PHOTOGRAMMETRIC BATHYMETRY

Melvin J. Umbach
Commander, NOAA
and
William D. Harris

Presented to XII Pan American Consultation on Cartography
PAN AMERICAN INSTITUTE OF GEOGRAPHY AND HISTORY
Panama, Panama
1973

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Survey
Rockville, Maryland 20852

ABSTRACT

The National Ocean Survey is using aerial photography and precise stereometric techniques for ocean bottom mapping in the relatively shallow coastal waters of Puerto Rico and the Virgin Islands where offshore hydrographic surveys for nautical charting is currently in progress. The problem of obtaining sufficient vertical control for leveling the individual stereoscopic models is solved by two-media block aerotriangulation and aerial photography optimized with respect to flying height, flight line spacing and photographic overlaps. Peripheral vertical control on the offshore side of the area is provided by selecting underwater control points. Compilation of depth curves and soundings is accomplished with conventional stereoplotters using model datum correction curves to convert readings from apparent to true depths. The results of these field tests of the photogrammetric method are discussed.

SUMARIO

El Reconocimiento Nacional Oceánico está empleando la fotografía aérea y las técnicas estereométricas más precisas para el levantamiento de mapas del fondo de los mares en las partes relativamente poco profundas que rodean a Puerto Rico y las islas Vírgines, donde actualmente se están llevando a cabo reconocimientos hidrográficos para cartas marítimas. El problema de obtener el suficiente control vertical para nivelar los modelos estereoscópicos individuales, se resuelve usando aerotriangulación de doble bloque combinada con fotografia aérea mejorado con respecto a la altura, el espaciamiento de las líneas de vuelo y la superimposición fotográfica. El control vertical periférico en el lado marítimo se obtiene por medio de puntos de control sumarinos seleccionados. La recopilación de las curvas de profundidad y los sondeos es verificando con estereógrafos convencionales, empleando modelos de curvas de corrección de datos para convertir las lecturas de profundidad aparentes a las verdaderas. El trabajo discute los resultados de estas pruebas prácticas del método fotogrametrico.

INTRODUCTION

One of the primary functions of NOAA's National Ocean Survey is the preparation and publication of accurate nautical charts for the safety of marine commerce. Acquisition, analysis, and dissemination of related basic oceanographic and hydrographic data for coastal engineering and scientific research purposes are of equal importance. The advent and expansion of the international fleet of deep draft freighters and super tankers along with the increased activities of pleasure craft, fishing vessels, and submersibles are creating demands for greater accuracies and increased detail on our nautical charts.

Exploitation of submerged lands' natural resources and man's concern with his environment, wetland areas, littoral zones, and flood plains have altered traditional mapping priorities and generated the development of new techniques to meet these new responsibilities.

Classic hydrographic mapping in shoal waters with surface craft is slow, hazardous, and expensive. Sounding lines must be very closely spaced for a complete topographic picture of the ocean floor; and the vessel is frequently required to break sounding lines to investigate and ascertain least depths of shoals, spikes, or other hazards.

Modern color aerial photography, with its remarkable clear-water penetration characteristics and dramatic presentation of submerged detail, provides a basic alternative tool and supplement for mapping the sea bed in shoals and waters of moderate depths. Although photometric and spectral photograph density and color measuring techniques show promise for mapping the general configuration of sandy beach slopes, at present the vertical accuracy requirements for nautical charting can be assured only through the use of precision three-dimensional photogrammetric techniques. While single stereoscopic models can occasionally be oriented for the compilation of depth curves and soundings around small islands or inlets, extensive offshore shoal areas require blocks of overlapping strips of aerial photographs to bridge the zones between vertical control points.

A shoal area off the southern coast of Puerto Rico, where a conventional hydrographic survey was being performed, was also photographed and the ocean floor stereomapped for a systems and accuracy evaluation for potential future use. The details of the photogrammetric method, its application, and comparison of the results of the two surveys are discussed below.

THEORY AND APPLICATION OF UNDERWATER MAPPING

Solution of the two media photogrammetric problem requires several minor departures from the method normally used when the bundle of light rays passes solely through the atmosphere. The effect of refraction at the water-air interface must be taken into account when aerotriangulation is to be performed where a portion or all of the imaged points are underwater. The solution of this problem requires the formulation of the mathematical model for two-media refraction.

