on-site work)			\$ 990
b. Materials			180
c. Air freight and miscellaneous			80
Total Expenses			1,250
			\$5,458
Profit @ 15%			\$ 819
TOTAL			\$6,277 ⁵

¹It was observed in June 1976 that Odense Steel Shipyard Ltd., in Denmark, successfully combined pipe-systems design and modeling to create 1:15 scale models of ship machinery spaces without preparing *Piping* systems or composite arrangement drawings. With input from production people, sufficient model detail is provided to identify multi-ton piping units, consisting of a number of different systems, which are planned for shop assembly. Dimensions are manually lifted from such models and recorded on a simple isometric sketch for each planned piping subassembly (on the average a subassembly consists of about eight pipe pieces and eight fittings). Each isometric, sketched on art 8 1/2 X 11 inch sheet, contains all material requirements, pipe piece details, and ship location references. Thus, each isometric combines all design data required for production, a significant amount of completed planning, and all information necessary for the remaining planning and scheduling functions. Further, each isometric sketch, being sufficient, is then coded for computer preparation of material lists, pipe bending instructions, work orders, schedules, etc. More details of this Odense design/modeling process are to be incorporated in the report for the study "Advanced Pipe Technology," also part of the National Shipbuilding Research Program, which is expected to be published in early 1977.

²For steam systems in the portion of the machinery space model shown in Figure 2-22.

³Where travel is involved, a Florida based photogrammetric firm working at Sun SB & DD is assumed.

⁴Rates vary among firms.

⁵Does not include shipyard's efforts for project coordination and proof reading of drawing check copies.

- f. The camera should not be located in any horizontal or vertical plane containing groups of pipes. Avoidance of these "critical planes" would minimize hidden pipes on the photographs.
- g. Consideration should be given to a larger photographic scale to increase the photogrammetric accuracy. Necessarily, this must include consideration of interrelated factors such as focal length, relative aperture, ability to change focal length for short focus and depth of field.

Another improvement may be the use of color film. This is still unproven but ordinary color snapshots are nonetheless desirable for reference.

2.4.7 Long Range Potential

As mentioned above, if the wire and disc modeling technique is used, a pipe can be mapped by identifying a few points along its path. Since a stereo plotter measures in all three dimensions simultaneously and since each axis can be digitized (a very common practice), the points defining a pipe can be digitized.

TABLE 2-7: *Summary of Demonstrated Applications*

<u>DEMONSTRATION</u>	<u>SECTION</u>	<u>DATA DEVELOPED</u>	<u>ACCURACY TESTS</u>	<u>COST</u>
Measurement of Complete Midbody Section	2.1	Half breadths and deck heights with comparisons to design; squareness of sides and transverse sections; planarity of tank top; deviation of centerline plane; deviations of trimmed sections from true planes; skew of transverse sections; deviations of bilge turns from true circles	N/A ¹	\$6,301
Measurement of Hold to Receive Spherical LNG Tank	2.2	Deviation of top edge of cylinder from true plane; deviation of weather deck overhead from true plane parallel to top edge of cylinder; out-of-roundness of cylinder; distances from axis of cylinder to points on weather deck opening; arc distances between vertical stiffeners on outside of cylinder	5 taped distances ave. difference $\frac{1}{16}$ inch; max. difference $\frac{1}{16}$ inch	\$ 5 , 6 2 2
Measurement of a Transverse Section	2.3	Shape of shell plating and deviations from design	5 taped distances ave. difference $\frac{1}{16}$ inch; max. difference $\frac{1}{16}$ inch	\$4,579
Measurement of Machinery Space Model	2.4	Elevation drawing of steam systems in portion of model	20 design distances - ave. error $1\frac{1}{8}$ inch; max. error $2\frac{5}{8}$ inch at scale of ship ³	N/A ²

¹Validity of tests uncertain: see paragraph 2.1.5.

²Only partial drawings were compiled: see paragraph 2.4.5.

³Includes errors in model as well as photogrammetric error. Accuracy can be improved.

Such digital representations could be manipulated to automatically plot system arrangement drawings, composites or isometrics at any desired scale. Also, pipe bending details could be automatically generated as has been demonstrated elsewhere.¹ Ultimately, the digital data could be merged with other automated design systems. For these potential applications it is clear that photogrammetry could serve as an excellent input “device” which would permit a combined pipe-systems designer/model maker to put his inherently interference-free piping arrangements into a computer.

2.5 *Summary of Demonstrated Applications*

The principal finding from the four shipbuilding applications of photogrammetry that were demonstrated are summarized in Table 2-7, page 23.

¹See Appendix C. Part 1, Article B.3.

3. A SURVEY OF PHOTOGRAMMETRY IN SHIPBUILDING

To determine past and current applications as of the initial stages of this project (February-May 1975) a thorough review of pertinent literature was conducted in parallel with a worldwide mail solicitation of individuals thought to have knowledge of such applications. In addition, interviews with U.S. shipbuilders generated further suggestions for other potential applications.

3.1 Literature Search and Direct Mail Solicitation

Coincident with an extensive literature search inquiries were sent to 68 persons in 59 countries.¹ Both efforts were sufficiently broad in scope to include industries having industrial functions similar to those in shipbuilding. The results indicate that photogrammetry has not been widely adopted.

The few instances wherein photogrammetry is routinely used for shipbuilding include a Norwegian patented service for producing sounding tables for LNG spheres, an East German process to aid the manufacture of ships propellers and measurement of drilling platform components in Britain. Aside from shipbuilding, photogrammetry has apparently been adopted by one company as the preferred means for "lifting" dimensional data from scale models of chemical plants. Some automobile manufacturers *use* photogrammetry to develop contours and cross sections of design models which would be roughly equivalent to developing a lines drawing from a model of a ship's hull.² However, producing a shell expansion which is a related application is not potentially productive because of the efficient computerized method already in use.

While they have not widely adopted photogrammetry, shipbuilders have shown considerable interest in its potential. This has been manifested by several papers, investigations and experiments which were uncovered during the literature search and mail campaign. Pertinent abstracts are in Appendix C. A brief summary categorized by shipbuilding functions is contained in Table 3-1.

3.2 Review of Suggestions from U.S. Shipbuilders

During the first several months of this project the photogrammetrist was required to acquire a basic understanding of shipbuilding functions. This was accomplished by background reading, and to a greater extent through visits to several U.S. shipbuilding yards and to a naval architect's office. While conducting these visits ideas were solicited for dimensioning tasks which might be suited to photogrammetric techniques of measurement. All phases of shipbuilding were considered. This section

TABLE 3-1: Applications of Photogrammetry Revealed by Literature Search and Direct Mail Solicitation

<i>Shipbuilding Function</i>	<i>Application</i>
<i>Design</i>	1. Measuring bow and stem wave forms under simulated speed and depth of water conditions in a towing basin.
	2. Determining trajectory and speed of a test model under varying power output and rudder position.
	3. Dimensioning from scale models.
	4. Measuring cavitation on model propellers.
	5. Measuring cavitation on propeller at sea.
	6. Development of pipe bending data.
	7. Dimensioned drawings of vendors' equipment.
<i>Fabrication</i>	1. Checking propellers during and after their manufacture.
	2. Checking shape of rolled and formed shell plates.
	3. Checking dimensions of nodes for drilling platforms.
<i>Erection</i>	1. Dimensioning of three-dimensional erection units (ships and drilling platforms).
	2. Predicting fit of large erection units.
	3. Determining as-built shape of hulls.
	4. Preparing sounding tables for LNG spheres.
<i>Outfitting</i>	None
<i>Ship Repair</i>	1. Dimensioned drawings of a historical ship.
	1. Determining trajectory and speed of a ship during launching.
<i>Miscellaneous</i>	2. Measuring subsidence of ways during launch.
	3. Determining trajectory and speed of a ship upon impact with a pier used to pivot the ship for alignment with its berth.
	4. Dimensioning of a ship's propeller after a period of service.

¹Twenty-seven responses were received (40%).

²Photographs of a hull model used to predict hydrodynamic performance characteristics could be cheaply made and easily filed. If necessary at a future date photogrammetric processing would produce the lines of the model tested for comparison to those used for construction of a ship.

contains the substance of such discussions. It also illustrates the degree of shipbuilding know-how acquired by the photogrammetrist.

3.2.1 Applications in Design

a. Drawings from Design Models

Some people believe that basic design, especially of distributive systems, should be first accomplished with a design model.¹ This is in contrast to the more conventional approach wherein the design is developed in the form of arrangement drawings first and then, perhaps, tested for interferences by means of a model. If the "design modeling" approach were to be adopted, the problem arises as to how the design, as conceived in the model, can be accurately captured and conveyed to all persons requiring knowledge of the design. In posing this question it is assumed that the model cannot be the only means for communication, and obviously some drawings based upon the model are required. Photogrammetry is seen as an accurate and efficient means for producing such drawings.² A description of the process, demonstrated with a ship's machinery space model, is contained in Section 2.4.

b. Shell Plating Expansion

It has been customary in the past to first prepare a shell plating model, upon which all butts and seams are scribed. To determine the developed form of each plate by photogrammetry would be a rather straightforward process by the semi-analytical method. Stereo pairs of the shell plating model would be introduced into a stereo plotter and the edges of each strake would be digitized in X, Y, Z stereo plotter coordinates. Subsequent computer processing would project the data for each plate to a plane to realize the developed shape. The same procedure could conceivably be followed for surfaces of very high curvature such as propeller bossings.

The photogrammetric solution seems to be naturally suited to this task, but the application has not been given serious consideration since modern computerized design sys-

tems have all but eliminated the practice of preparing shell plating models.

C. Shape of Shell Plating Around Hawsepipe

It is usually necessary to build an anchor handling model to assure a proper anchor handling arrangement. Once a final design has been established, it must be converted into offsets and elevations for fabrication and erection purposes. One procedure presently employed uses a molding technique. A silicone rubber³ casting is made directly from the lower hawsepipe and shell bolster area of the model. This casting is then used as a pattern to reproduce the original model in a plastic substance⁴ that can be readily sawn. Offsets are measured from the parallel sections obtained by sawing.

Analog photogrammetry is very well suited to this dimensioning task. A stereo pair of photographs of the anchor handling model would be placed in a stereo plotter and the surface of the resulting optical model would be traced along any desired waterline or frame. Output from the stereo plotter would be a graphical presentation of the shape of each line relative to the ship's centerline. Actual offsets at intersections of frames with waterlines would be shown in numerical form.

But, while photogrammetry can easily accomplish such measurements it is not likely to be more productive than existing procedures. Moreover, the frequency of occurrence of this dimensioning requirement is rather low. Even weighed against the fact that photogrammetry can produce more data, this potential application of photogrammetry seems more academic than productive as seen from the shipbuilders' point of view. However, consideration should be given to just photographing the shell bolster area of the constructed ship. Then, if an anchor handling problem occurred, photogrammetry could be used to analyze the as-built surface.

