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SHIRAN Flight Test Program

SHIRAN is a micro-wave, phase-measuring, distance-determining system that enables the evaluation of the slant ranges from an airplane to four transponders located at ground control sites. Also applied is a terrain profile recorder that indicates the airplane's height.

Abstract: *During the summer of 1963 Aero Service Corporation, a division of Litton Industries, conducted a program for flight test and evaluation of Cubic Corporation's SHIRAN DME System. The flight test operation, trilateration, and network adjustments result in probable errors less than ten feet over distances ranging from 95 to nearly 500 miles. Supplementary subjects studied during the tests included investigation of constant errors, overwater tests, repeatability tests, and two-crossing vs. twelve-crossing measurements.*

Introduction

The development of the SHIRAN first order geodetic survey system was funded and directed by the Directorate of Reconnaissance Engineering, Research and Technology Division, Wright-Patterson AFB, Ohio, to provide a highly accurate range measuring system to implement future world-wide aerial electronic surveying and photo-mapping programs. Michael J. Pappas was program manager for the Government. ASD Technical Documentary Report ASD-TDR-62-872 entitled "SHIRAN Phase I System Analysis and Preliminary Design" describes in detail the technical aspects and operating principles of the SHIRAN equipment. SHIRAN, a micro-wave CW-phase measuring concept, performs the basic HIRAN function with greater efficiency and accuracy and has the additional capability of simultaneously measuring slant ranges to four ground stations. By integrating the TPR (Terrain Profile Recorder) for establishing height and the ML313/AM airborne psychrometer for the determination of refraction corrections, the following mission accuracies were specified for the SHIRAN system:

Electronic Surveying; The probable error of a single observed distance between two ground stations shall be 0.0017 n. miles.

Controlled Photography: Positioning of nadir points within 24 feet as referred to the ground stations from which they were established. This accuracy shall apply to 90 per cent of the measurements.

Secondary Control Point: Accuracies as specified above shall apply.

Program

The SHIRAN flight test program was conducted between 24 July and 6 November 1963. The base of operations was Litchfield Park Naval Air Facility, near Phoenix, Arizona. The test program was conducted over an area extending from the southern part of Arizona to central Nevada. An overwater multi-altitude line crossing off the California coast was included to test and evaluate the effect of multi-path propagation on the SHIRAN system.

The Arizona-Nevada trilateration network consisted of six ground stations set up over United States Coast and Geodetic Survey monuments which permitted the measurement of 15 lines varying greatly in length. (See Figure 1.) The operational and computational procedures were patterned after those developed by the Air Force HIRAN mapping groups. The photo test area, in the vicinity of Phoenix, extended approximately 34 miles north and south by 30 miles east and west. Ground stations Gentry, Catalina, Ajo, and Quartz, in the trilateration network, were used for the controlled photography.

The overwater Point Loma-Gaviota line crossings were accomplished in August. The line-crossing missions (using the HIRAN