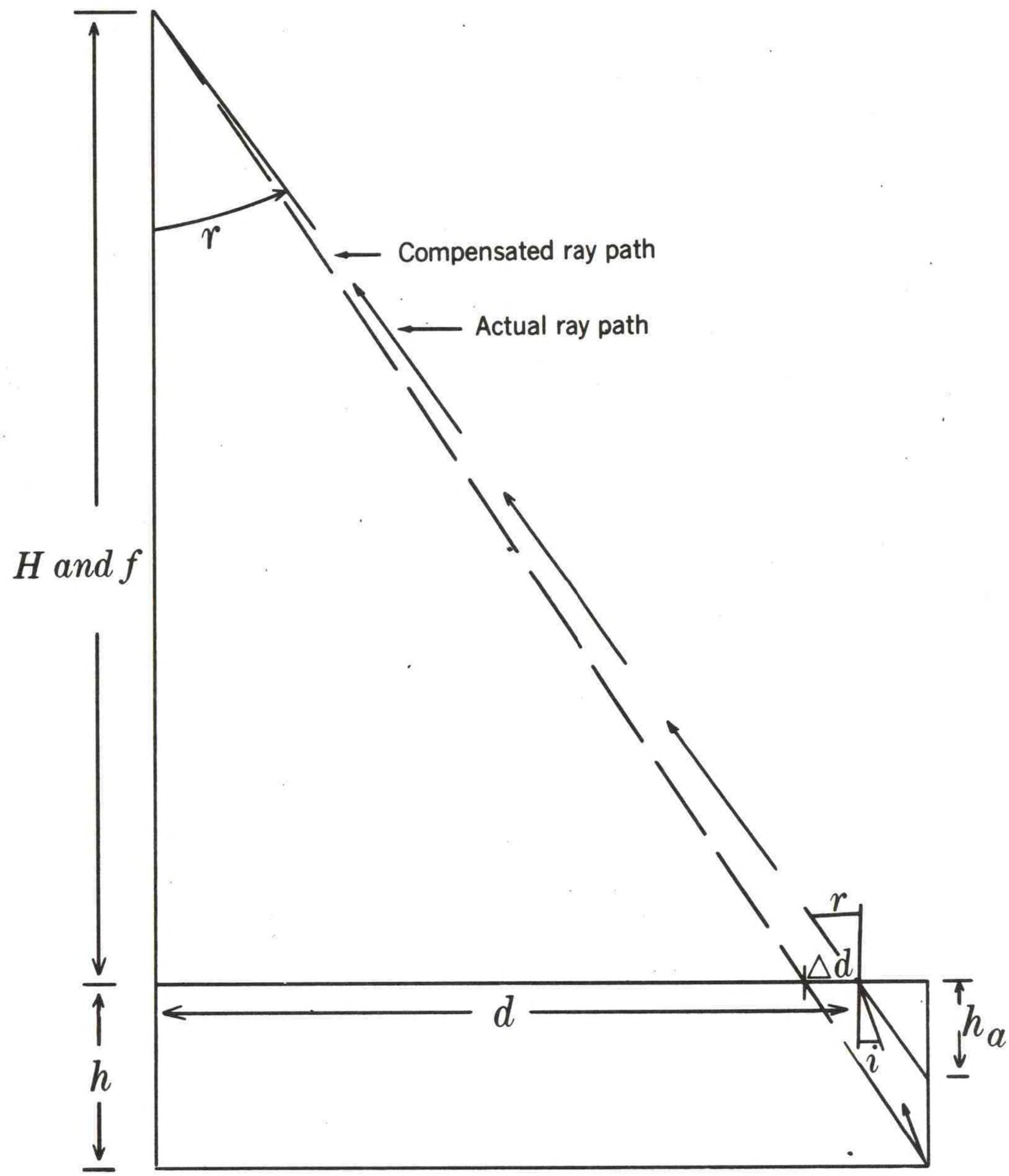
To be theoretically correct and entirely acceptable for photogrammetric triangulation, the mathematical model must be based upon the actual underwater point rather than its refracted, or apparent, position. This is because there is no single apparent object position which will satisfy the condition of collinearity on the several photographs which image each underwater point. This direct formulation of the model has the additional advantage that both elevated and underwater geodetic control points can be treated indiscriminately during aerotriangulation.

The direct method for the treatment of refraction is straight forward for points of known depth which are the vertical control points. Only the index of refraction, nominal flying height, and water depth at the time of photography need be known in order to determine, with sufficient accuracy, the coordinate corrections to be applied to the measured image coordinates on near vertical aerial photography. The uncompensated effects of sea waves are then automatically treated as photograph image coordinate residuals in the analytic aerotriangulation solution. The influence of random wave slopes, periods, and heights on the accuracy of depth measurements has been statistically investigated in-house for the geometric conditions of block aerotriangulation and found to be tolerable for moderately calm seas and aerial photography with approximately seventy percent overlap.

The Mathematical Model

The basic mathematical model for treating the photograph image coordinates for the effect of two-media refraction on underwater points consists of the expression of the radial displacement which is indicated in Figure 1, and can, for vertical photographs, be expressed as:

$$\Delta d = \frac{dh\,(1 - \frac{1}{a})}{H - h} \qquad (1)$$



Radial Image Displacement Due
To Water Surface Refraction

Figure 1

where:

Δd is the required correction, in meters, to be applied to the photograph image. Its sign is always <u>negative</u> or toward the photo center.

d is the radius of the photograph image, in meters, and is equal to $(x^2 + y^2)^{\frac{1}{2}}$.

h is the depth of the underwater point with respect to the surface datum at the time of photography. It is expressed in meters and is always negative in sign.

H is the flying height, in meter, with respect to mean-sea-level.

a is the ratio of tangents of the angles of refraction (r) and incidence (i), from Rinner . It is dependent upon (d), (f), and (n).

$$a = \frac{\tan r}{\tan i} = [n_2^2 + (n^2 - 1) \tan^2 r]^{\frac{1}{2}} \quad (2)$$

where:

n is the index of refraction for rays passing from water into air. Its nominal value is 1.340 for sea water.

f is the camera focal length in meters.

$\tan r$ is the ratio d/f for a vertical photograph.