¹MachineW space design modeling, as performed by Odense Steel Shipyard Ltd., is described in footnote 2 on page 22. Also, this opinion is expressed in Chapter II, Section F, page 6. "Use of Scale Models as a Management Tool." National Shipbuilding Research Program report by the U.S. Department of Commerce Maritime Administration in cooperation with Todd Shipyards Corporation, May 1974.

²Also, see Appendix C. Part 1. Articles B. 1 and B.2.

³"Silastic."

⁴A mixture of polyester auto body putty and polyester resin.

3.2.2 Applications in Fabrication

a. *Measurement of Flat Panels and Sub-Assemblies*

As flat panels and sub-assemblies are fabricated, it is common practice, as a matter of quality control, to check their dimensions. For the most part this checking is accomplished simply by measuring the lengths of sides and diagonals. This rather basic checking procedure is viewed as being adequate in most instances. Since relatively few dimensions are required, usually in a short period of time, and since the needed dimensions are readily obtained with a steel tape, photogrammetry cannot compete.

b. *Measurement of Small Erection Units*

Several shipbuilders have expressed some concern with annoying fitting discrepancies which often occur. The difficulty seems more predominate when curved surfaces are involved. It has been suggested by more than one shipbuilder that photogrammetry be applied to this problem as a quality control measure.

There is no question that fully analytical photogrammetry can be used for dimensioning individual modules and perhaps even to the extent of predicting the fit between modules. However, the question arises as to the value of such detailed information unless there is time to plan remedial work such as compensation in erection units not already built. Save for a gross discrepancy, it is likely that such information would only serve to predict the need for extra man hours during erection.

It is accepted that the described discrepancies do exist, but it seems more prudent to direct shipbuilders' efforts toward better dimensional controls in the burning and fabrication stages. If photogrammetry is to be applied at all, it should only be in a temporary capacity for checking three-dimensional modules as an aid to perfecting other quality controls.

3.2.3 Applications in Erection

a. *Measurement of a Complete Midbody*

In the "jumboizing" process entire midbody sections are inserted into existing

ships. Because of the large size of such units it is difficult by conventional means to determine, in detail, the as-built configuration. Necessary measurements include:

- (1) half breadths and heights which locate the intersections of decks, shell and other structural members which contribute to longitudinal strength,
- (2) shape such as turns of-the-bilge,
- (3) comparisons of items (1) and (2) to design data,
- (4) squareness of all sides,
- (3) deviations of transverse sections from ideal planes,
- (6) racking of the entire unit,
- (7) parallelism of the forward and after transverse sections.

As a practical matter items (6) and (7) are of major interest since racking and parallelism cannot be readily ascertained by conventional means.

Although emphasis is placed upon a determination of racking, this is not to minimize the capability of photogrammetry for generating data for each of the other listed items from the same set of photographs. It is also important to recognize that comprehensive dimensioning of a midbody unit is practically identical to requirements for dimensioning mating faces of separately built ship halves.

In the context of jumboizing it has been suggested that photogrammetry might be used to measure the receiving ship after it has been cut. These measurements would be compared to data previously developed for the midbody so as to predict its fit. This concept is precisely that described in subparagraph 3.2.3.b which pertains to measurement of mating faces of a ship built in halves. However, insofar as "jumboizing" is concerned, the concept is not practical when the joining process commences within a few hours of cutting the ship. There is not sufficient time to permit measurement by photogrammetric methods. However, consideration should be given to just photographing the exposed transverse sections

¹A description of this process, as demonstrated for shipbuilders is contained in Section 2.1.

after the ship is cut. Then if there are unanticipated matching problems caused by differences between the ship as built and the owner furnished “as-built” drawings, facts regarding the differences could be established by photogrammetric processing.

b. *Measurement of Mating Sections of a Ship Built in Halves*

Measurement of mating sections would permit predicting their fit well in advance of moving either or both sections. A total measurement program should include virtually the same data described in subparagraph 3.2.3.a for measuring a ship’s mid-body.

There is no question photogrammetric measurement of mating sections of ship halves and predicting their fit would be productive. If such predictions saved even one workday in a large capacity building dock the costs for applying photogrammetry would be more than offset.

One shipbuilder has suggested a variation in the application of photogrammetry to measuring mating sections of ship halves. This variation would have photogrammetry applied to at least one half of the ship *after* the trim line has been established by a laser, but before trimming has been performed. Thus a check would be made on the perpendicularity of the trim line relative to the ship’s centerline and base planes. The reason for such a check is not lack of confidence in the laser; it is the physical difficulty of establishing true references. It was also suggested that if one ship half has been built neat, the possibility *exists* for accurately plotting its as-built dimensions and for adjusting the trim on the other ship half to suit.

c. *Measurement of a Hold Receiving an LNG Tank*¹

One design for transporting LNG makes use of a spherical tank which, when lowered into a ship, rests upon a cylindrical support skirt. Fabrication and erection of this cylinder is quite *critical* considering that

the diameter is about 120 feet and that it must match a portion of the cylinder attached to the sphere’s equatorial ring. A comprehensive measurement program should provide the following data:

- (1) radius of the circle which best fits a representative number of measured points around the top of the cylinder,
- (2) departures of the measured points around the top of the cylinder from the best-fit circle,
- (3) distances between vertical stiffeners attached to the outside of the cylinder,
- (4) departures of measured points from a plane best fit to the top of the cylinder,
- (5) skew of the plane of the weather deck relative to the plane best fit to the top of the cylinder, and
- (6) upward projection of the best-fit circle for the purpose of predicting clearances between edges of the weather deck opening and the spherical LNG tank, during its installation.

Consideration has also been given to measuring the mating surface of that portion of the support skirt attached to the equatorial ring of the sphere. The data sought would consist of the planarity of the mating surface and its circularity; see items (1) and (2) above. With both parts of the skirt so measured, their fit could be predicted before the sphere was installed.

d. *Measurement of a Drilling Rig*

One shipbuilder has reported annoying fit discrepancies when floating deckhouses onto supporting columns of semi-submersible drill rigs. At present steel-tape measurements are taken across the vertical columns which are each about 18 feet in diameter, not perfect cylinders, and about

¹An applicable demonstration is described in Section 2.2.

90 feet apart. Aside from access problems, there is doubt whether the tapes are uniformly tensioned for reliable measurements.

The shipbuilder suggested that photogrammetry be used to determine relative heights and orientations of the columns. This information would be of value for trimming the columns to a common plane and for predicting their fit to the deckhouse. This potential application is viewed as being feasible and productive. The approach would make use of the fully analytical method.

3.2.4 Applications in Outfitting

a. Measurement of Propeller and Rudder Keyways

To provide totally useful data for keyways it is necessary to dimension both the male and female components. While it is feasible to measure the male component by photogrammetry, the female presents severe space restrictions which cannot be handled by ordinary photographic techniques suitable for photogrammetric dimensioning. Moreover, large keyways are becoming obsolete.

b. Measurement of Surface Contact of Reduction Gears

Present practice for determining the contact of reduction gears makes use of a "blueing in" process. The face of each tooth on one gear is coated with a substance which upon rotation of the gears is deposited on the mating teeth. The amount of contact between the mating teeth along the pressure line is indicated by the presence of deposited coloration.

The actual amount (percent) of contact made is apparently determined via human judgment. Photographic procedures are sometimes used, but again, the determination of the amount of contact is still partial and subjective.

Analysis of the photographs could certainly be made quantitative by applying simple photogrammetric principles. However, if there is no need for greater accuracy

relative to present methods the added effort for a photogrammetric analysis is not warranted.

c. Measurement for Shaft Alignment

To set foundations for propulsion-shaft spring bearings, it is necessary to determine the height relationship between the bottom of the shaft alley and the reference line. In the interest of productivity two shipbuilders have suggested that it would be desirable to weld spring-bearing foundations in place before the erection units in which they are located are welded together. Some shipbuilders already do this by simply allowing greater tolerances and planning for the use of thicker chocks during installation of each bearing.

In concept photogrammetry would be used to survey the bottom of the shaft alley and to dimension the individual erection units. Subsequent digital processing would "connect" the units together so that the entire shaft alley could be analyzed as a single unit. It is doubtful, however, whether the application of photogrammetry is practical due to space restrictions on taking photographs in a shaft alley. Even if it were possible to acquire suitable photographs, the digital connection of erection units could very well be unlike that which is actually achieved.

d. Dimensioning for Walkways in Machinery Spaces

Often when only one ship of a type is built, or when a ship is the first of a series, the final layout of walkways in machinery spaces evolves from design drawings modified many times as the machinery outfit progresses and interferences are disclosed. It has been suggested that, following installation of the main machinery components, photogrammetry might accelerate the entire process.

The photogrammetric approach is not particularly straightforward since photographs would generally be taken from unusual points of view. Numerous obstructions of view so typical of machinery spaces also complicate the photogrammetric solution. The manual effort involved in taking

and analyzing the photographs may not be competitive with present procedures. However, more detailed study should be undertaken before firm conclusions are reached.

e. *Measurement for Locating Framework for LNG Insulation*

To position the insulation system in a hold designed for a Conch LNG tank a framework of balsa/plywood support panels must first be laid out along the junctions where the sloping and vertical bulkheads intersect one another and the tank top. The framework is also needed along the tops of the vertical bulkheads. Once in place, this framework ideally conforms to the design shape of the inner hull irrespective of the as-built configuration.

An original suggestion regarding the possible use of photogrammetry was as a means for checking the locations and “heights”¹ of the support panels after installation. Subsequently, this concept was revised to employ photogrammetry prior to placing the panels rather than after the fact. Specifically, photogrammetry would be used to accurately dimension the as-built inner hull of the ship. Further data processing would then be performed to generate the needed elevation data for each main ground and also the location of its main stud. The physical location of the stud on the actual steel would be found by scribing two or three arcs from nearby photogrammetric targets using radii determined from the data processing.

Two potential photogrammetric solutions for this task were developed. One solution employed a large number of targets on the inner hull and the fully analytical method of photogrammetry whereas the second solution used fewer targets and a combination of fully analytical and semi-analytical photogrammetry.

The estimated cost and turnaround for either solution were found to be about the same as that experienced by the shipyard using strictly manual procedures. Thus, in

the instance considered, a photogrammetric solution was not productive. However, the shipyard did feel that more serious consideration would have been given to a photogrammetric approach had it been presented before the yard had undertaken and mastered the manual technique.

f. *Development of Sounding Tables for LNG Tanks*

Fully analytical photogrammetry can be employed to precisely determine the as-built configuration of a tank as represented statistically by a few hundred targets attached to the shell. In the case of a spherical tank photographs would be taken from the inside of the tank.² Photographs of a tank of the Conch design would likely be taken from outside due to numerous internal obstructions to view. In either case, the digital model of the tank would be integrated in increments required for the sounding tables with appropriate corrections applied for service temperature and internals.

