Evaluation of an APR System for Photogrammetric Triangulation of Long Flights[*][†]

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ABSTRACT: *The Army Map Service investigated the radar altimeter method of datum control in terms of its value to the Army Map Service in future mapping programs. The test data included three flight lines at altitudes of 20,000 and 30,000 feet over distances of 365 and 675 miles. The radar altimeter was a modified Electronics Associates NBA-2 installed in a B-17-type aircraft. The test area, located in the vicinity of Los Angeles, provided diversified terrain and radar-reflective surfaces, including extreme elevation differences of 8,000 feet. Two methods were used for photogrammetric reduction of the data: one developed by the National Research Council of Canada; the other patterned after normal Army Map Service triangulation instrument procedures. It was concluded that: airborne profile data can be applied to the stereotriangulation of strips up to 215 miles long with an expected vertical RMSE of 10 feet in flat terrain, 20 feet in mountainous terrain; APR data can be improved in mountainous terrain by fitting the radar profile to a photogrammetric model surface; for optimum accuracies the APR flights, adjusted with Henry's formula, should be flown in straight-line patterns with geodetic control at each end.*

TO EXPEDITE mapping in remote areas and to minimize costs, the Army Map Service is continually investigating procedures for the procurement of datum control. One such procedure was brought to the attention of the Army Map Service in 1954 by published results of tests performed by T. J. Blachut of the National Research Council of Ottawa, Canada. The Council tested the use of an Airborne Profile Recorder (APR) system for the procurement of data to control the vertical and horizontal scales of photogrammetric triangulation. During the summer of 1955, the late C. W. Price of the Army Map Service worked at the National Research Council with Blachut and his staff on a test of the APR. The excellent results achieved by Blachut in this test influenced the Army Map Service to investigate the radar-altimeter in terms of its value to the Army Map Service mapping program.

Two primary objectives motivated the test: 1) to provide information regarding the expected accuracies of the radar altimeter system under current Army Map Service mapping conditions; and 2) to determine and develop optimum production techniques and to train key Army Map Service personnel in the application of radar control for photogrammetric aerial triangulation. With these objectives in mind, a study was made to select a test area that would best fit certain restrictive conditions. Generally, the requirements of the test area were that it contain adequate geodetic control; provide beginning, intermediate and ending datum points; provide diversified terrain and radar reflective surfaces; and provide ideal weather conditions throughout for the obtaining of photography.

The selected test area is in Southern California (see Figure 1). It extends from Los Angeles to Searles Lake in the north-south

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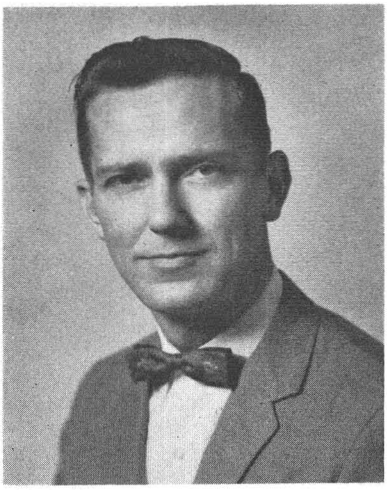
[†] Any mention herein of a commercial product does not constitute endorsement by the United States Government. Nothing herein is to be construed as necessarily coinciding with U. S. Army doctrine. Changes in official doctrine, as they become necessary, will be officially published as such by the Department of the Army.

direction and from the Pacific Ocean to Lake Mead (the site of Hoover Dam) in the east-west direction. This area provides for datum points, the Pacific Ocean at Los Angeles and at Paso Robles, a dry lake-bed at Searles Lake and the water surface of Lake Mead. The terrain varies from sea-level to 8,000 feet, and contains deserts, woodlands, large cities and cultivated areas. Weather conditions suitable for obtaining photography are better than the average in the United States; and previous mapping of the test area resulted in the establishment of an abundance of geodetic ground control.

Three separate flights were planned. *Flight 1*, at a flight altitude of 30,000 feet, started at Los Angeles and extended north to Searles Lake. At Searles Lake the flight line was broken to allow time for film and chart changes before proceeding to the Pacific Ocean at Paso Robles. The entire line covered a distance of 365 miles. *Flight 2*, also at 30,000 feet, started over Paso Robles and extended east to Searles Lake, the turnaround point. From Searles Lake this flight covered the area to and back from Lake Mead. The last leg of this flight was from Searles Lake to Los Angeles. The total length of Flight 2 was 675 miles. *Flight 3* followed the same path and direction as Flight 1; the flight altitude, however, was 20,000 feet.