The apparent depth of an underwater point (h_a) is given by Rinner as:

$$h_a = \frac{h}{a} \quad (3)$$

Equation (2), for n = 1.340 becomes:

$$a = \frac{\tan r}{\tan i} = [1.7956 + (0.7956) \tan^2 r]^{\frac{1}{2}} \quad (4)$$

To obtain the refraction corrected values (x , y) of photo image coordinates (x,y),

$$x^{1} = x \left(1 + \frac{\Delta d}{d}\right)$$

$$y^{1} = y \left(1 + \frac{\Delta d}{d}\right) \qquad (5)$$

Underwater Vertical Control Points

Since the change in the value of (a) and its effect on (d) caused by 1 or 2 degrees of tilt in the aerial photograph is insignificant when the flying height is more than 100 times as great as the water depth, the refraction compensated coordinates of all vertical control points can be determined prior to analytic aerotriangulation using equations (4), (1), and (5). This should be done following coordinate refinement for film and camera distortion and for comparator error.

Underwater Photogrammetric Points

To be theoretically correct, the unknown depth (h) of these points should be solved as an additional unknown in the aerotriangulation process using the mathematical model stated in equation (1) for the simultaneous compensation of two-media refraction. In this way these points of unknown depth would, through an iterative process, be treated for the effects of refraction in the same way that underwater control points are treated. It is the only way that the principal of collinearity used in aerotriangulation can be strictly adhered to without treating the systematic effect of differential refraction as accidental errors in the minimization of image coordinate residuals.

The above approach will be incorporated into our present block solution computer program as a special purpose case in the near future. In the meantime, our present block aerotriangulation program, together with compilation instruments and side computations for converting the mean apparent depths of points to mean true depths, will yield sufficient accuracy for the application of photogrammetry for inshore hydrography. This approximate approach generates error residuals on the plate coordinates of underwater control points that appear unrealistically large. However, the resulting error of water depth determination is less than two percent of the depth when aerotriangulation is performed using 65 to 70 percent photographic overlap both along and between flight lines.

Stereoscopic Compilation

Tewinkel[2] and Meijer[3] have demonstrated that when depth curves and spot depths are to be mapped with a stereoplotter, the apparent depths of model control points, which are the product of the aerotriangulation, should be used for leveling the model just as if there were no water refraction. The true depth of these and all other points within the leveled stereomodel can be obtained by applying the variable depth correction factors as shown in Figure 2. This figure was constructed by applying the Meijer method to 1:15,000 scale photography at 2X model scale with a photographic endlap of 70 percent. Table 1 is an aid for converting depths between true and apparent values. It should be noted that, in the absence of sun spots within the neat model, the entire area can be measured using alternate flight lines. In this case, an improved value for each depth can be obtained by using all flight lines for two independent sets of depth determinations. Mean values of the sets would then be accepted for the final manuscript compilation.

In the event that small-scale, high-altitude bridging photography of certain portions of an area that will be stereomapped does not show sufficient detail to provide control points for at least alternate models of large-scale photography, a secondary analytic aerotriangulation would be required using the low altitude photography. Should extensive areas fall in this category, it is conceivable that the work could be expedited by omitting the setting of each small-scale stereomodel for the determination of the mean true depths of pass points and supplementary vertical control points. The mean true depth of all image points can be computed from the output of the small-scale aerotriangulation. The mean true depth (h_m), which is valid for both sets of photographs, must be determined by the following formula, which involves the determination of the mean value of (a) for each point in the aerotriangulation.

$$h_m = h_a \frac{(\Sigma_{i=1}^{n} a_i)}{n} \qquad (6)$$

where:

h_a is the mean apparent depth of the point as determined in the block aerotriangulation, in meters.

a_i are the individual values of (a), as defined in equation (4), for each photo image of the underwater point.

n is the number of photos on which the point is imaged.

The resulting value (h_m) is then used as (h) for the treatment of these points as underwater control points in an independent block aerotriangulation using the larger scale photography.

TEST AND EVALUATION

To evaluate the accuracy of block aerotriangulation and stereoscopic compilation for underwater mapping and to determine whether or not the metric concessions critically detract from the final product, a full-scale operational test was performed and will be described in this section.