3.2.5 *Applications in Sea Trials*

a. *Measurement of Hogging and Sagging*

Photogrammetric measurement of the hogging and sagging of a ship at sea could conceivably be accomplished by semi-analytical or fully analytical methods. In either case at least a few targets would be attached to the hull of the ship. Photographs would be taken with two synchronized cameras located in a chase ship or aircraft. Photogrammetrically determined locations of the targets using any pair of photographs would represent the shape of the ship at the instant of exposure. Comparison of results from different pairs of photographs would indicate the changing deformation of the ship.

For normal situations it is not believed that there is a real need for such data. However, this is another case where photographs could be made and filed in anticipation of subsequent events which may justify photogrammetric processing.

¹Heights in this context means distances between main grounds of the panels and the actual steel. Distances vary due to deviations of the as-built steel from the design.

²In January 1976 General Dynamics Corporation, Quincy Shipbuilding Division awarded a contract to develop sounding tables for 40 LNG tanks of the Moss-Rosenberg spherical design. Fully analytical photogrammetry was the specified method of measurement.

f. Measurement of Bow Wave and Wake

To monitor bow wave and wake the photogrammetric approach would be to expose photographs with two synchronized cameras from above the ship. Analog photogrammetry would be utilized to map the wave forms. Again, this is a case where photographs could be maintained on file in the event that a future circumstance justifies processing.

3.2.6 Applications in Ship Repair

a. Measurement for Repair of Hull Damage

Repair of hull damage is oftentimes delayed when as-built or design drawings of the ship are not available. One method for obtaining such data is to hang a probing device over the undamaged side in order to measure the required offsets. Sketches may also be prepared from measurements made inside the ship.

Analog or semi-analytical photogrammetry is very well suited to gathering data from outside of the hull. Moreover, the photogrammetric approach could be more productive and would be more accurate than present methods. To relate the photogrammetrically determined shape to the ship's base and centerline planes, a minimum of three points whose offsets and elevations are known (or can be readily determined) must be visible on the photographs.

3.2.7 Miscellaneous Applications

a. Development of As-Built Drawings¹

Virtually any area which can be readily photographed is conducive to the preparation of as-built drawings.² These may be relatively simple areas such as panels containing a multiplicity of gauges, switches, indicator lights, etc., or more complex spaces containing piping, ducting and wireways. Also, dimensioned drawings of vendors' equipment can be similarly prepared

prior to delivery of the equipment to the shipbuilder.

In new construction of larger ships composite drawings are theoretically updated to as-built status upon completion of the ship. In practice this is oftentimes not sufficiently done. Whether photogrammetry can play a useful role in bringing the drawings up to as-built status is questionable from cost effectiveness and productivity considerations; a manual ship check may be just as efficient.

When only one ship, or the first of a new design is built, oftentimes much of the piping, ducting, gauges, switches, etc. are field run or placed. Thus, each such ship can serve as a full scale design model for preparing drawings of such details. Photogrammetry may be very useful for this purpose.

In ship upgrading work the first course of action is to conduct a ship check to determine existing as-built conditions. Oftentimes as-built drawings are not available and it becomes necessary to develop them anew. Typically, this involves a team of men who take ordinary snapshots and prepare sketches in the ship for use in preparing sufficiently detailed arrangement drawings. In the most difficult upgrading work several man years may be expended just to obtain the as-built drawings needed for planning. If as-built drawings are required after the upgrade work is completed, an additional and even greater effort is oftentimes necessary to produce the final drawings.

The greatest application for photogrammetrically prepared as-built drawings appears to be in mapping of pipes, ducts and wireways in overhead spaces. For the photogrammetric method to be productive it is felt that it is necessary to develop a procedure built around a simplified stereo plotter which can be operated with minimum training by technician level personnel within a shipyard or naval architect's office. A tolerance at the scale of the ship on the order of $\pm\frac{1}{2}$ inch is required.

¹ Although normally considered a design function, preparation of as-built drawings has been separated from the section treating potential applications of photogrammetry in design. It is felt that photogrammetric methods may be suited to dimensioning vendors equipments and to ship upgrading work as well as to the more conventional requirement for as-built drawings of new ships.

² Machinery spaces are excepted since it is not generally possible to 'stand off' with a camera to obtain unobstructed views.

3.3 *Productivity of Applications Suggested by U.S. Shipbuilders*

The following categorizations are in the context of the application descriptions contained in Section 3.2 preceding:

LIKELY TO BE PRODUCTIVE

- Ship's midbody for "jumboization."
- Mating sections of ships built in halves.
- Ship's hold for a spherical LNG tank.
- Structure of semi-submersible drilling rigs.
- Sounding tables for LNG tanks.
- Repair of hull damage.
- Piping arrangement drawings from design models.
- As-built drawings.

PRODUCTIVITY UNCERTAIN

- Grounds for LNG tank insulation systems.
- Machinery space walkways.
- Hogging and sagging.
- Bow wave and wake factors.

NOT LIKELY TO BE PRODUCTIVE

- Shell-plate expansion.
 - Shell plating around hawsepipe.
 - Smaller erection units.
 - Flat panels and subassemblies.
 - Propeller and rudder keyways.
 - Surface contact of reduction-gear teeth.
 - Foundations for propulsion-shaft bearings.
-

4. OPTIONS FOR APPLYING PHOTOGRAMMETRY IN A SHIPYARD

To adopt photogrammetry as a measurement tool a shipbuilder has first to select from three alternatives: develop a total in-house capability, retain a photogrammetrist by subcontract, or use a combined in-house/subcontract arrangement. Each are objectively discussed herein. All estimates are based upon the monetary values existing in March 1976.

4.1 Total in-House Capability

A totally self-sufficient photogrammetric unit requires capital for hardware, software and training of selected personnel. Estimated costs, itemized in Table 4-1, depend upon whether a shipyard desires a capability for analog, semi-analytical, fully analytical photogrammetry or a combination of these.

As implied in Table 4-1, rather extensive training would be required for implementing an in-house capability. Initially, as a minimum, a two-man team dedicated to photogrammetric surveying would be required. Preferably, one person should have prior experience in photogrammetry while the other should have experience in shipbuilding. If semi-analytical or fully analytical photogrammetry is desired, computer support on a timely basis would also be necessary. A start-up period of about three months should be allowed before production work commences.

4.2 Total Subcontract Arrangement

Total subcontracting of photogrammetric work is basically the method by which demonstration surveys de-

scribed in Chapter 2 were performed. Although the shipyards did participate to the extent of fabricating targets, attaching targets and taping distances, these functions would normally be performed by the photogrammetric firm. However, there are situations (e.g. scheduling and safety restrictions) wherein attachment of targets and taping of distances would be best performed by the shipyard.

Typical costs involved for subcontracted photogrammetric surveys of some shipbuilding applications are contained in Tables 2-1 through 2-6. Appendix D lists firms which provide photogrammetric services.

4.3 Combined In-House/Subcontract Arrangement

If there is a series of alike ships to be built the shipyard may wish to consider assuming responsibility for just the field effort. Primarily this would involve taking the photographs and taping control distances but may also include targeting if fully analytical photogrammetry is employed. Photographs secured by the shipbuilder would then be forwarded to a photogrammetrist for analysis. The first one or two surveys, however, should be entirely overseen by the photogrammetrist in order to instruct shipyard personnel in procedures to be followed for subsequent surveys. These procedures would be quite straightforward and would not vary from survey to survey.

To illustrate the combined concept, consider the costs for photogrammetrically surveying a hold in an LNG ship; see Tables 2-3 and 2-4. If it is desired to survey 40 holds¹ and if the shipyard fabricated and installed targets and taped distances, the photogrammetrist's charge would be about \$5,600 for the first survey and about \$4,400 for each

TABLE 4-1: *Estimated Start-Up Cost for Implementing Photogrammetry In-House²*

circa March 1976

COST ITEM	METHOD OF PHOTOGRAMMETRY		
	<u>ANALOG</u>	<u>SEMI-ANALYTICAL</u>	<u>FULLYANALYTICAL</u>
1. Camera(s)	\$4,000- \$ 20,000	\$4,000-\$20,000	\$13,000-\$20,000
2. Stereo plotter	33,000- 105,000	46,000- 118,000	N/A
3. Comparator	N/A	N/A	24,000- 35,000
4. Computer programs	N/A	2,000- 30,000	40,000
5. Manuals and in-plant training	14,000	14,000	12,000
TOTALS	\$51,000-\$139,000	\$66,000-\$182,000	\$89,000-\$107,000

¹Eight ships with 5 holds each.

²In preparing these estimates, only hardware and software deemed suitable for shipbuilding have been considered so as to present realistic estimates. Ranges in hardware costs reflect differences in sophistication and capability of instruments. See Appendix D for suppliers of photogrammetric hardware and services.

of the 39 subsequent surveys.¹ Thus, the total cost would be approximately \$177,200. If the shipyard were to purchase a camera and undertake all field work for, say, 38 surveys (the first two would be supervised by the photogrammetrist, the photogrammetrist's charge would be **about \$5,600 for the first survey, \$4,400 for the second survey** and \$2,500 for the remaining 38. In this case then, the total subcontract cost would be roughly \$105,000. To this add \$16,000 for the camera and photographic supplies. The result is a reduction in subcontract costs of about \$56,200.

The combined approach may also be attractive to a shipbuilder since it allows total flexibility for taking pictures. The need to coordinate timing with the photogrammetrist's field team would be eliminated.

¹Higher cost for the first survey is due primarily to the need for an initial visit to the shipyard and to develop the photogrammetric procedures.

APPENDIX A

GLOSSARY OF PHOTOGRAMMETRIC TERMS

Analog Photogrammetry-the method in which a stereo pair of photographs is used in a stereo plotter to create a three-dimensional optical model and measurements of the optical model are produced as a direct graphical presentation.

Comparator- a device for measuring relative locations of images of points on a photograph; the instrument consists of an x-axis, a y-axis, a stage upon which the photograph is laid, a measuring reticle and viewing optics.

Contour- a line of constant value within the scene; for example, the shape of the hull at any waterline.

Convergent Photography -the procedure in which the optical axes of the photographs are purposely inclined relative to one another and with respect to the scene; normally done to increase the accuracy of fully analytical photogrammetry.

Cross Section - a trace of shape of the scene, usually in a direction perpendicular to a reference line; for example, the shape of the hull at any frame.

Digital Model -a scaled three-dimensional rendition of the scene photographed generated by digital processing of comparator measurements of images of specific points within the scene or by point by point digitizing of an optical model in a stereo plotter; the digital model consists only of points in the scene whose images are measured.