A contract for the procurement of APR data was let by the Army Map Service on 31 January 1958 as a joint venture of Worldwide Aerial Surveys, Aero Service Corporation and Fairchild Aerial Surveys, Incorporated. The contractors' aircraft and crew arrived at the project site on 24 April 1958. The aircraft, a modified B-17, was equipped with the following:



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A radar-altimeter, Model NBA-2, manufactured by Electronic Associates Limited, with an operating frequency of approximately 2,400 megacycles and modified by the Aero Service Corporation to operate through a range of 30,000 feet.

The clearances were recorded by a Leeds Northrop three-pen recorder at a speed of 12 inches-per-minute on chart paper that covers a range of 1,200 feet in 10-foot increments.

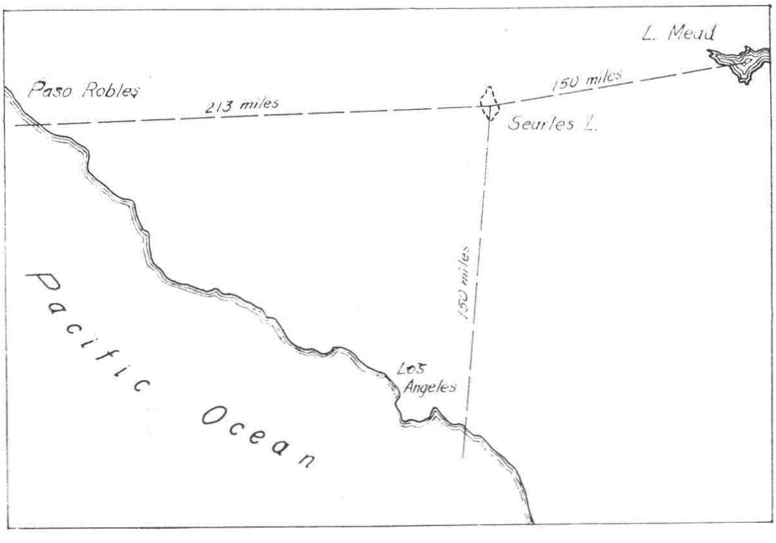


FIG. 1. Flight line layout.

Height deviations were sensed by two instruments: an aneroid-type which was an integral part of the radar-altimeter; and a hypsometer-type, manufactured by Canadian Applied Research Limited. Deviations, as determined by each of these instruments, were recorded on separate charts for later comparison.

A parabolic-type antenna four feet in diameter was mounted rigidly on the aircraft frame. Provisions were made for in-line-of-flight adjustments for attitudinal changes due to the pitch of the aircraft.

The static source was a Pitot-head mounted on a universal joint and specially designed to provide constant orientation into the slipstream. The Pitot-head assembly was mounted on a frame which projected the assembly approximately three feet in front of the leading edge of the aircraft wing.

The positional camera was a 35-mm. film, $\frac{3}{4}$-frame format, movie-type having a 2-inch focal-length and a 400-foot magazine capacity, mounted rigidly to the parabolic antenna. The exposure interval was keyed to the vertical camera and set to provide five positional exposures for each 6-inch exposure. The precise instant of the exposure of the positional camera was recorded by marker pips in the margin of the clearance chart.

The survey camera was a standard KC-1 precision camera which is normally used for mapping operations at the Army Map Service. The camera is equipped with a planigon lens, has a 9″×9″ format and 6″ focal-length.

Drift of the aircraft was measured with a B-3 drift-meter aligned with the longitudinal axis of the aircraft frame. Drift readings were made over pre-determined check points spaced at intervals of approximately 50 miles, and at all significant changes in the speed and the drift of the aircraft.

Several service tests of the equipment were made prior to the procurement of the operational test data to insure its proper functioning at the operational altitudes, and to determine certain calibration constants needed for data reduction.

A service test of the mapping camera and the radar-altimeter equipment was performed over a controlled area. The data from this test were used with the geodetic ground control to check for abnormal distortion in the camera-stereo instrument combination and to determine the delay constants of the radar equipment. Results of this test proved very favorable and the aircraft was taken to the project site.