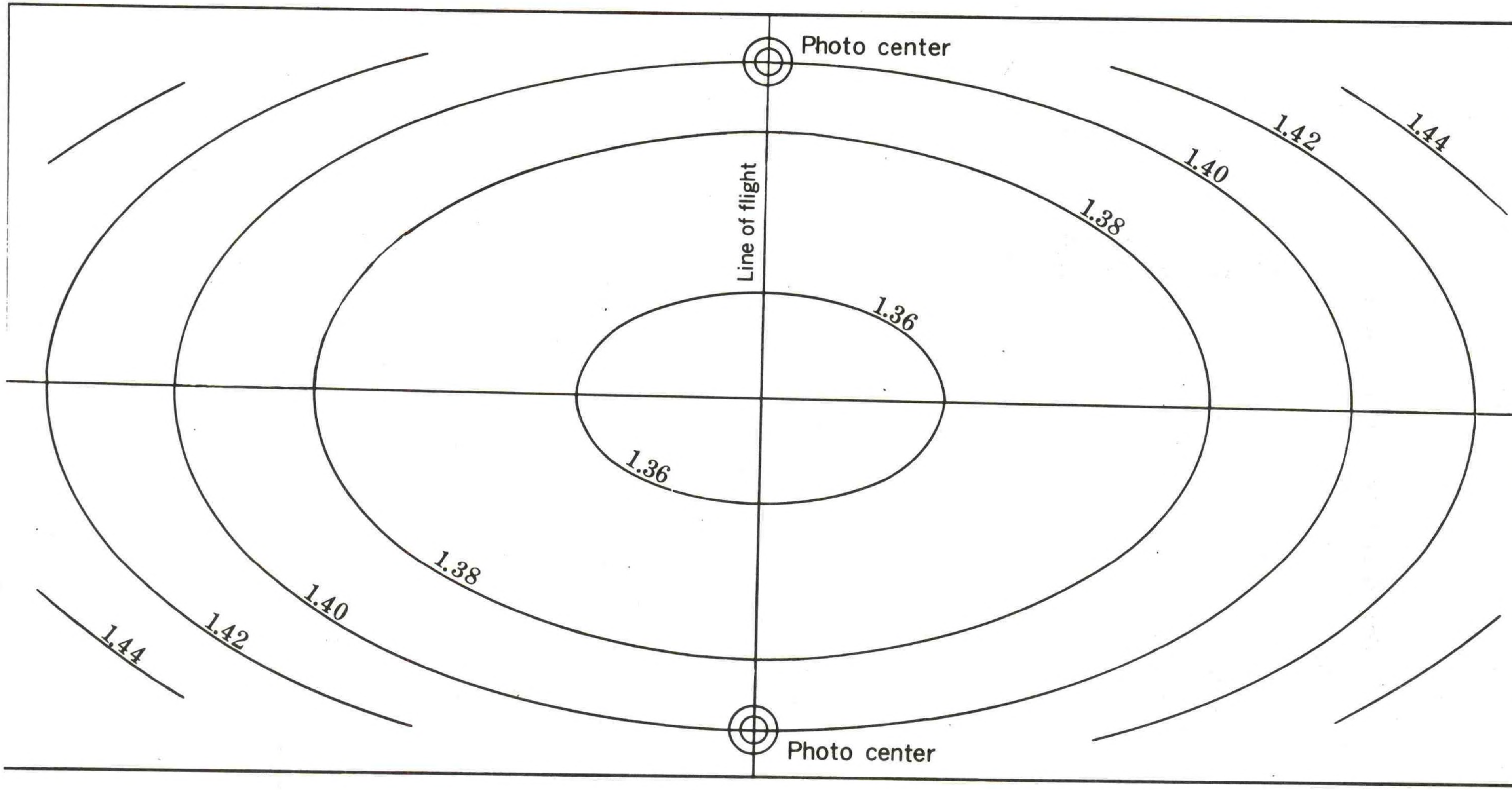
Test Site

A small shoal area off the southern coast of Puerto Rico was selected as the test site due to the clear water and irregular bottom characteristics. Figure 3 shows the general locale of the area. Several other areas in the West Indies would have been preferable, but modern, accurate hydrographic surveys of this area recently completed by National Ocean Survey vessels made it the logical choics for a comparison and a reasonable evaluation of the photogrammetric product.

Flight Planning and Aerial Photography

Figure 4 is a larger scale presentation of the test area that includes the available geodetic control configuration and the actual flight lines consisting of seven strips and forty photographs. The aerial photography was acquired by the National Ocean Survey's De Havilland Buffalo, which is equipped with tandem mounted Wild RC-8 aerial cameras. Color aerial photography for water penetration was taken through a 420 millimicron glass antivignetting filter using reversal type broad-band color positive film to accomodate the wide range of expected spectral transmission found in turbid coastal waters.

The second camera, equipped with a 740 millimicron filter, was used for synchronous infrared photography to arrest



Model of Depth Correction Factors For RC-8 Aerial Photography With 70% Overlap

a. Multiply measured depth by factors to get true depth.

b. Divide depth of contour desired by these factors to get depth setting required.

Figure 2

True Depth (feet)	Depth Correction Factors					
	1.36	1.38	1.40	1.42	1.44	1.46
2	1.5	1.5	1.4	1.4	1.4	1.4
4	3.0	2.9	2.9	2.8	2.8	2.7
6	4.4	4.3	4.3	4.2	4.2	4.1
8	5.9	5.8	5.7	5.6	5.6	5.5
10	7.4	7.3	7.1	7.0	6.9	6.8
12	8.8	8.7	8.6	8.5	8.3	8.2
14	10.3	10.2	10.0	9.9	9.7	9.6
16	11.8	11.6	11.4	11.3	11.1	11.0
18	13.2	13.0	12.9	12.7	12.5	12.3
20	14.7	14.5	14.3	14.1	13.9	13.7
22	16.2	15.9	15.7	15.5	15.3	15.1
24	17.6	17.4	17.1	16.9	16.7	16.4
26	19.1	18.8	18.6	18.3	18.1	17.8
28	20.6	20.3	20.0	19.7	19.4	19.2
30	22.1	21.7	21.4	21.1	20.8	20.5
32	23.5	23.2	22.9	22.5	22.2	21.9
34	25.0	24.6	24.3	23.9	23.6	23.3
36	26.5	25.6	25.7	25.4	25.0	24.7