Distortion -see lens distortion.

Fully Analytical Photogrammetry -the method in which images of specific points within the scene are measured directly on single photographs, stereo pairs or convergent photographs using a comparator; a three-dimensional digital model may be formed by computation and then further processed by digital means for final presentation of graphical and/or numerical results.

Intersect -see intersection.

Intersection -in fully analytical photogrammetry, the process of digitally projecting optical rays from corresponding images of the same point on two or more photographs to their intersection at that point within scene; the process is equivalent to triangulating the location of a point through measurements of horizontal and vertical angles with a transit or theodolite from two or more known locations.

Lens Distortion -geometric errors introduced into the recorded photographic image by the inability of the lens to allow a point in the scene, the optical center of the lens and the image of the point to lie on a straight line.

Measuring Reticle -a dot or cross hair within a stereo plotter or comparator used to sight upon specific points of interest or to trace continuous details such as cross sections, profiles and contours.

Model -see optical model.

Optical Axis -that line which passes through the optical center of the lens and is perpendicular to the focal plane of the camera.

Optical Model -a scaled three dimensional rendition of the scene photographed, created in a stereo plotter by projecting light through the original negatives or transparent copies thereof; the separately projected images are viewed with special optics so as to fuse like images and create a perception of depth.

Optical Ray -a straight line emanating from a photographic image passing through the camera lens and continuing to the corresponding point in the scene.

Photogrammetric Measurement -a measurement made directly on a photograph or in a three-dimensional optical model.

Photogrammetry -the science of extracting meaningful two or three-dimensional measurements of a scene from one or more photographs of the scene.

Profile -a trace of shape of the scene, usually in a direction parallel with a reference line; for example, the shape of the hull at any buttock.

Reticle -see measuring reticle.

Scene -the portion of the real world as imaged by a camera; in shipbuilding the scene is usually a specific object such as a ship's hull, a midbody section or a scale model of a machinery space.

Semi-Analytical Photogrammetry -the method in which a stereo pair of photographs is used in a stereo plotter to create a three-dimensional optical model and photogrammetric measurements of the optical model are processed digitally to obtain final results.

Single-Image Photography -the procedure in which successive photographs overlap one another by only a small amount; any portion of the scene is imaged (essentially) only on a single photograph.

software -computer programs.

Standard Deviation -a statistical measure of error commonly used in photogrammetry; as a practical matter, one standard deviation multiplied by 2 would be roughly equivalent to tolerance.

Stereo Pair -two photographs whose optical axes are nominally parallel and which are exposed such that (about) 50% or more of the scene on one photograph also appears on the other photograph.

Stereo Plotter -a projection device used to create a three-dimensional optical model from a stereo pair of photographs; see optical model.

Tolerance -maximum allowable or expected plus-minus error of a measurement. For universal applicability in photogrammetry, the value may be expressed in parts per thousand of the major dimension of the scene photographed.

Triangulate -see intersection.

APPENDIX B

A LAYMAN'S EXPLANATION OF PHOTOGRAMMETRY

1 DEFINITION OF PHOTOGRAMMETRY

Photogrammetry is the process of extracting meaningful two or three-dimensional measurements of a scene from one or more photographs of the scene. The derived information may be in the form of coordinates of points, distances, outlines of features or shapes of surfaces. A glossary of photogrammetric terms is presented in Appendix A, to which the reader is urged to refer while reading further.

2 GENERAL CONCEPTS AND METHODS OF PHOTOGRAMMETRY

The desired dimensional data of the scene photographed can be obtained through several combinations of photogrammetric processes; the various possibilities are illustrated in Figure B-1. In most instances the combination of processes used for a given practical situation is dictated by the nature of the object, the required accuracy of results and the type of data presentation desired.

2.1 Camera(s)

A photogrammetric camera is of robust construction to ensure a constant relationship between the lens and the focal plane. The lens is virtually free of distortion. Film or glass plates are used to register the exposure; some cameras can accept both glass plates and film while others can accommodate only one or the other.

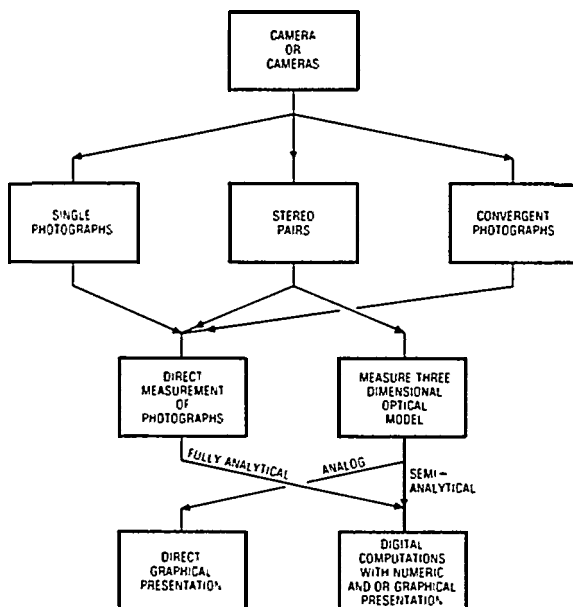
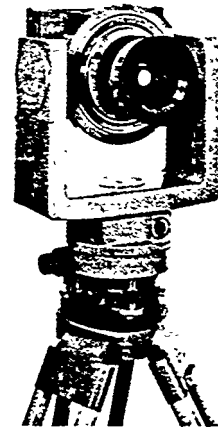
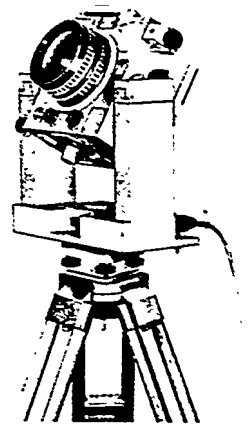


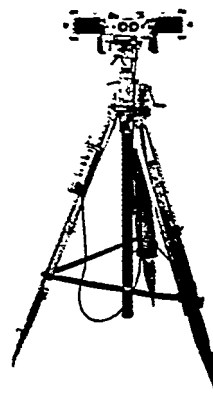
FIGURE B-1: Typical Combinations of Photogrammetric Processes.



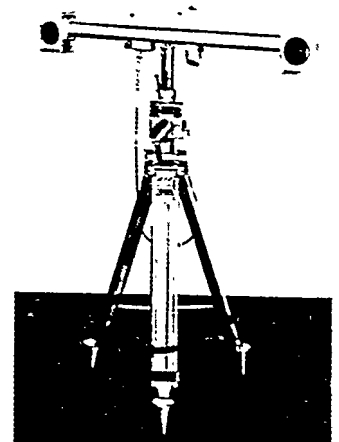
WILD P31



ZEISS JENA UMK



WILD C40



CARL ZEISS SMK

FIGURE B-2: Examples of Single and Dual Cameras.

When the scene to be photographed is stationary, a single camera may be used to take photographs from one or more camera locations (i.e., the camera is moved between exposures). Alternately, two or more cameras may be used and if the scene to be photographed is in motion, the camera shutters must be synchronized. Oftentimes a pair of cameras are rigidly mounted at a known separation upon a bar with the optical axes of the cameras parallel. Such an arrangement can be used for static and dynamic situations and also introduces some simplification in the photogrammetric process owing to the known relationship between the cameras. Typical cameras are shown in Figure B-2.

2.2 Classification of Photographic Coverage

The size and shape of the scene to be photographed and the accuracy desired of the final results generally dictate the type of photographic coverage employed.

2.2.1 Single Image Photography

When the area of interest lies in a plane, a single photograph or a series of slightly overlapping photographs may be used. See Figure B-3.

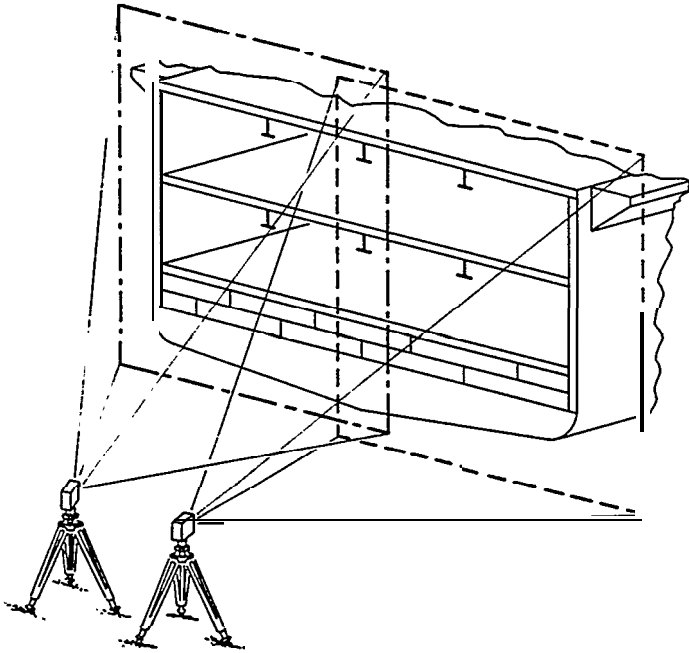


FIGURE B-3: Illustrating Single Image Photography. Photographs overlap only slightly. Any portion of the scene is seen (essentially) only on one photograph. A single camera may be used to take all photographs.

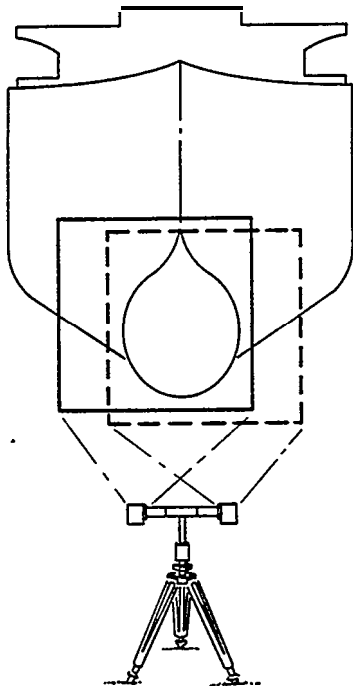


FIGURE B-4: Illustrating Stereo Photography. Adjacent photographs usually overlap by at least 50 percent and camera axes are nominally parallel. When viewed in a stereo plotter the imagery common to adjacent photographs is perceived in three dimensions. A single camera may be used to take all photographs.

2.2.2 Stereo Photography

When the scene is three-dimensional and contour, cross section or profile data are desired, two or more photographs are taken such that their optical axes are parallel and such that each photograph overlaps its adjacent photograph by 50% or more. Any two adjacent photographs are called a stereo pair. See Figure B-4.