Six flights at an altitude of 6,000 feet were made over a blimp hangar at various angles of approach to compute the center of illumination of the radar beam relative to the positional-camera axis. On these flights the terrain clearances were recorded on the radar chart and the positional-camera photos were exposed with 60-per cent forward overlap. By using a least squares computation of the measurements of the photo and the object centers on the positional exposures and the radar graph, the two components of displacement were computed. The results from three separate tests of this nature, performed at extended intervals throughout the project, indicated that there was no change in the relationship between the axes of the camera and the antenna. A comparison of the individual flights indicated an average deviation from the computed displacement to be five minutes of arc; in other words, the radar-beam center could be positioned on the 6-inch mapping photography with a probable error of 0.22 mm.

When the final flight was completed and the test materials accepted, data reduction was started immediately. The data reduction was broken into phases because of the enormous amount of materials involved in the test. The first phase involved the determination of the aircraft's drift and the true air speed throughout each flight. Although the drift was measured in flight with a B-3 drift-meter at pre-determined check points, these values were re-defined and extended by using the positional photographs. Crab measurements were made on all positional photographs and were averaged over intervals of approximately 25 miles. The indicated airspeeds were converted mathematically to true airspeeds by using standard formulas and ignoring only the compressibility factor which was judged to be negligible at the aircraft speeds used.

The second phase was the final determination of the flight-line closure. The isobaric surface for each flight was computed with T. J. G. Henry's formula, using the final drift and the true air speed values and the distances scaled from a 1:1,000,000 scale chart. The initial and ending radar clearances were averaged over the water surface and computed tide was applied to each. By initialling to the beginning datum and applying the isobaric surface corrections, the closures were computed and linearly distributed throughout each flight. The clearance for each positional photograph was corrected graphically by the closure and isobaric surface, and the resulting adjusted clearance was used to determine the final raw APR elevation for each point.

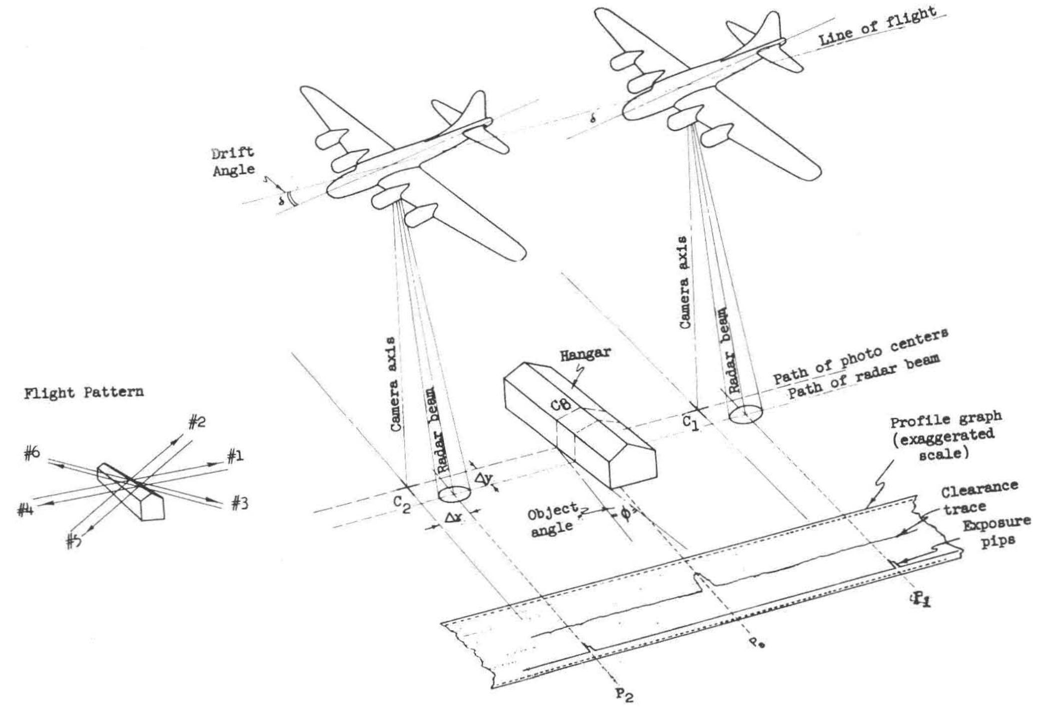


FIG. 2. Positional camera calibration.

The final phase of the data reduction was the transfer of the positions of the radar-beam center from the positional photographs to the mapping photography. This transfer was accomplished by projecting the photographs on a screen; on this the calibration data had been previously plotted. The points were then transferred by photo identification.