Table 1. Conversion from True Depth to Apparent Depth

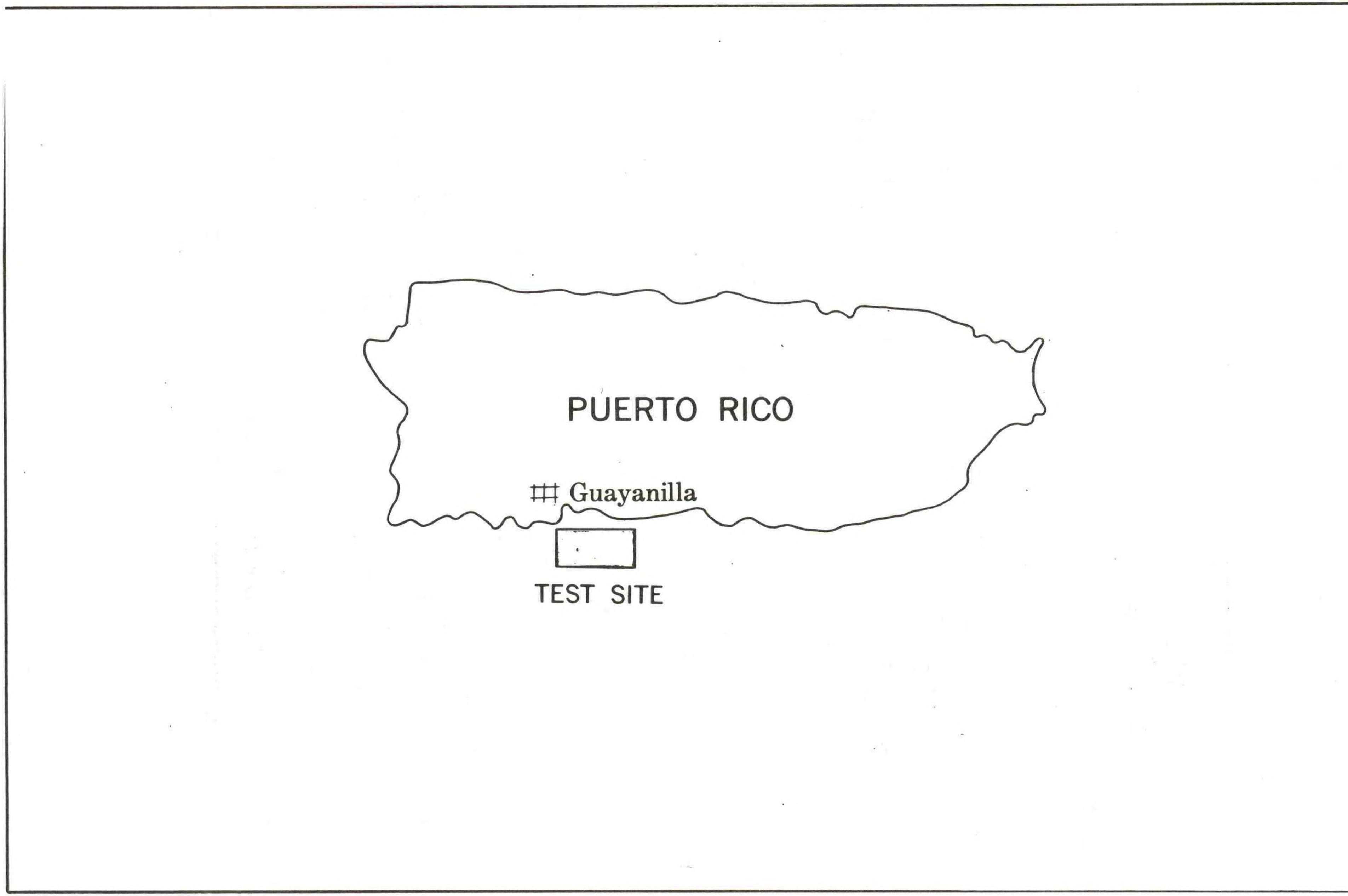


Figure 3

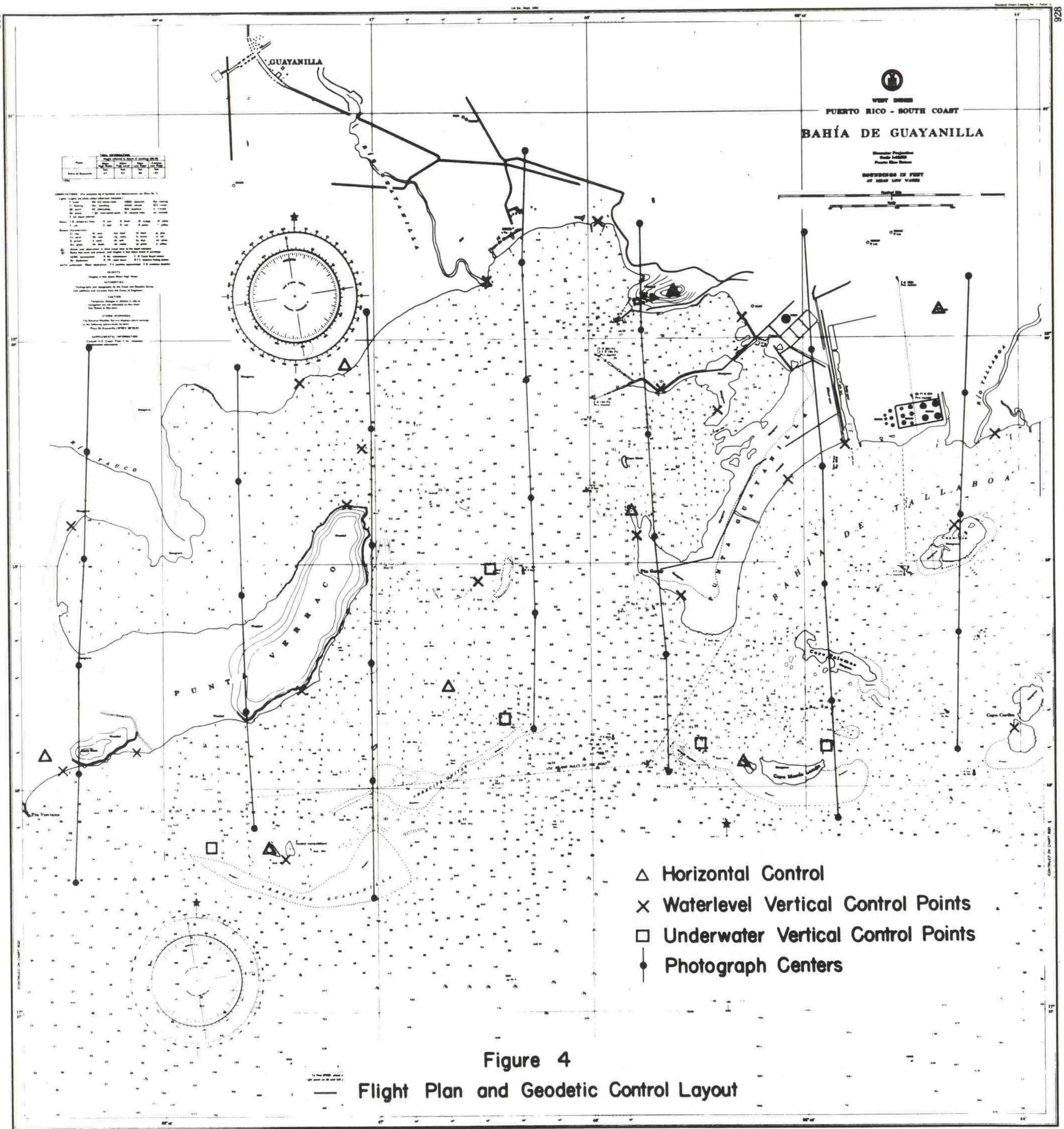


Figure 4
Flight Plan and Geodetic Control Layout

images of the moving surf and delineate the water line at the time of photography. Although acquisition of infrared photography is not absolutely essential, it reduces the vertical control requirements by enabling the stereoscopic transfer of discrete "water level" points along the beach from the infrared to the color photography even in heavy surf.

Expereince gained from previous underwater photography indicates that an optimum photo scale of 1:15,000 from a flight altitude of 7,500 feet be used for the accurate stereomapping of the ocean bed in this particular area. The principal factors involved in the selection of the optimum photographic scale are the spacing of photogrammetric points required to span areas devoid of bottom imagery and the vertical accuracy required in the stereoscopic compilation process.

Photographic endlap and sidelap of approximately 70 percent were specified to optimize the balance of error residuals caused by sea surface roughness and by the effect of a smaller than normal base to height ratio on the geometry of the block aerotriangulation and stereoscopic compilation.

The relatively large overlaps are also essential for the acquisition of complete photographic stereo coverage free free of obscuring sun reflection from the water surface on the southern half of each exposure. To reduce the reflection area as much as possible, aerial photography was prohibited for several hours on either side of local apparent noon. Pre-flight computation of the size and shape of the solar reflection on the aerial photographs is a n necessary part of flight planning over water bodies.

Control and Tidal Datum

Although only four-corner horizontal control stations are normally used for the National Ocean Survey's Block Solution, eight existing stations were premarked and utilized in this test project. The additional control provided the means for a more meaningful accuracy evaluation.