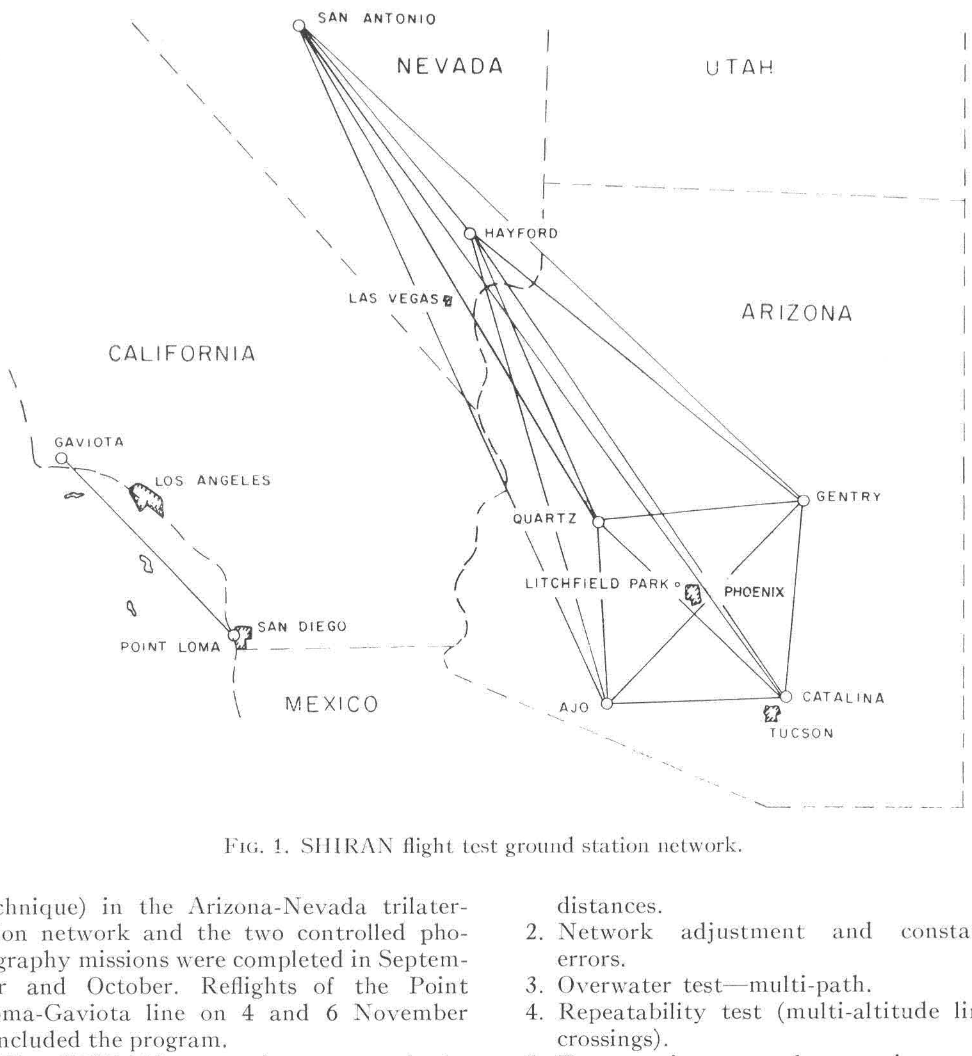

FIG. 1. SHIRAN flight test ground station network.

technique) in the Arizona-Nevada trilateration network and the two controlled photography missions were completed in September and October. Reflights of the Point Loma-Gaviota line on 4 and 6 November concluded the program.

The SHIRAN magnetic tapes and the meteorological data were flown to San Diego daily following test flights. The tapes were programmed immediately for the CDC 1604 computer of the University of California at San Diego. SHIRAN internal consistencies were evaluated and preliminary comparison was made with computed USC & GS geodetic distances. The results were telephoned to Phoenix the following morning, thus providing information for programming the succeeding tests.

The accuracy of the SHIRAN system in performing line measurements over land and water and at varying altitudes was evaluated, and comprehensive analyses of various network adjustments were made. The evaluation was divided into the following:

1. Comparison of SHIRAN and geodetic distances.
2. Network adjustment and constant errors.
3. Overwater test—multi-path.
4. Repeatability test (multi-altitude line crossings).
5. Two crossing vs twelve crossing measurements.
6. Controlled photography.
7. Secondary control point (SCP) photography.

The results and evaluations pertinent to Items 6 and 7 were not included in this paper because of limited space.

COMPARISON OF SHIRAN AND GEODETIC DISTANCES

Prior to the adjustment of the trilateration network, the twelve measurements of each line were averaged and evaluated for internal consistency. The mean SHIRAN reduced value for each line was then compared with the computed inverse distance based on the

TABLE 1

SHIRAN-GEODETIC DISTANCE COMPARISONS

Line	SHIRAN (*n. miles*)	*Geodetic* (*n. miles*)	*S-G*$\times 10^4$ (*n. miles*)
Cat-Gentry	111.3648	111.3673	−25
Ajo-Gentry	159.6634	159.6643	− 9
Ajo-Cat	104.6148	104.6172	−24
Quartz-Gentry	113.0140	113.0154	−14
Quartz-Cat	139.8666	139.8689	−23
Quartz-Ajo	95.9722	95.9754	−32
Hayford-Gentry	261.2550	261.2564	−14
Hayford-Cat	333.9010	333.9027	−17
Hayford-Ajo	284.6983	284.6971	+ 8
Hayford-Quartz	197.9326	197.9332	− 6
Antonio-Gentry	397.2113	397.2118	− 5
Antonio-Cat	472.7701	472.7712	−11
Antonio-Ajo	418.4664	418.4659	+ 5
Antonio-Quartz	335.8142	335.8151	− 9
Antonio-Hayford	138.9145	138.9171	−26