The photogrammetric instrument triangulation was accomplished by using two different methods. The first method, developed by Blachut, consists, in general, of absolutely orienting the first model of the strip to be triangulated to known geodetic control. The photogrammetric extension is carried forward by introducing the known B_z of the second exposure and orienting the model relatively using the ϕ corrections to the first camera station. Each model is independently scaled to one APR elevation and a recording is made of all orientation elements of the plates and the model. Each model of the bridged strip then is adjusted by smoothing a graphical presentation of the model surfaces which have been computed from the recorded $\Delta\phi$'s and datum differences. Although this method is considered to be very good technically, and will provide control of a strip of infinite length for both vertical and horizontal, it was not used on all flights of this test for several reasons. The first and most important of these is the necessity that data be provided to the first-order-instrument operator before the bridging operation can be started. In an organization as large as the Army Map Service, it is desirable from a production standpoint to keep separate such operations as data reduction and instrument triangulation. The second reason for not pursuing this method further was the requirement that the operator make pre-determined settings on the instrument and record the orientation elements. Again, considering the great amount of triangulation accomplished at the Army Map Service, this requirement would increase the probability of undetected errors.

The second instrument method was similar to the one normally used at the Army Map Service on production assignments. Here the first model is oriented relatively and "set" to an approximate scale as determined by the flying height and mean terrain elevation of the photography. This model then is tipped-up to accommodate the expected fall-off of the strip in Z, and each successive exposure is relatively and absolutely oriented to the previous one until the end of the strip is reached. An independent surface of models at

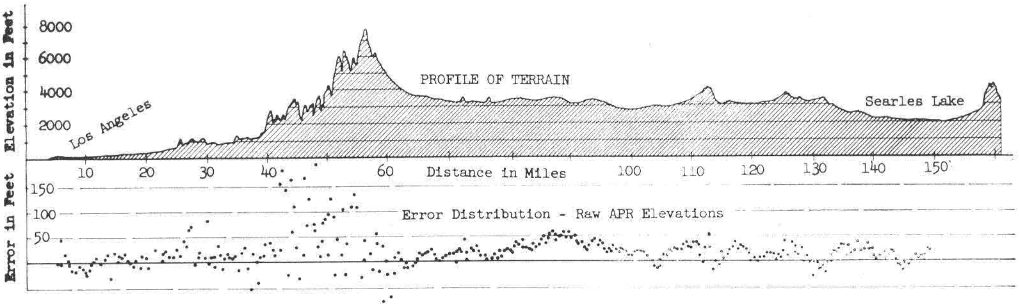


FIG. 3

arbitrary scales results. In the adjustment process this surface is adjusted mathematically to fit a series of geodetic points. To provide a visual presentation of the APR elevation errors, however, the strips on this particular test were adjusted graphically. The graphical adjustment was determined by plotting the elevation differences between the converted instrument values and the ground elevations and from these data plotting tip and tilt curves which represent the best fit to the control. From this correction the true elevations of all the 35-mm. points were determined on all strips. Based on empirical data, these elevations are assumed to be accurate to ±10 feet. The adjusted raw APR elevations were checked for accuracy by comparing them to the photogrammetrically determined elevations for all the 35-mm positioning points one. such comparison is shown on Figure 3.

At the upper part of Figure 3 is a reduction of the actual profile recorded on Flight 3. Directly below is the distribution of the errors of each 35-mm. point along the profile. It can be seen readily that the recorded profile is much less reliable in mountainous terrain. The mean error in elevation of all points along this portion of Flight 3 was 22.1 feet. A similar evaluation of all flights indicated that the APR is capable of recording the ground profile with an average error of 12.4 feet over extremely long flights, averaging 17.3 feet in mountainous terrain and 10.3 in flat terrain.

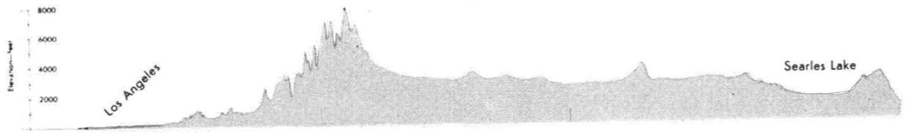
To determine the accuracy of stereo-triangulation based on APR elevations, the strips were adjusted a second time using the raw APR values only. Because the APR points fall in or near the center of the flight, the strips were adjusted in the tip direction only with no regard to tilt. The accuracy of the resulting elevations was determined by comparing each positioning-point elevation from the adjustment of the strip to APR values to the elevations of the same points as determined from geodetic ground control.