Vertical control was abundant in the areas where the water line was identified through the stereoscopic transfer of points along the entire surf zone from the infrared to the color mapping photography. In order to reference these control points and the ensuing photogrammetrically determined depths to a meaningful and common datum, tidal observations were required during the aerial photography, and for an additional length of time sufficient to determine this reference plane on tide staffs located throughout the area.

Although not applicable during this test case, due to the small tidal range, every effort should be made to acquire the photography during, or very close to, mean low water. Among the advantages, are greater clarity of bottom detail and, since we are involved in low-water line mapping, the acquisition of a single set of photography that can be used for dual purposes. However, this alternative leads to complications in that the tidal datum must be determined prior to photography, and tide observers are required at intervals along the shoreline during photography to inform the flight mission of tide stages via radio communication. Further restrictions are imposed by confining photography to those few times during the year when mean low water occurs during suitable sunlight conditions.

Tidal observations during aerial photography are required to relate measured depths of discrete, identifiable subsurface objects, or underwater target panels, if the block of aerial photography does not include shoreline that can be used as vertical control. The five square symbols in Figure 4 mark the sites of underwater control points used on this test project. Surface floating,vertical control is undesirable because of the false parallax introduced by a combination of horizontal and vertical motion between exposures. In addition, moored panels have a tendency to "propoise", or dive into moving surf and become physically unstable.

DATE PROCESSING AND EVALUATION

Following routine lab film processing, aerotriangulation was performed and underwater contour maps prepared.

Aerotriangulation

The National Ocean Survey "Block Analytical Aerotriangulation Solution" was applied to the aerial photography following the treatment of plate coordinates for displacement due to sea surface refraction as previously described. Technical aspects of block aerotriangulation have been amply documented by Keller and Tewinkel[4], and are sufficiently well known throughout the photogrammetric community that there is no need for describing the system further.