2.2.3 Convergent Photography

When the scene is three-dimensional and the accuracy requirements are stringent, two or more photographs may be taken with their optical axes purposely inclined with respect to one another and to the scene photographed. Such photographs are called convergent photographs. See Figure B-5.

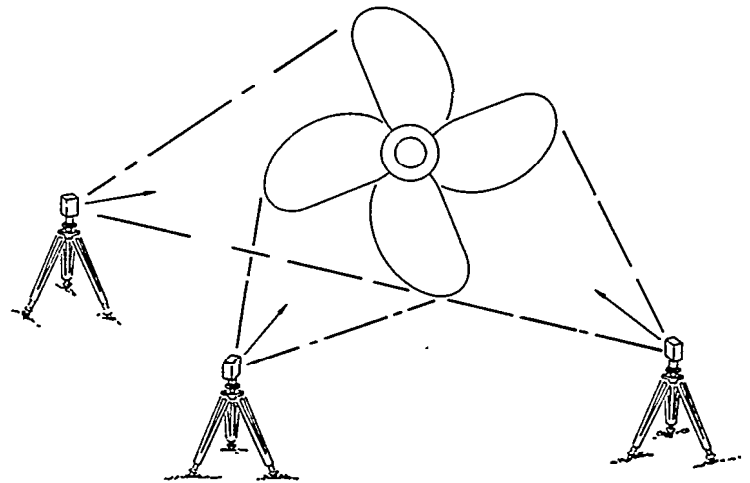


FIGURE B-5: Illustrating Convergent Photography. Camera axes are purposely inclined to one another and with respect to the scene. A single camera may be used to take all photographs.

2.3 Classification of Photogrammetric Measurement “

Photogrammetric measurements¹ may be made directly on the original negatives (or reproductions therefrom) or in a three-dimensional model created from a stereo pair.

2.3.1 Direct Measurements of Photographs

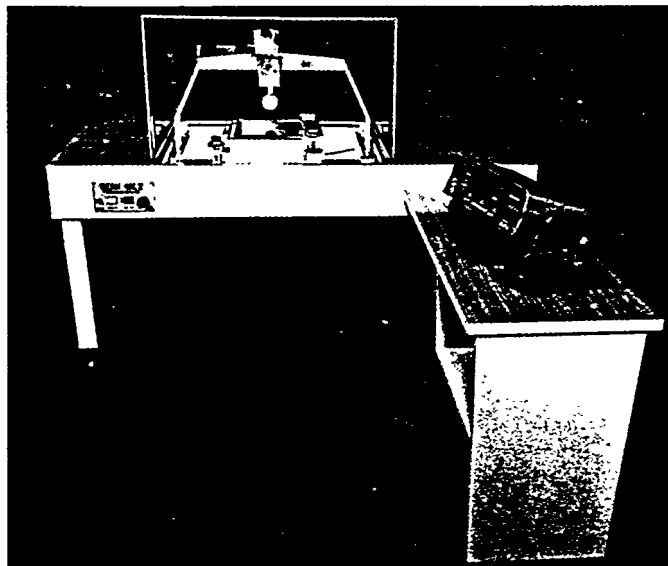
When photogrammetric measurements are to be taken directly on a photograph, details of the scene for which data are desired must be well defined on the photograph. To provide the needed definition contrasting markings (e.g., paint) may be used or targets may be placed at specific points of interest within the scene. The photographs, or more precisely, relative locations of the details of interest on a photograph, are measured on a comparator. A comparator for measuring single photographs simply consists of a fixed

¹Photogrammetric measurements are not the same as the desired measurements of the scene photographed. The desired measurements of the scene are derived from the photogrammetric measurements.

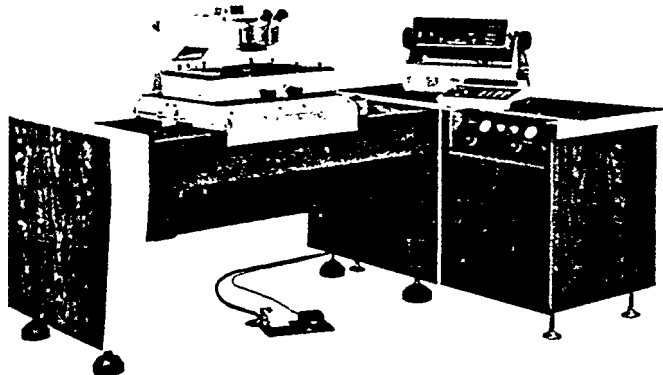
measuring reticle, a fixed optical viewing system, a stage upon which the photograph is laid and which may be moved along two axes. Typically, the movement of the stage is digitized with a least count of 1 micrometer (0.00004 inch). Typical comparators for measuring single photographs are shown in Figure B-6.

2.3.2 Measurements in a Three-Dimensional Model

A stereo pair of photographs may be used to create a three-dimensional optical model of the scene (or portion thereof) which is common to the two photographs. The two photographs can be likened to the images received by the human eyes. Since the same scene is viewed from two slightly different perspectives by the eyes, there is a sense of depth perception (i.e., three-dimensionality). The same effect can be achieved with a stereo pair of photographs. Original negatives or transparent reproductions thereof may be placed into side-by-side projectors and when

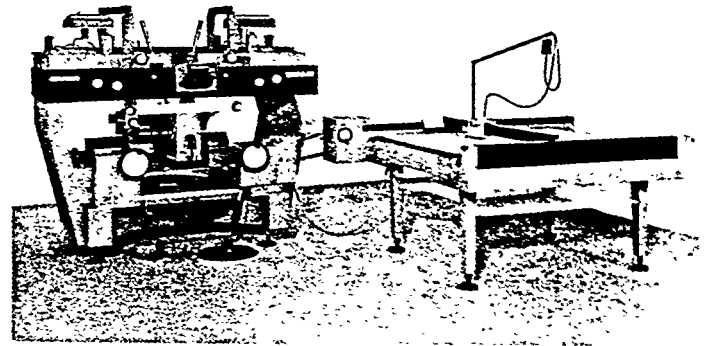


KERN MK 2

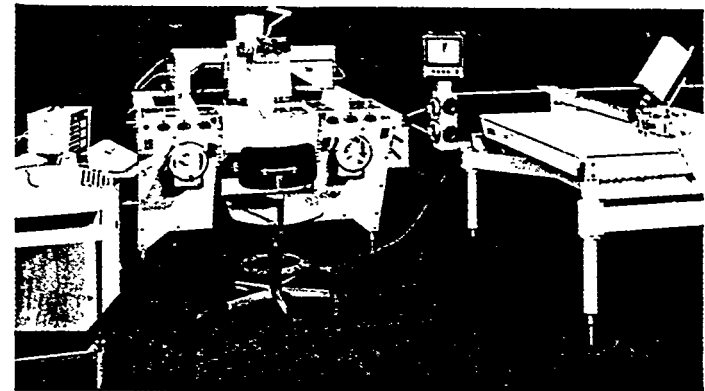


H. DELL FOSTER RSS 600

FIGURE B-6: Examples of Comparators for Measuring Single Photographs.



WILD A10



KERN PG3

FIGURE B-7: Examples of Stereo Plotters for Measuring Optical Models.

the projected images are viewed through special optics, the observer actually sees a three-dimensional optical reproduction of the scene photographed. This optical reproduction is commonly referred to as a model since it is a true rendition of the scene photographed. However, the model is usually at something less than one-to-one in proportion to the scene photographed; hence, the term "model." The instrument in which the model is viewed and measured is called a stereo plotter. See Figure B-7.

2.4 Classification of Data Processing and Presentation of Results

Data processing and presentation of results derived from photogrammetric measurements are dictated by the type of photogrammetric measurements taken.

2.4.1 Direct Graphical Presentation

When an optical model is cross sectioned, profiled, or contoured, or when outlines of features are traced, these traces of form may be produced directly. This is accomplished on a drafting table which is linked to the measuring reticle of the stereo plotter. The stereo plotter operator moves the reticle about the surface of the optical model and the pencil automatically follows and draws the movements. This graphical presentation may be mechanically or electronically scaled up or down as desired. That is, the

graphical plot need not be the same scale as the optical model. This combination of measurement and presentation is known as analog photogrammetry (see Figure B-1).

2.4.2 Digital Calculations Followed by Numerical and/or Graphical Presentation

When locations of individual points are measured within an optical model (as opposed to cross sectioning, profiling or contouring) some digital processing usually follows. As examples, this may involve transformation of photogrammetric coordinates measured in the model to a ship coordinate system or the measured points may be subjected to a surface fitting routine. In the former case the results would most likely be presented in numerical form; for instance, offsets and elevations, half breadths, deck heights, etc. In the latter case the results would probably be displayed graphically; for instance, a contour map depicting departures from an ideal surface. In either case, the combination of measuring an optical model and presenting results after some intermediate digital calculation is known as semi-analytical photogrammetry (see Figure B-1).

When measurements are taken directly from photographs, data processing is always required. As a minimum, a digital model must first be produced. This digital model is equivalent to the optical model with the exception that the digital model consists only of those specific points whose images were measured on the photographs. Point data of the digital model are usually subjected to further processing, as just described, prior to final presentation of results. The combination of taking photogrammetric measurements directly on the photographs and subjecting these to digital processing is known as fully analytical photogrammetry (see Figure B-1).

3 CONTROL FOR PHOTOGRAMMETRY

Since photogrammetry is an indirect measurement process, it is necessary to have a known reference upon which the photogrammetric solution may be based.

3.1 Scale Reference

Photogrammetric measurements are necessarily at the scale of the photographs or of the optical or digital models formed from the photographs. The scale relationship between the photogrammetric measurements and the scene photographed must be precisely established. This may be accomplished within the scene or at the camera stations.

3.1.1 Scale Reference Within the Scene

Scale reference within the scene is readily created by placing a survey rod within the field of view of the

camera(s), by stretching a steel tape across or next to the scene or by precisely measuring the distance between two well defined points marked within the scene.

3.1.2 Scale Reference at the Camera Stations

The scale of a photogrammetric solution may also be determined if the camera stations are separated by known distances. As mentioned earlier, some dual camera systems are purposely manufactured with this concept incorporated. Distances between camera stations may also be measured with a steel tape.

3.2 Absolute Reference

Before describing methods for establishing an absolute reference it must be mentioned that some measurement tasks do not require an absolute reference. Specifically, if distances between points (for example, half breadths and heights) are the desired end product, then there is no need to relate the photogrammetric coordinate system to any other absolute coordinate system (such as a ship coordinate system). Also, if it is desired, for example, to determine the shape of a curve or surface, here again, an absolute reference is not required. An absolute reference is required only when the results must be reported in a specific fixed coordinate system. It is also noteworthy that scale may be implicit in an absolute reference and, therefore, a scale reference need not always be separately established.