Figure 4 depicts the errors on all three flights for the north-south leg from Los Angeles to Searles Lake. It can be seen that the large random errors of APR in mountainous terrain have the effect of decreasing the final accuracy of adjustment, since the tip curve upon which the adjustment is based is much less defined.

Figure 5 shows the errors on all three flights for the east-west leg from Searles Lake to Paso Robles. On this leg the terrain is more mountainous than on the previous leg; this fact is reflected in the final accuracies. In addition, it will be noted that the west end of the flight went abruptly from mountainous terrain to sea level, introducing another undesirable feature in terms of adjustment. This situation caused that portion of the adjustment curve to be held mainly to one reading of a coast line supplemented by APR points with large random error.

Figure 6 records the errors for the two legs of Flight 2 from Searles Lake to Lake Mead. Here the terrain contains a good distribution of relatively flat areas, and the resulting accuracies are extremely good. In summary, the combined results of all flights indicate that APR can be used with photogrammetric triangulation with an RSME of approximately 20 feet in mountainous terrain and 10 feet in relatively flat terrain.

The accuracies shown in Figure 6 reflect the results that are obtainable by using certain refining techniques. One of those techniques is quite important when one is using APR in mountainous terrain. On Figure 3 it was noted that the random error in the mountains can become quite large for arbitrary points such as positioning-camera exposure centers. If the mountains extend over any long distance on the flight line, a less reliable correc-



Flight No. 1—30,000 feet

m_z = 9.2 feet

Flight No. 2—30,000 feet

m_z = 10.3 feet

Flight No. 3—20,000 feet

m_z = 19.9 feet

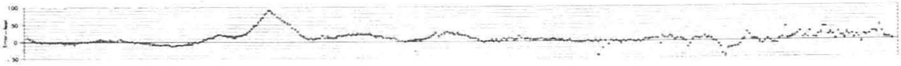
FIG. 4. Final error distribution—Los Angeles to Searles Lake.

Flight No. 1—30,000 feet

m_z = 14.2 feet

Flight No. 2—30,000 feet

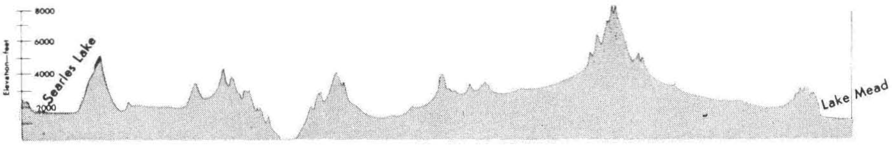
m_z = 19.8 feet



Flight No. 3—20,000 feet

m_z = 23.8 feet

FIG. 5. Final error distribution—Searles Lake to Paso Robles.



Flight No. 2—30,000 feet

$m_z = 11.3$ feet

Flight No. 2—30,000 feet

$m_z = 10.5$ feet

FIG. 6. Final error distribution—Searles Lake to Lake Mead.

tion curve results. To resolve this problem, the Army Map Service developed a method whereby the curve was related to a profile through the model or, in other words, an infinite number of points. Generally this consisted of nothing more than drawing the profile of the model surface on the stereoplanigraph at maximum vertical exaggeration through the positioning points, which recorded the ground path of the radar-beam. After making scale adjustments by using the positioning points, the elevations of the prominent features on the instrument profile were determined by visually fitting them to the radar recorded profile. Residual errors in scale were compensated by using an equal number of high and low points on the profile surface.

The validity of this method was proven by the resulting improvement in the accuracy of the strip in those areas where it was used, and by decreasing the randomness of the points relative to the correction graph.

One other important conclusion was drawn from the results of this test. This is, for optimum accuracies APR flights should be planned in straight-line patterns with datum control at both ends. As shown in Figure 1, the flights on this test were planned in an L-shaped pattern. By indexing the APR to sea level at the ends only, a datum error of 31 feet was encountered at Searles Lake in the center of the Flight-line 1. This error was attributed to the random error in the determination of the isobaric surface which had different degrees and directions of slope with the change in flight direction at Searles Lake. Normally, a straight-line flight will involve non-linear slopes, but the direction will remain unchanged and the random error in datum is minimized when the flight is adjusted linearly to control at either end.

The results of this test and the descriptions of the methods used are general and confined to only the most important. The complete report on this test may be available at the Army Map Service by the time this paper is published.