$PE_s = 0.6745\sqrt{\frac{\Sigma_x{}^2}{N}} = \pm 0.0012$ n. miles Mean −13

TABLE 2

FREE ADJUSTMENT RESULTS

Line	*Residual*$\times 10^4$ (*n. miles*)
Cat-Gentry	+ 6
Ajo-Gentry	−12
Ajo-Cat	+ 4
Quartz-Gentry	+10
Quartz-Cat	+ 4
Quartz-Ajo	+19
Hayford-Gentry	+ 5
Hayford-Cat	+ 2
Hayford-Ajo	− 4
Hayford-Quartz	+16
Antonio-Gentry	− 7
Antonio-Cat	−12
Antonio-Quartz	+ 8
Antonio-Hayford	+18
Antonio-Ajo	− 8

$PE_s = \pm 0.011$ n. mile

ground survey positions. These comparisons are shown in Table 1.

The PE_s of ± 0.0012 n. miles was well within the specification of ± 0.0017 n. miles. An analysis of the signs of the errors suggested the existence of a possible constant or systematic error in the SHIRAN range measurements or computed inverses. This possibility is discussed in the section on trilateration adjustments.

NETWORK ADJUSTMENTS AND CONSTANT ERROR

The trilateration network was designed to yield optimum information on SHIRAN distance measuring consistency. Four sliver triangles were incorporated in the network to assist in providing a strong determination of any constant error. The sliver triangles involved nine of the 15 lines in the network, and included the four approximately colinear stations: Cat, Quartz, Hayford, and Antonio.

Depending on the constraints included in the network, adjustment information was obtained in specific areas of investigation. The free adjustment technique involved a minimum of constraints and provided information on the internal consistency of SHIRAN measurements. In the basic free adjustment employed, two coordinates of one station and only one coordinate of a second station were held fixed. Eight free adjustments were made with these constraints holding various combinations of coordinates fixed. The results given in Table 2 of these basic free adjustments were identical in every case—i.e., they compared within 0.0001 n. miles, no matter which station was held fixed. The maximum residual was 0.0019 n. miles, and the probable error of a single observation was ± 0.0011 n. mile.

In a second series of adjustments, the terminal points of a line and the included base length were held fixed. This adjustment technique was repeated for each line in the network. Selected results for this series of adjustments are shown in Table 3. In no case was the PE_s greater than 0.0015 n. mile, and the average PE_s was 0.0012 n. mile.

In a second series of adjustments the terminal points of a line and the included base length were held fixed. This adjustment technique was repeated for each line of the network. In no case was the PE_s for a base line adjustment larger than 0.0015 n. miles and the average PE_s was 0.0012 n. miles. The results for six of the 15 base lines are given in Table 3. The base line adjustments, as in the case of "free" adjustments, improved upon the specified accuracy requirement of ± 0.0017 n. miles for the PE_s.

INVESTIGATION OF CONSTANT ERROR

The possibility of a constant error was explored by repeating the base line adjustments with the inclusion of a K-factor. Selected results for these adjustments are given in Table 4. The magnitude of the K-value as determined by these adjustments was 0.0016 n. mile. This agrees closely with the mean

TABLE 3

NETWORK ADJUSTMENTS HOLDING TWO STATIONS FIXED

Code Nos.: (1) Gentry L. O. Tower (2) Catalina 2 Reset (3) Ajo (4) Quartz (5) Hayford (6) San Antonio

Residual = $V \times 10^4$ *n. miles*

Line	*Stations Fixed*					
	1–3	*1–4*	*2–5*	*2–6*	*3–4*	*3–6*
Cat-Gentry	+13	+ 5	+12	+15	+ 5	+ 5
Ajo-Gentry	fixed	−11	−16	−17	− 8	−12
Ajo-Cat	+11	+ 4	+ 7	+ 9	+ 4	+ 3
Quartz-Gentry	+15	fixed	+ 7	+ 6	+ 4	+10
Quartz-Cat	− 1	+ 5	+12	+17	+ 5	+ 4
Quartz-Ajo	+25	+18	+18	+18	fixed	+20
Hayford-Gentry	+ 6	+ 5	+11	+ 4	+ 7	+ 5
Hayford-Cat	− 1	+ 1	fixed	+15	+ 1	+ 2
Hayford-Ajo	− 3	− 4	0	− 6	0	− 4
Hayford-Quartz	+17	+15	+22	+15	+11	+15
Antonio-Gentry	− 6	− 7	− 7	+ 3	− 5	− 8
Antonio-Cat	−15	−13	− 4	fixed	−13	−12
Antonio-Ajo	− 7	− 7	− 9	− 1	− 4	fixed
Antonio-Quartz	+10	+ 8	+ 8	+18	+ 4	+ 9
Antonio-Hayford	+19	+18	+12	+28	+18	+19
Mean	+ 6	+ 2	+ 4	+ 9	+ 2	+ 4
PE_s	±13	±10	±12	±15	± 8	±11