3.2.1 Absolute Reference Within the Scene

Absolute reference within a scene is usually established by discrete points within the scene whose coordinates in the reference coordinate system are known. For example, to relate photogrammetric measurements of a section of ship's hull to the ship coordinate system, at least three discrete points of known offset, elevation and longitudinal distance would permit a determination of the relationship. It is not necessary, however, that all three coordinates of any single reference point be known. Points whose coordinates are only partially known can be used too. For instance, as a minimum, two points of known offset and longitudinal distance plus three points of known elevation will also suffice.

3.2.2 Absolute Reference at the Camera Stations

To establish an absolute reference at the camera stations it is necessary to survey the locations of the camera stations (position and elevation) and to determine the directions in which the cameras are pointed, relative to the reference coordinate system.

4 ACCURACY OF MEASURING BY PHOTOGRAMMETRY

4.1 *Definition of Accuracy*

In photogrammetry, accuracies are usually expressed in terms of standard deviations or parts per thousand of the distance from the camera(s) to the scene. These conventions have been discarded in favor of a scheme which is more practical for day to day estimating and which is based upon the criterion of tolerance (i.e., maximum expected or allowable $\pm$ error).¹ Still, to be of universal applicability, it is necessary to express tolerance in terms of unitless ratios. Specifically, tolerance is expressed herein as parts per thousand of the major dimension of the scene photographed and applied to the accuracy of single points.

To illustrate the method of expressing tolerance, suppose that it has been established (by this report) that a particular photogrammetric method can yield tolerances **on the order of ± 1 part in 15,000 of the major dimension of the scene photographed.** Assume also that the scene is a transverse section and that the breadth of the section is 150 feet while the height is 100 feet. The "major dimension" is taken to be the diagonal distance which, by calculation, is 180 feet. Division of the diagonal distance by 15,000 gives the expected tolerance of ± 0.012 foot or about $\pm 5/32$ inch for a single point.

There are two significant peculiarities of accuracies obtainable by photogrammetry. First, as already indicated, tolerance as defined above applies to the absolute accuracy of locating an individual point. For all practical purposes all points are located with essentially the same accuracy. Thus, points which are physically close to one another will have less relative accuracy than points which are more widely separated. The second peculiarity is that the accuracy of about 50% of the points will actually be more precise than the indicated tolerance by about a factor of 2.1

4.2 *Accuracy of Analog Photogrammetry*

As analog photogrammetry deals primarily with stereo pairs of photographs, the accuracy of results in the direction to and away from the observer is less than in planes parallel to the observer. This is directly a result of the fact that the separation between the cameras is usually small relative to the distance from the cameras to any point in the scene, thereby forming a slender triangle whose apex in the scene is not strongly determined by the adjacent sides. Another determining factor affecting accu-

racy is the quality of the stereo plotter employed. These range from relatively unsophisticated "approximate solution" instruments to very sophisticated computer controlled stereo plotters.

For approximate reference the following table may be used as a guide for tolerances to be expected of analog photogrammetry.

<i>Tolerance in Planes Parallel to Observer²</i>	<i>Tolerance in Direction to and From Observer³</i>
± 1 part in 2,000 to ± 1 part in 14,000	not useable to ± 1 part in 12,000

4.3 *Accuracy of Semi Analytical Photogrammetry*

Tolerances expected of the semi-analytical method are about the same as the maximum figures for analog photogrammetry. This is because the distance between the cameras is usually near the maximum which can be accommodated by the stereo plotter and also because a stereo plotter of medium to high quality is normally used.

4.4 *Accuracy of Fully Analytical Photogrammetry*

Because the photogrammetric measurements are taken directly from the photographs and processed entirely by digital means, the fully analytical method affords greater opportunity for sophistication (for example, to correct for small errors such as lens distortion, film deformation, etc.). For this reason, the fully analytical method is preferred when point data of high accuracy are needed. When stereo pairs are used in the fully analytical process, **expected tolerances are typically about ± 1 part in 14,000.**

The accuracy of fully analytical photogrammetry may be further enhanced by the use of convergent photographs and more sophisticated computer programs. This enhancement in accuracy is achieved by intersecting each point in the scene from many camera stations. Moreover, the triangles formed by the camera stations and points in the scene are no longer slender and the tolerance to and away from the observer tends toward equality with the tolerance in the planes parallel to the observer. **Tolerances upwards of ± 1 part in 60,000 are state of the art.**

5 ADVANTAGES AND DISADVANTAGES OF MEASURING WITH PHOTOGRAMMETRY

5.1 *Advantages*

- a. Complexity of shape or detail of the scene is not restrictive.

¹Throughout this report tolerance has been equated to two standard deviations. Theoretically it is more correct to equate tolerance to three standard deviations. The former is justified as a practical matter since only 4.6 out of 100 dimensions would theoretically exceed the stated tolerance. Experience has shown further that the maximum error is actually about 2.5 standard deviations rather than three standard deviations. Moreover, a "typical" accuracy is about one standard deviation.

²Increases with more sophisticated stereo plotters.

³Increases with increasing separation between the cameras, but the distance is ultimately limited by mechanical restrictions of the stereo plotter.

- b. Relative directions to all points of interest within the field of view of a camera are recorded instantaneously with a single opening of the shutter. (This is in contrast to time consuming measurement of horizontal and vertical angles with a transit or theodolite.)
- c. All data (photographs) can be obtained in a short period, thereby minimizing the effect of thermal and gravity induced changes within the scene upon the consistency of the final results.
- d. The amount of data to be extracted from the photographs does not pose severe time and cost limitations.
- e. The process is virtually noncontacting.
- f. Due to the short period of time required for taking the photographs, there is minimum interference with ongoing work. In some instances work may not be interrupted at all.
- g. Dynamic situations can be accommodated with the use of two or more cameras having synchronized shutters.
- h. The orientation or attitude of the scene is of no consequence. Photographs can be taken from above, below or to the sides so long as there is room to stand off with the camera.
- i. With the fully analytical method of photogrammetry, the accuracy can be varied over a wide range to suit the particular need.
- j. The photographs constitute a permanent record and may be reused to check results or gather additional data.
- k. Photographs may be taken and archived for any potential need to produce data at a future point in time. This applies to potential litigation as well as to pure technical requirements.
- c. Measurements in very confined spaces are generally not practical due to the large number of photographs needed to cover the entire scene. Also, the depth of focus of the camera lens may not be able to accommodate varying distances to points within the scene.
- d. The first cost for an in-house capability ranges from \$50,000 to \$180,000 depending on the extent of the capability desired.¹
- e. Again, depending on the complexity of the capability desired, a photogrammetrist or special training of a shipbuilder is required for an in-house capability.

5.2 **Disadvantages**

Measurement by photogrammetry has drawbacks as well as advantages. Notable disadvantages are:

- a. Results of photogrammetric measurements are not produced instantaneously. Depending on the difficulty of the task considered, the time required to produce final results may range from several hours as a minimum to several days. An extreme situation might involve several weeks.
- b. Useful photographs cannot be taken in rain, snow or fog.

¹These considerations are treated in greater detail in Chapter 4.

APPENDIX C

SUMMARY OF LITERATURE SEARCH AND DIRECT MAIL CORRESPONDENCE

A thorough review of the photogrammetric literature and a concerted direct mail campaign were conducted with the objective of determining past and present uses of photogrammetry within shipbuilding and industries having similar industrial functions. The results are organized under two headings: literature and correspondence. All abstracts of literature have been prepared especially for this report and are not those of the original authors of the articles. Pertinent excerpts are included from noteworthy portions of the correspondence.

I. LITERATURE

A. General

1. "Applications of Industrial Photogrammetry in the Shipbuilding Industry" by H. Wienert, *Seewirtschaft*, 1 (1969), pp. 792-795 (British Ship Research Association Translation No. 3245).

Following a general introduction to photogrammetry, the author states that since photogrammetry was brought into service in the Institut für Schiffbau, Restock only a relatively short time ago, described areas of use and possible applications so far recognized or still to be studied are not necessarily all inclusive. Areas of use are classified as:

- a. extending known conventional techniques such as measuring propellers, scale models, etc.,
- b. exploiting new measuring procedures hitherto not possible or at least not economically feasible, and
- c. collecting and processing primary data, such as from a model design, for further use in automated design systems and production processes.

Specific applications mentioned include propeller dimensioning, checking the accuracy of structural parts, dimensioning from models, determination of wave patterns in a model basin, determination of wave patterns about a ship, predicting the fit of adjoining prefabricated sections, mapping of yard and port installations and measuring a ship's form in preparation for repair of collision damage.

¹Although not stated by the author, it is believed this is a tolerance.

B. Design & Planning

1. "Photogrammetry as an Aid to Manufacture of Ship Piping" by W. G. Smith, British Ship Research Association Report NS306, 1971.

When design modeling is utilized it is necessary to extract dimensional information regarding pipe lengths and positions from the model. At present this is accomplished by direct measurement of the model with a rule followed by the preparation of isometric sketches and then the pipe arrangement drawings. Because direct measurement of the model is laborious, often-times inaccurate and the need to prepare the arrangement drawings duplicates the information inherent in the model itself, a simplistic photogrammetric method for extracting the needed information from the model has been developed. Due to inaccuracies in the model itself, differences between the steelwork design and the actual ship and in the photogrammetric measurements, it is still expected that pipe sketches for closing lengths and made-to-place pipe will be required. Nonetheless, it is believed that over 80% of the pipes within a machinery space can be handled by the photogrammetric method. To investigate the practicality of a simple photogrammetric method, a number of photographs were taken of a $\frac{1}{10}$ th scale disc and wire machinery space model of a dredger. Measurements were found accurate to $\pm 3\%$.¹

2. "Photogrammetry Applied to Pipe Systems of Chemical Plant," by R. Ferrand, *Photogrammetric Record*, October 1965.

The design of pipe routes is usually accomplished directly on a scale model which is modular in construction to permit access to central areas. Pipe centerlines and diameters are represented by the wire and disc technique. Ultimately it is necessary to transfer dimensional data inherent in the model to diagrams for the pipe fabricator and the plant erectors. Photogrammetry was seen as a precise method for extracting the necessary information. A particular attraction was that it would eliminate cumbersome manual measurements which oftentimes require reference to columns or a datum which are not readily accessible.

An experiment was conducted to compare the time required, accuracy and completeness of

the manual and photogrammetric methods. It was determined that the photogrammetric method generated more data in (at least) less than one half the time per dimension, without the blunders which oftentimes occurred with manual measurements. The maximum discrepancy at the scale of the actual plant was less than 2 inches by the photogrammetric method. Encouraged by results of initial experiments, a photogrammetric camera system and a stereo plotter which would plot plan and elevation views simultaneously were specially developed for dimensioning from design models. At the time of preparing the article, a project using the new technique had not yet been completed.