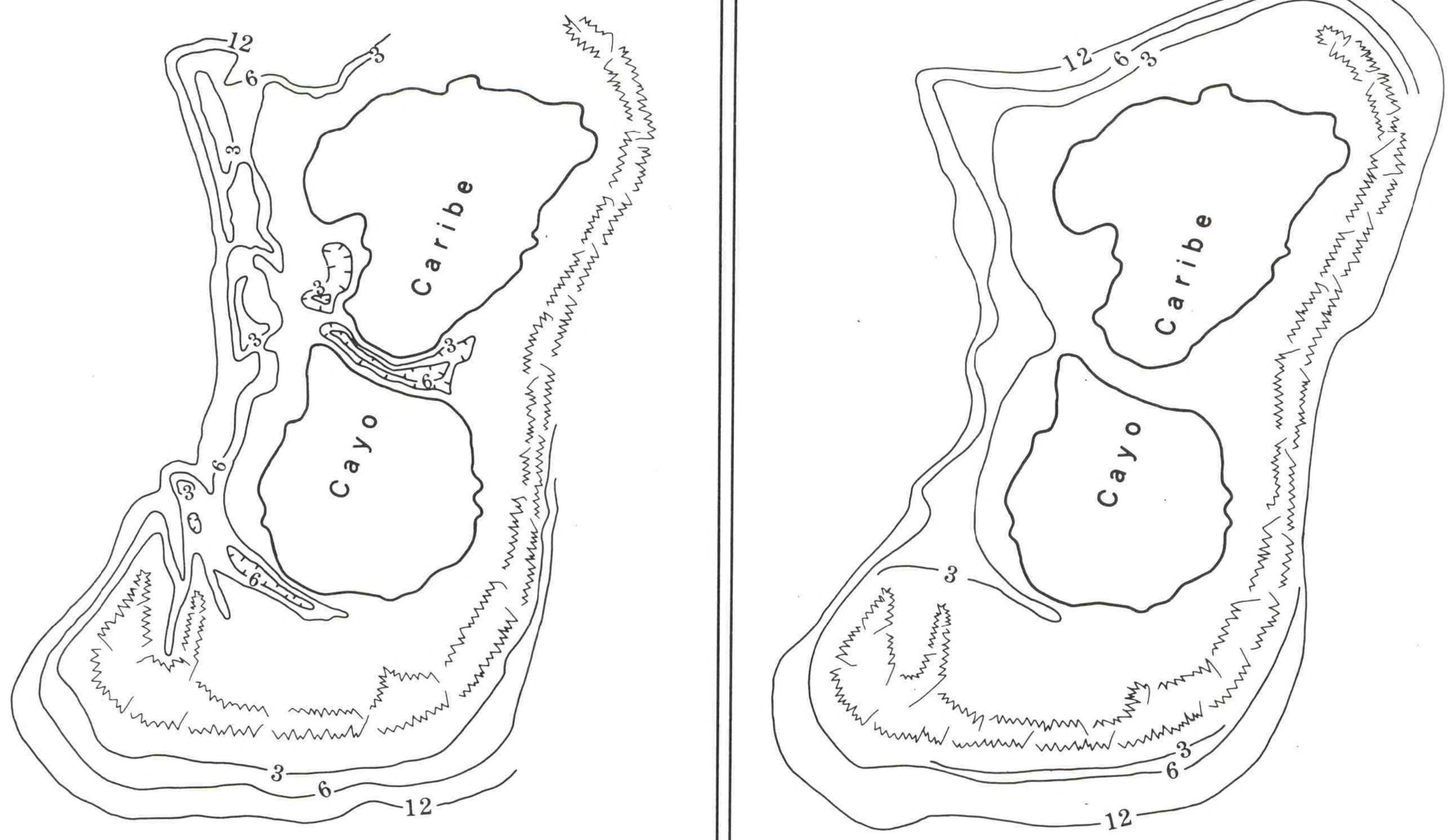
To evaluate the accuracy and validity of this approach, several solutions were made under varying control constraint conditions. Initially, a "free" photogrammetric block aerotriangulation solution was performed. This solution is a unique adjustment to a minimum of horizontal and vertical control that permits no deformation of the photogrammetric geometry. Other control was carried through the solution and solved for as unknowns. All available control was finally appropriately weighted and introduced as a geometric constraint during the second solution. The root mean square errors (RMSE) of the plate residuals for the "free" and constrained control configurations were 8.6 microns and 10.4 microns, respectively.

Routine block solutions over land masses normally yield approximately five microns for the RMSE of plate residuals. This increase in RMSE of plate residuals is attributable to a combination of the enforcement of a single apparent depth for each point, a larger standard error of pointing on underwater objects, and the refractive effects of sea surface roughness. The root mean square error of the differences between photogrammetrically determined depths and the true depths of withheld control in the "free" solution was 0.55 meters, with a maximum difference of 1.4 meters. The RMSE of depth differences resulting from the constrained solution using all available control was 0.18 meters, with a maximum difference of 0.4 meters. These statistics, coupled with detailed studies of residual and depth difference patterns, evidenced the practicability of this approach through this approach through this phase of the project.

Map Compilation

Stereocompilation of bottom topography was accomplished by an experienced photogrammetrist using a Wild B-8 Aviograph Stereoplotter. A properly scale diagram of the refraction compensation curves (refer to Figure 2) was positioned beneath the transparent plotter working surface to provide the instrument operator with the data that enabled him to apply the vertical datum corrections during model compilation. Solar glare and tidal current induced turbidity hampered the operator in several small areas; but this was considered more of an annoyance than a problem. Future aerial photographic missions must be more closely coordinated with tidal current phases when suspended sediments obscuring bottom detail are absent.