TABLE 4

NETWORK ADJUSTMENTS: SOLUTIONS FOR *K* HOLDING TWO STATIONS FIXED

Code Nos.: (1) Gentry L. O. Tower (2) Catalina 2 Reset (3) Ajo (4) Quartz (5) Hayford (6) San Antonio

Residual = $V \times 10^4$ *n. miles*

Line	*Stations Fixed*					
	1–4	*3–6*	*2–5*	*2–6*	*3–4*	*3–1*
Cat-Gentry	+ 1	+ 3	0	0	+ 2	− 8
Ajo-Gentry	− 8	− 6	− 6	− 5	− 6	fixed
Ajo-Cat	+ 2	+ 3	+ 1	0	+ 1	− 7
Quartz-Gentry	fixed	+ 5	+ 8	+ 7	+ 5	+ 4
Quartz-Cat	− 2	− 1	− 2	− 2	+ 1	+ 4
Quartz-Ajo	+15	+ 9	+12	+12	fixed	+ 9
Hayford-Gentry	0	− 2	0	0	+ 2	− 2
Hayford-Cat	+ 4	+ 4	fixed	+ 2	+ 3	+ 7
Hayford-Ajo	− 4	− 6	− 4	− 3	− 2	− 6
Hayford-Quartz	+ 8	+ 9	+ 7	+ 7	+ 7	+ 8
Antonio-Gentry	− 5	+ 1	− 4	− 5	− 4	− 6
Antonio-Cat	− 4	− 7	− 6	fixed	− 6	− 1
Antonio-Ajo	− 6	fixed	− 5	− 5	− 4	− 7
Antonio-Quartz	+ 6	− 1	+ 5	+ 3	+ 4	+ 5
Antonio-Hayford	+ 9	+ 6	+10	+ 6	+10	+ 7
PE_s	± 7	± 6	± 7	± 6	± 5	± 7
K	+16	+16	+16	+17	+13	+18
PE_k	± 5	± 3	± 3	± 2	± 4	± 3

TABLE 5

NETWORK ADJUSTMENTS: SOLUTIONS FOR K HOLDING THREE STATIONS FIXED

Code Nos.: (1) Gentry L. O. Tower (2) Catalina 2 Reset (3) Ajo (4) Quartz (5) Hayford (6) San Antonio

Residual = $V \times 10^4$ *n. miles*

Line	*Stations Fixed*					
	2-4-5	*2-3-4*	*1-5-6*	*1-3-6*	*3-5-6*	*3-4-6*
Cat-Gentry	+10	+ 6	+ 3	+ 6	+ 6	+ 5
Ajo-Gentry	−12	fixed	− 9	fixed	−10	− 6
Ajo-Cat	+ 2	+ 6	+ 2	+ 6	+ 5	+ 4
Quartz-Gentry	+ 5	fixed	+ 9	+ 7	+ 6	+ 2
Quartz-Cat	fixed	0	+ 1	− 1	+ 1	+ 1
Quartz-Ajo	+25	fixed	+16	+12	+11	fixed
Hayford-Gentry	+10	+ 4	fixed	− 1	+ 4	+ 3
Hayford-Cat	fixed	+ 2	+ 1	+ 3	−10	+ 3
Hayford-Ajo	−14	− 2	− 9	− 6	fixed	− 2
Hayford-Quartz	fixed	+10	+ 8	+11	+ 5	+10
Antonio-Gentry	− 7	− 5	fixed	fixed	− 4	− 1
Antonio-Cat	− 1	− 9	− 5	−11	− 7	−10
Antonio-Ajo	− 1	− 9	− 5	fixed	fixed	fixed
Antonio-Quartz	− 1	+ 6	+10	+ 1	− 7	fixed
Antonio-Hayford	+13	+10	+12	+ 7	fixed	+13
PE_s	± 9	± 7	± 7	± 8	± 6	± 6
K	+ 8	+ 8	+ 8	+12	+ 8	+ 7
PE_k	± 4	± 3	± 4	± 3	± 3	± 3

SHIRAN-Geodetic difference (Table 1) of 0.0013 n. mile.