3. "Pipe Production Information: A Computer-Aided Method" by B. Dodd and J. B. Jack, British Ship Research Association Report NS396, 1974.

A simplified photogrammetric process is applied to photographs of a wire and disc machinery space model to generate three-dimensional coordinates along the course of each pipe (see article 1 above). These data are stored directly in a mini-computer controlled interactive graphics system which simultaneously displays each digitized pipe in an isometric view. Special programs to generate and display pipe-bending data also reside within the mini-computer.

4. "Using Photogrammetry to Facilitate Planning and Designing Jobs," by Josef Paulus, Jena Review 1975/2. "

When planning new plants or modernizing existing ones dimensioned drawings of machinery are required at the scale of the installation plan. Documentation normally provided by the vendor is oftentimes inadequate for this purpose. Analog photogrammetry was adopted as an efficient and accurate method for generating the necessary drawings. Through the use of extra photographs extreme reaches of moving and removable elements of a machine are also accurately shown on the drawings. It is also suggested that vendors could use the same process to generate such drawings prior to delivery. The possibility of dimensioning from scale models is also mentioned.

C. Erection

1. "Accurate Measurement of Large Ship Structures by Photogrammetry," by J. E. Holliday, J. B. Jack and W. G. Smith, British Ship Research Association Research Report NS 336, 1971.

In an experiment designed to demonstrate the potential usefulness of photogrammetry for analyzing the dimensional equivalence of mating faces of half ships which will be joined afloat, a partially erected midship section of a 135,000-DWT tanker was photographed on its building berth. A horizontal strip of 11 overlapping pictures was obtained at a distance of 12 meters from the section by moving a single camera at specific intervals across special scaffolding erected for the purpose.

To provide control for the photogrammetric solution, the locations of ten chalked crosses on the transverse section were determined through conventional triangulation by observing horizontal and vertical angles to the crosses from the ends of a baseline which was established perpendicular to the centerline plane. To provide detail within the photographs in locations suitable for correlating adjacent overlapping photographs, tennis balls were strung on taut piano wires at predetermined locations relative to the transverse section. Each stereo pair of photographs was set up in a stereo plotter and observed data were ultimately transformed to the "chalk" control points by the semi-analytical process. Offsets and elevations of "hard" points were determined with a tolerance of approximately 0.11 inch. It is estimated that analyses of an entire midship section would require ten days in the shipyard plus another ten days for data reduction.

2. "Dimensional Quality Control of Large Ship Structures by Photogrammetry" by I. Newton, Photogrammetric Record, October 1974.

In a cooperative effort between the University of Newcastle upon Tyne and the Wallsend Research Station of the British Ship Research Association, mating faces of the bow and stem sections of a 258,000-DWT tanker were dimensioned by photogrammetric methods. Tensioned piano wires were strung horizontally and vertically across each mating face so as to mark desired limits of photographic coverage. The camera was operated from a platform

slung from a crane and the platform was maneuvered so that two horizontal strips of overlapping photographs could be secured from a distance of 16 meters of each face. Each strip consisted of 13 photographs. The photographs were taken on rest weekends just prior to launchings of the sections and after the sections had been trimmed using a laser device to define the trim lines. For each transverse section, work in the shipyard was completed in three days.

To provide control for the photogrammetric solution a baseline was established somewhat removed from each transverse section. From the ends of the baseline horizontal and vertical angles were observed to 27 well distributed targets which were fixed to each transverse section by strong magnets or stenciled with paint. In addition, elevations of the ends of the baselines were determined as well as elevations of control point targets along the "molded" edge of the bottom shell.

All stereo pairs were set up in a stereo plotter; approximately 200 detail points on each transverse section were observed. XY coordinates (obtained through the semi-analytical process) of the detail points plus the design coordinates for the same points were plotted on an automatic drafting machine at a scale of 1:100 with differences between the design and photogrammetrically determined coordinates exaggerated by a factor of 10. Plots prepared for the adjoining faces were superimposed to reveal differences between the two sections. The tolerance of determining the detail points is estimated to be 0.47 inch in offset and in elevation.

3. "Close-Range Photogrammetry as an Aid to Measurement of Marine Structures" by Ian Newton, Photogrammetric Engineering, December 1975.

Development of the North Sea oil fields has created an unprecedented demand in Europe for fixed-base offshore platforms. Typical platforms contain some 17,000 tons of steel, are approximately 500 feet high and measure about 295 feet by 245 feet at the base reducing to 130 feet by 115 feet at the deck level. Owing to their size, weight and complexity, fabrication of these structures created a number of problems. One was to devise an efficient and accurate dimensional control system to ensure a fit between components when they are lifted into position during erection. Brown and

Root-Wimpey Highlands Fabricators Ltd. commissioned a feasibility study to investigate the potential usefulness of photogrammetry as a dimensional control system for nodes, sub-assemblies and deck stabbing guides. Subsequent to this study the firm established an in-house photogrammetric capability.

The nodes, up to 50 feet in length, were measured after fabrication to assure that they were within specified dimensional tolerances. Data of interest included radii and roundness of the main tube and all stubs, the direction cosines of all stubs and the lengths of the stubs. Subassemblies were measured to assure that they were within given tolerances for overall size and to allow lineup of pile and conductor guides. In addition to overall dimensions, coordinates of the centers of all pile and conductor guides were determined so that the measured unit could be digitally translated and rotated into its eventual position on the main structure so as to check its fit prior to lifting. Measurement of the relative locations at the deck stabbing guides was performed to determine whether the deck module required adjustment ashore before its fit was attempted at sea.

The remainder of this article describes separate work on dimensioning a bulbous-bow unit and mating faces of a tanker built in halves. This latter work is treated in preceding articles.

D. *Propellers*

1. "Photogrammetric Measurement of a 26-Foot Diameter Propulsion Screw," Final Report Prepared for Aires Marine Shipping Company and Naval Ship Research and Development Center, by DBA Systems, Inc., Melbourne, Florida, January 1975.

After having been in service it was desired to determine the shape of a 26-foot diameter screw. Approximately 120 targets attached to the blades of the screw were triangulated by the fully analytical method using five convergent photographs. Tolerances achieved were about 0.010 inch in each coordinate direction. Several targets on the hub were used to define a plane from which targets on the blades were referenced.

2. "The Use of Industrial Photogrammetry in the Production of Ships Screws" by Gunter Knodler and Helmut Kupke, Jena Review 3/1974.

A photogrammetric technique for measuring raw and finished propellers during the running production process is being developed jointly by VEB Dieselmotorenwerk Rostock, the Restock Institute for Shipbuilding and the Jena Optical Works. The method is first used to determine distortion in and required corrections to the mold. In the second phase photogrammetry is used to generate a digital model of the casting. The digital model is computer compared to the design to determine necessary machining refinements. In the last phase the finished propellers again photogrammetrically measured and computer processed in the same manner as the casting.

3. "A Photogrammetric Method for Measurement of the Thickness of the Cavitation Stratum on a Model of a Ship Propeller, Conducted in one of the Ship Model Tank's Cavitation Tunnels" by Svein Olav Tveitdal, The Norwegian College of Engineering, Institute of Geodesy and Photogrammetry, January 1972.

This thesis work gives complete details on development of a photogrammetric system for measuring the extent and thickness of the cavitation stratum about a model of a propeller. Topics treated include calibration of the camera system (two electric Hasselblad 500 cameras), calibration of the photogrammetric stereo plotter (which was actually used as a comparator), measurement corrections required due to water-glass-air interfaces and photogrammetric calculations.

After experimenting with a dummy specimen photogrammetric measurements were made of a model of a propeller rotating *in* a cavitation tunnel. Prior to inserting the propeller a series of targets were adhered to the propeller blades and the relative locations of the targets were measured with the aid of a three axis milling machine. The two cameras and a strobe unit were mounted outside of the tunnel viewing through a specially inserted plane parallel glass viewing port. Fourteen stereo pairs of photographs corresponding to seven positions of the propeller in each of two cavitation states were subjected to the photogrammetric analysis. Photogrammetric measurements were taken on the targeted points and on the apparent surface of the cavitation stratum. The former points allowed transformation of the in-water data to the free-air condition since the locations of the targets had been previously

measured on the milling machine. Once the mathematical transformation was determined, measurements on the cavitation surface were then transformed to the free-air condition. Differences between these transformed data and the previously determined (by milling machine measurement) shape of a blade gave the thickness of the cavitation stratum. Data were extracted in radial sections through the stratum with an estimated tolerance of determining **stratum thickness of about ± 0.68 mm.**

4. "On Stability and Volume of Marine Propeller Cavitation and Corresponding Spectral Distribution in Hull Pressure Fields" by K. Holden. T. Sontvedt and O. Ofsti, Symposium on High Powered Propulsion of Large Ships (Part 1), Publication No. 490, Netherlands Ship Model Basin, December 1974.

Full scale investigations of propeller cavitation necessitated development of equipment and procedures to detect blade cavity thickness, time variations of blade cavitation, amplitudes of propeller induced pressure fluctuations-stability. phase relationship and spectral distributions, and natural ventilation of cavitation. Cavity thickness distribution is determined by photogrammetric methods and natural ventilation, with a limited amount of air suction, is observed by TV and photogrammetry. Photo and flash equipment were placed in steel tubes welded into the hull of a 224,000-DWT tanker. Photogrammetric analyses were according to the methods developed by Tveitdal as described in article 3 above.

5. "Recent Development of Industrial Photogrammetry in Japan," by Dr. Taichi Oshima, Photogrammetric Engineering and Remote Sensing, March 1976.

In a review of recent engineering applications of photogrammetry, one paragraph briefly describes measurement of the thickness of cavitation bubbles about a model of a propeller. The fully analytical method of photogrammetry was employed.

E. Model Basin

1. "Wave Surface Configuration" by Professor Francis H. Moffitt, Photogrammetric Engineering, February 1968.

A makeshift photogrammetric system employing a pair of synchronized Rolleiflex pictorial cameras was developed to measure

waves produced by a model of a ship in a towing basin. Stereo pairs of photographs corresponding to different towing velocities and water depth conditions were observed in a stereo plotter. For deep water runs the graphic output of the stereo plotter was in the form of profiles along the crests of the bow and stem wakes, with selected cross sections perpendicular to the profiles. For all shallow water runs the stereo plotter was used to contour the wakes in intervals of 0.2 inch relative to the still water level.

2. "A Photogrammetric Space-Time-Problem: Locating of Ship Positions for the Determination of Test Model Properties" by Dr. techn. F. Loschner, Bulletin de la Societe Francaise de Photogrammetrie, No. 41 (in German).

Photogrammetry was used to determine course stability, maneuverability and cruising speed as a function of engine output and rudder position for a large test model built according to a new design. The model was fit with strobe lights so that the tests could be conducted at night with the camera shutters always remaining open. The trajectory of the model was recorded by two cameras as a series of flashes or dots on the photographs. Positions of the dots representing the trajectory were determined with an accuracy of 10 cm.¹ Precise timing of the flashes also allowed a determination of speed.