Figure 5 shows a side-by-side comparison of the photogrammetrically determined bottom topography with that acquired



DEPTH CURVES BY PHOTOGRAMMETRIC METHODS

DEPTH CURVES BY CONVENTIONAL METHODS

Figure 5

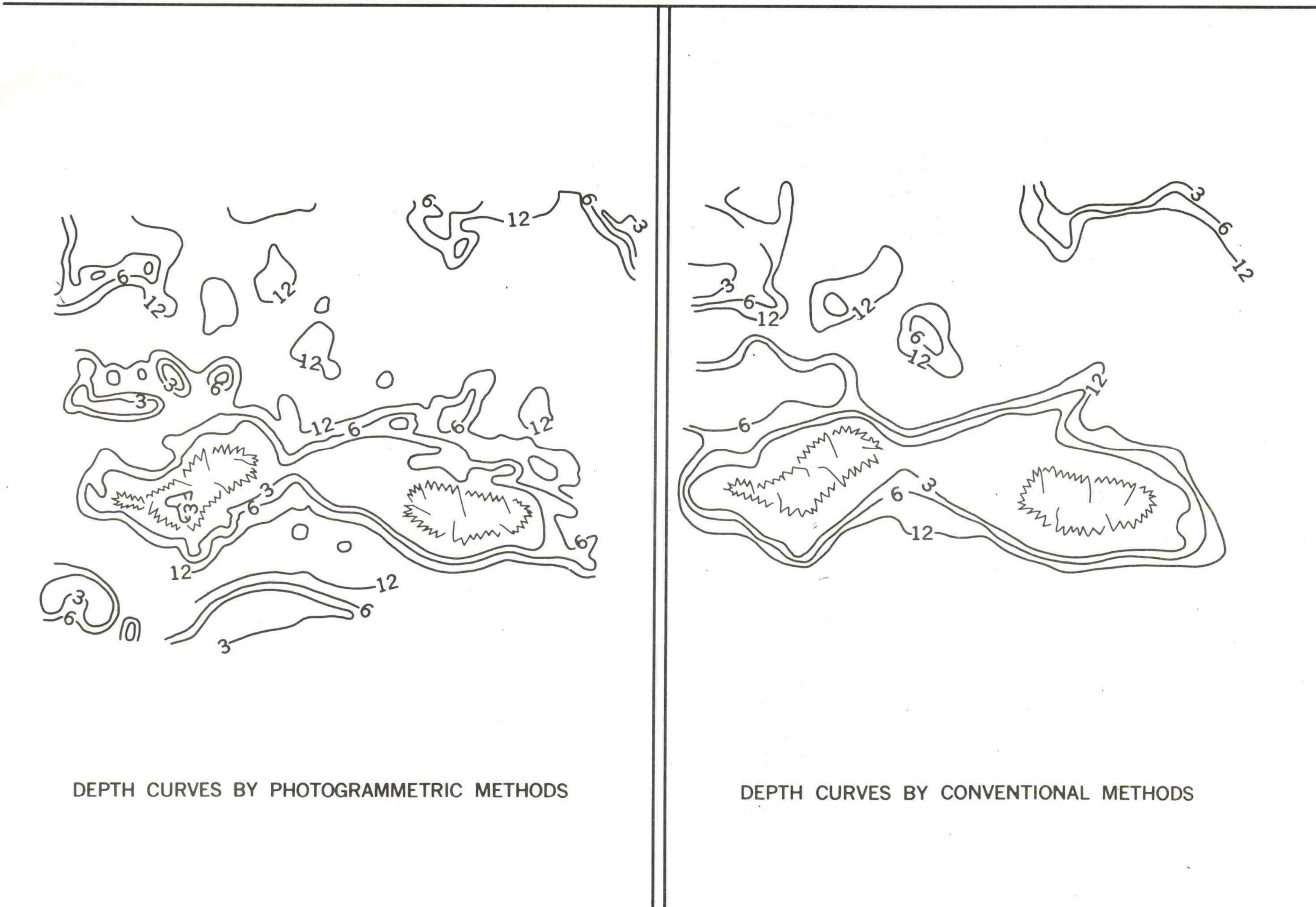

DEPTH CURVES BY PHOTOGRAMMETRIC METHODS
DEPTH CURVES BY CONVENTIONAL METHODS

Figure 6

by standard hyrodgraphic survey methods. A large number of spot soundings and intermediate depth curves were omitted from the figure for clarity and to facilitate comparison. Figure 6 shows another comparison of a typical area within the survey limits.

CONCLUSIONS AND FUTURE PLANS

Accuracies attained on this test by block aerotriangulation, as reflected by plate residuals and ground coordinate deviations, and the good to excellent agreement between depth curves on the two chart manuscripts, have provided solid supportive evidence attesting to the relevance and accuracy of this approach. Although cost comparisons between the two techniques were not documented throughout the processes, there is no question that, of the two, the photogrammetric approach is the more economical.

The National Ocean Survey, based on these encouraging results, is advancing underwater contouring by photogrammetric methods to an operational level this year. The Agency plans to prepare photogrammetric underwater contour manuscripts in clear water areas in advance of hydrographic surveys for spot verification by classical hydrographic field methods.

References

1. Rinner, Dr. Ing. Karl, "Two Media Photogrammetry", Photogrammetric Engineering, Volume 35, No. 3, p. 275.

2. Tewinkel, G. C., "Water Depths from Aerial Photographs", Photogrammetric Engineering, Volume 29, No. 6, p. 1037.

3. Meijer, Dr. W. O. J. Groenveld, "Formula for Conversion of Stereoscopically Observed Apparent Depth of Water to to True Depth", Photogrammetric Engineering, Volume 30, No. 6, p. 1037.

4. Keller, M., and Tewinkel, G. C., "Block Analytic Aerotriangulation", ESSA Technical Report C&GS 35, National Ocean Survey, Rockville, Md. 20852.