Analysis of the results for the PE_s of each K-adjustment shows a significant improvement with respect to previous adjustments made without the K. The average PE_s in the K-adjustments is 0.0007 n. mile, which is almost half the 0.0012 n. mile obtained when the adjustments were free and did not include K.

The existence of the K-error was investigated further in additional adjustments involving more constraints. Table 5 lists six adjustments holding various combinations of three stations fixed, which reduced the number of unknowns, thus strengthening the least squares solution in the remaining unknowns. The results are noteworthy in that the value of PE_s was equivalent to the free adjustment results and K was reduced to ±0.0010 n. mile from ±0.0016 n. mile.

Several explanations are possible for the existence of the constant error, K. For example, the constant error could be a function of errors in the determination of propagation velocity which is largely dependent on the index of refraction computation. Another possibility is that the K-error could be related to horizontal error as a function of line length and error in aircraft altitude. A more complete analysis and investigation of the constant error K is beyond the scope of this article but is available in the final Technical Documentary Report, SEG 64-53, "SHIRAN Flight Test and Evaluation Report."

It should be noted that, with or without the incorporation of the K-factor, the SHIRAN system accuracy remains within the specified PE_s (0.0017 n. mile). The inclusion of the K-factor, however, appreciably reduces the adjustment residuals and improves the probable error of a single observation.

OVERWATER TEST—MULTI-PATH

An overwater test was designed to investigate the effect of multipath propagation on the SHIRAN system. The test consisted of the repeated measurement of a line 184 n. miles in length at 2,000-ft. intervals from the minimum altitude of 4,500-ft. to a maximum altitude of 33,500-ft. The ground station sites selected for the overwater test were Point Loma, in the vicinity of San Diego, and Gaviota, near Santa Barbara. The first overwater test was flown 15 August. The results of this test should be qualified due to the unusual refraction profile existing at the time of the

TABLE 6

RESULTS OF OVERWATER TESTS 4 AND 6 NOVEMBER 1963
(Line Gaviota-Point Loma)

Line No.	*Altitude (Feet)*	*SHIRAN Reduced (SR) n. miles*	*V=SR −Mean SR (×10⁴) n. miles*
4 November 1963: Geodetic Distance=184.2735 N. Miles			
1	13,671	184.2760	+4
2	12,750	184.2763	+9
3	11,675	184.2792	+38
4	10,655	184.2736	−18
5	9,640	184.2788	+34
6	8,550	184.2757	+3
7	7,495	184.2757	+3
8	6,495	184.2736	−18
9	5,500	184.2744	−9
10	4,442	184.2733	−20
11	3,440	184.2730	−24
Mean SHIRAN =184.2754 N. Miles		$PE_s = \pm 0.0014$ n. mile	
6 November 1963: Geodetic Distance=184.2766 n. miles (New Mast Location)			
3	6,050	184.2786	+6
4	6,060	184.2786	+6
5	6,000	184.2763	−17
6	6,045	184.2786	+6
7	7,065	184.2797	+17
8	7,042	184.2789	+9
9	7,055	184.2763	−17
11	7,000	184.2794	+14
12	7,100	184.2778	−2
13	7,050	184.2784	+4
14	5,935	184.2770	−10
16	6,040	184.2765	−15
Mean SHIRAN =184.2780		$PE_s = \pm 0.0008$ n. mile	

test. A prominent inversion (a 50 *N*-unit variation in 400-ft. altitude) in the index of refraction profile apparently had an adverse effect on line crossings flown at an altitude below 12,000-ft. Lines flown above 12,000-ft. demonstrated reasonable internal consistency. The PE_s of these measurements was ± 0.0007 n. mile with a maximum deviation of -0.0020 n. mile.

The overwater tests were repeated on 4 and 6 November 1963, at the termination of the Flight Test Program. These results are shown in Table 6. Regarding the overwater test flown 4 November, nine of the eleven deviations from the mean were less than 0.0024 n. mile. The two large positive deviations fell within a 95 per cent distribution limit, and the PE_s was ± 0.0014 n. mile.