F. Miscellaneous

1. "Photogrammetric Survey of Trajectory of Launched Ship" by A. Linsenbarth and A. Rymarowicz, Presented to the 1972 Congress of the International Society of Photogrammetry, Ottawa, Canada.

A pair of cameras with shutters synchronized for exposures at intervals of 3 seconds were used to photograph a 26,000-DWT ship as it was launched. Three points on the ship and several stationary control points on the ground were signalized with lights so that successive exposures could be taken on one set of photographic plates. Analog photogrammetric evaluation allowed mapping of the three dimensional trajectory of the ship. Since the time between exposures was known, the speed of the ship at several points was also determined.

2. "The Photogrammetric Measure of the Speed of the Magdala Tanker Towed in the Harbor of Saint-Nazaire," by M. Carbonnelle, Bulletin d'Information de l'I.G.N. No. 7 - October 1968 (in French).

Magdala is the first French tanker in the 200,000-DWT class. To assist alignment during transfer to an outfit berth, a circular pier of about 65 feet in diameter was built approximately 130 feet in front of the berth. This pier was to function as a pivot and was equipped with very powerful shock absorbers. To evaluate the effectiveness of these devices it was necessary to determine the trajectory and speed of the ship just prior to contact, at contact, and just after contact. Velocity data was to be within 1 centimeter/second but absolute positioning of the trajectory of the ship was not as critical.¹ Since conventional surveying techniques did not provide a suitable solution, a photogrammetric scheme was devised. Targets were placed on the hull of the ship and also on land such that all could be seen by two cameras. The camera shutters were synchronized and actuated at precise intervals in time. Fully analytical triangulation of the targets provided information regarding position of the ship. The time interval between successive stereo pairs of photographs allowed determination of velocity as well.

3. "Recent Development of Industrial Photogrammetry in Japan," by Dr. Taichi Oshima, Photogrammetric Engineering and Remote Sensing, March 1976.

This article provides a review of more recent uses of photogrammetry for industrial purposes. Three paragraphs are given to the use of fully analytical photogrammetry, in combination with laser measurements, 35-mm moving pictures and soil pressure measurements for the purpose of monitoring subsidence of the launching ways during the launch of a large tanker. Measurements were performed at the Mitsubishi dock by the Ohbayashi Construction Company.

4. "Instant Draughtsman in the Dockyard," by Angela Croome, New Scientist, August 1972.

Photogrammetry is playing a major role in the five-year plan for refurbishing the external

¹It is not known whether this is a tolerance or one standard deviation.

stem section and redecoration of the cabins within the stem of the warship HMS Victory, Nelson's flagship at the Battle of Trafalgar. Photogrammetrically prepared detailed drawings of the complex stem section and of the cabins are used by the shipwright craftsmen to fashion wood refurbishments.

II. CORRESPONDENCE

1. Letter of 4 April 1975 from Professor Kennert Torlegard, Royal Institute of Technology, Division of Photogrammetry, *Stockholm*, Sweden to John F. Kenefick, Photogrammetric Consultant, Inc.

"... During my time as consulting engineer with VIAK AB, we performed tests with photogrammetric technique in order to, for example:

- check the shape of steel plates for the bulb, bow and stem of ships
- measure ship sections being built in separate wharfs and predict the disclosures in the assembling work
- check the final shape of the hull
- digitizing the shape of wooden car models
- check the dimensions and shape of pre-fabricated housebuilding elements

In many cases the above measuring problem was better solved by other techniques than photogrammetry, due to the time requirements and the wishes of an in-house method."

2. Letter of 2 May 1974 from Dr. Ing. Walter S. Ferri, Officine Galileo, Florence, Italy to John F. Kenefick, Photogrammetric Consultant, Inc.

"The picture sent to you shows an oil tanker on the whole (about 300,000 tons) in a shipyard. We were required for the control of faces A and B of the two contiguous pieces,¹ but the photogrammetric solution has not been found."

3. Letter of 25 February 1975 from Associate Professor Wolfgang Faig, The University of New Brunswick to John F. Kenefick, Photogrammetric Consultant, Inc.

"Unfortunately, your letter of Feb. 17 requesting information on Photogrammetric Applications in the shipbuilding industry arrived about two days too late. Last Thursday, we had a

guest lecturer here at UNB addressing exactly this very problem. Dr. Aleksandra Bukiewicz, professor at the Warsaw Polytechnique is just completing her term as a visiting scientist at the National Research Council in Ottawa. She was a member of a Polish study group working on this problem at the shipyards in Gdansk, Poland. "

4. Verbal discussion at General Dynamics Corporation, Quincy Shipbuilding Division disclosed that the firm Bloms Oppmaling A/S of Oslo, Norway has patented a combined surveying/photogrammetric technique for developing sounding tables for LNG spheres. Volumes are guaranteed to be within 0.1%.²

¹It is believed this is in reference to predicting fit-up between separately-constructed bow and stem sections.

²It is not known whether this is a tolerance or one standard deviation. •

APPENDIX D

SOURCES OF PHOTOGRAMMETRIC SERVICES

Most photogrammetric work relates to aerial mapping which compared to land-based short-range applications is virtually the entire U.S. market for photogrammetric services. Thus, most photogrammetric firms deal primarily with aerial surveying as of March 1976 there were only two known to specialize in short-range work.

While it is true that aerial-survey firms could conceivably work with land-based photography, it is a general rule that most aerial survey firms lack experience in the kind of planning and implementation that is prerequisite for industrial processes. Moreover, these firms may tend to apply equipment and software, designed for aerial use, which may not be suited to shipbuilding. This is not to say that there are no aerial survey firms having experience with land-based projects. Those that are known to have some experience, even though limited, are listed herein.

It is strongly recommended that a shipbuilder seeking photogrammetric services require that each respondent submit the following information for evaluation prior to any subcontract award:

- a. Pertinent recent experience using land based cameras, including description of project, equipment used, method(s) of photogrammetry employed, results achieved (including accuracy tests) and names, addresses and telephone num-

bers of personnel familiar with the work within the customer's organization.

- b. Planned method of operation for the shipbuilder's project, including equipment to be used, method(s) of photogrammetry to be employed, an accuracy analysis which demonstrates that the shipbuilder's tolerances can be achieved, a schedule of performance and identification of all proposed second-tier subcontractors to be employed by the photogrammetric firm.
- c. Discussion of corporate background, most recent financial statement(s) covering 12 months of operation and resumes of key personnel to be specifically assigned to the project.

The shipbuilder must be fairly specific as to data required and its method of presentation. Although, this is oftentimes refined by mutual agreement. Above all, the shipbuilder must be firm on tolerances required of the data and, as already indicated, the photogrammetrist must be able to demonstrate that his methods can produce data which conform to these demands. This is a point of caution. Photogrammetrists have been known to become involved with just finding a solution at the expense of sufficiently accurate results.

On the other hand, the shipbuilder must not overstate requirements as this could lead to a noncompetitive situation. Also, data derived under very rigid specifications may be of no greater practical value than that from realistically stated requirements.

See pages D-2, D-3 and D-4 for service, consulting, and hardware firms.

SERVICE FIRMS¹
circa March 1976

FIRM	SERVICES MARKETED
john f. kenefick Photogrammetric Consultant, Inc. ² P.O. Box 3556 Indialantic, Florida 32903 (305) 723-8515	computer programming fully analytical photogrammetry analog and semi-analytical photogrammetry ³
Henderson Aerial Surveys, Inc. 5125 West Broad Street Columbus, Ohio 43228 (614) 878-3925	analog photogrammetry semi-analytical photogrammetry
Raytheon Company/Autometric 400 Army-Navy Drive Arlington, Virginia 22202 (703) 979-6100	computer programming analog photogrammetry fully analytical photogrammetry
LaFave, Huntley. White and McGivern 850 Hudson Avenue Rochester, New York 14621 (716)467-1010	analog photogrammetry
"DBA Systems, Inc." ⁴ P.O. Drawer 550 Melbourne, Florida 32901 (305) 727-0660	computer programming fully analytical photogrammetry
Ralph L. Woolpert Company 2324 Stanley Avenue Dayton, Ohio 45404 (513) 461-5660	analog photogrammetry semi-analytical photogrammetry

¹This listing includes firms believed to have fairly recent pertinent experiences in the indicated areas. However, in several instances the depth of these experiences is not known and except for the first listed the experiences are not known to be within shipbuilding. Additional information may be solicited from the American Society of Photogrammetry, 105 North Virginia Avenue, Falls Church, Virginia 22046: (703) 534-6617.

²Specializes in and actively seeks out land-based photogrammetric work.

³stereo plotter work is subcontracted.

⁴Specializes in and actively seeks out land-based photogrammetric work.

CONSULTING FIRMS¹

circa March 1976

john f. kenefick
Photogrammetric Consultant, Inc.
P.O. Box 3556
Indialantic, Florida 32903
(305) 723-8515

Donald R. Graff, P.E.
Consultant in Surveying and Mapping
P. O. BOX 311
Beaver Dam, Wisconsin 53916
(414) 885-9191

LaFave, Huntley, White and McGivern
850 Hudson Avenue
Rochester, New York 14621
(716) 467-1010

¹Available on a paid consulting basis and known to have experience with land-based photogrammetry. The first listed has experience in shipbuilding.

HARDWARE MANUFACTURERS

FIRM	PRODUCTS MARKETED
Wild Heerbrugg Instruments, Inc. 465 Smith Street Farmingdale, Long Island, New York 11735 (516) 293-7400	comparators stereo plotters cameras
DBA Systems, Inc. P. O. Drawer 550 Melbourne, Florida 32901 (305) 727-0660	comparators cameras (special order)
Gallileo Corporation of America 150 Fifth Avenue Pelham, New York 10803 (914) 738-1154	comparators stereo plotters cameras
Zena Company P. O. Box 338 South Plainfield, New Jersey 07080 (201) 754-4109	stereo plotters cameras
Kern. Instruments, Inc. 111 Bowman Avenue Port Chester, New York 10573 (914) 939-0200	comparators stereo plotters
O.M. I. Corporation of America 1319 Powhatan Street Alexandria, Virginia 22314 (703) 549-4064	comparators stereo plotters
H. Dell Foster Company P. O. Box 32581 San Antonio, Texas 78216 (800) 531-5355	comparators
Carl Zeiss, Inc. 444 Fifth Avenue New York, New York 10018 (212) 730-4400	comparators stereo plotters cameras
Danko Arlington, Inc. Kelsh Instrument Division 4800 East Wabash Avenue Baltimore, Maryland 21215 (301) 664-8930	cameras (special order)