The final overwater test was performed on 6 November 1963 and flown following standard HIRAN procedures (two altitude groups, six crossings in each group). The internal consistency of the results is comparable to overland measurements. The PE_s was equal to ± 0.0008 n. mile, the maximum deviation from mean was 0.0017 n. mile, and the difference between the mean SHIRAN length and the geodetic length was 0.0014 n. mile.

REPEATABILITY TEST

A second multi-altitude experiment was performed between stations Ajo and Catalina. This repeatability test checked the behavior of SHIRAN over rocky and mountainous terrain and over widely varying geometries. These tests were flown on 19 September and 11 October with the mean SHIRAN and PE_s agreeing to 0.0003 and 0.0001 n. mile respectively. The results for one of the test flights are given in Table 7.

The repeatability of SHIRAN range measurements was well demonstrated in the Ajo-Cat multi-altitude line crossing. The deviations of 14 of 20 measurements were less

TABLE 7

RESULTS OF REPEATABILITY TEST FLOWN 19 SEPTEMBER 1963
(Line Catalina-Ajo)

Line No.	*Altitude (Feet)*	*SHIRAN Reduced (SR) n. miles*	*V=SR −Mean SR (×10⁴) n. miles*
Geodetic Distance=104.6172 n. miles			
1	11,061	104.6153	+5
2	12,044	104.6160	+12
3	13,186	104.6149	+1
4	14,234	104.6146	−2
5	14,234	104.6146	−2
6	14,234	104.6150	+2
7	15,286	104.6128	−20
8	16,361	104.6151	+3
9	17,412	104.6146	−2
10	17,412	104.6152	+4
11	18,436	104.6164	+16
12	19,522	104.6152	+4
13	20,611	104.6142	−6
14	22,749	104.6125	−23
15	24,760	104.6159	+11
16	27,001	104.6136	−12
17	30,117	104.6148	0
18	33,201	104.6155	+7
19	36,252	104.6147	−1
20	36,349	104.6147	−1
Mean SHIRAN =104.6148 n. miles		$PE_s = \pm 0.0006$ n. mile	

TABLE 8

COMPARISON OF SHIRAN TRILATERATION RESULTS TWO CROSSING VS TWELVE CROSSINGS IN N. MILES

Line	*Two Crossings*	*Twelve Crossings*	*Difference* $\times 10^4$
Cat-Gentry	111.3668	111.3648	+20
Ajo-Gentry	159.6632	159.6634	− 2
Ajo-Cat	104.6134	104.6148	−14
Quartz-Gentry	113.0142	113.0140	+ 2
Quartz-Cat	139.8664	139.8666	− 2
Quartz-Ajo	95.9723	95.9722	+ 1
Hayford-Gentry	261.2552	261.2550	+ 2
Hayford-Cat	333.9008	333.9010	− 2
Hayford-Ajo	284.6984	284.6983	+ 1
Hayford-Quartz	197.9334	197.9326	+ 8
Antonio-Gentry	397.2110	397.2113	− 3
Antonio-Cat	472.7678	472.7701	−23
Antonio-Ajo	418.4664	418.4664	0
Antonio-Quartz	335.8134	335.8142	− 8
Antonio-Hayford	138.9150	138.9145	+ 5
Average Difference = 0.0006 n. miles			

than 0.0010 n. mile, the PE_s was 0.0006 n. mile, and the maximum deviation from the mean was 0.0023 n. mile. The comparison of the final reduced Ajo-Cat distance compared to the geodetic inverse value yielded a difference of 0.0025 n. mile. An inspection of the various levels in Table 7 indicates that the overland measurements verified the ability of SHIRAN to measure lines precisely over a wide range of altitudes. There was no trend in the measurement errors that could be attributed to multi-path propagation.

TWO CROSSINGS VS TWELVE CROSSINGS

The possibility of reducing the number of observed line crossings per line measurement was investigated. The first two crossings from the higher altitude group of each line were selected, averaged, and compared with the mean of twelve crossings. The results of this comparison, shown in Table 8, indicate that the average degradation in accuracy is approximately 3 to 4 feet.

The evaluation was carried a step further by performing a free adjustment using the "two crossing" means. The results were compared with the normal free adjustment. The comparison showed differences of only 0.0001 or 0.0002 n. mile in the Probable Error and the adjustment residuals. Although only one series of adjustments was carried out using the data from the two crossing technique, it is apparent that the twelve crossings normally required for trilateration measurements can be reduced. To determine the minimum number of crossings required to consistently yield first order accuracy, the results of additional testing and actual field operations will have to be thoroughly evaluated.