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Loran-C Navigation as an Aid to Aerial Photographic Operations*

Loran-C guidance increases the accuracy and efficiency of aerial photographic operations

ABSTRACT: *New and improved state-of-the-art Loran-C receivers interfaced to navigation computers are now available to assist in aerial photographic operations. Loran-C navigation systems can be installed in all types of aircraft at a price comparable to other navigation systems lacking Loran-C's capabilities and accuracy.*

Loran-C guidance can increase the efficiency of conventional photogrammetric mapping projects and substantially reduce aerial survey costs. Aerial photographic mission design and planning can be enhanced with Loran-C navigation and sampling procedures, and sequential aerial photography can be accomplished with greater accuracy and reduced costs.

The Forest Pest Management Aerial Survey Team in Doraville, Georgia, evaluated the Loran-C system for use in aerial photography and other aerial operations requiring precise navigation. The accuracy and operational characteristics of Loran-C systems are ideal for aerial photographic operations.

INTRODUCTION

ONE OF THE NEW DEVELOPMENTS in aerial surveys and photography performed by Forest Pest Management has been the use of Loran-C airborne navigation systems. Loran-C can be used to increase the efficiency of aerial photographic operations, decrease the effort required for ground truth data collection, and ultimately reduce costs. Loran-C navigation systems also increase the flexibility of aerial photographic survey design for a variety of custom, user-oriented missions including sequential aerial photography to measure and detect changes over a given period of time, accurate aerial photographic point sampling of predetermined locations, and parallel flight line navigation (Dull, 1980). The Loran-C system characteristics include easy installation in most types of aircraft, small size and light weight, relatively low cost, and extended area of operation. These characteristics make Loran-C an ideal navigation aid for aerial photographic operations.

This evaluation reviews the navigational accuracy obtained during a wide variety of operational aerial photographic missions utilizing a Loran-C TDL-424 Navigator manufactured by Teledyne Systems, Inc.*

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* Mention of a proprietary or commercial product does not constitute recommendation or endorsement of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products that also may be suitable.

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LORAN-C SYSTEM DESCRIPTION

Loran is an acronym for "long range aid to navigation." A handful of stations provide nationwide coverage, with the system operating in the very low frequency (VLF) band at 100 kilocycles. At this low frequency, the system provides coverage from ground level over the entire range of flight altitudes to distances of 1200 nautical miles from the transmitting stations (Anon., 1980).

To obtain a position fix, Loran-C uses synchronized, pulsed signals from three or more Loran ground stations. A master ground station transmits the signal. Two or more secondary transmitting stations receive the signal and use it to synchronize their transmitters so that, at the proper time interval, each transmits a signal. The difference in time of arrival of these signals at the receiver is a measure of difference in distance from the receiver to each of the ground stations. The points having the same measured difference in distance from a pair of stations form a hyperbola, called "a line of position." The intersection of two or more of these lines defines the position of the aircraft.

Loran-C uses advanced electronic technology, including the more accurate cycle matching signal coding method, rather than the envelope matching Loran-A method (Panshin, 1978). Other technical improvements included multiple pulse transmission, phase coding, freedom from sky-wave contamination, and the ability to use more sophisticated receivers. Improved technology has enabled industry to reduce the size of Loran-C receivers and lower the cost for airborne systems (Ritter and O'Hara, 1976; Stearns, 1980). Increased production is expected to further reduce the price of the receivers. New and improved systems have appeared on the market over the past several years.

Loran-C is the designated government sponsored civilian navigation system for the Coastal Confluence Zone. The system is operated by the U.S. Coast Guard for marine as well as airborne and ground navigation (Anon., 1980). The station configuration for coverage of this zone will provide coverage for two-thirds of the land area of the United States. Reconfiguration of existing chains and the addition of a mid-continent chain will provide complete coverage of the United States.

Loran-C is considered a medium to high accuracy navigation system (Van Etten, 1975). Navigation systems having a probable error with a radius around a point of 0.1 to 0.2 nautical mile (approximately 200 to 400 metres) are classified as medium accuracy systems, while probable errors with a radius of 0.01 to 0.02 nautical mile (20 to 40 metres) would classify the system as high accuracy.

The Loran-C system provides excellent repeatability. A Loran-C fix at a known location will normally vary less than 100 metres (Icenbice, 1976), and in many areas the variation is less than 50 feet. Therefore, the knowledge of what the readings are at a particular location can be extremely useful if the navigator wants to return to the location at a later date.

If coordinates obtained from a map are used for navigation, however, signal propagation anomalies may create errors of up to 0.25 nautical mile (nmi). Position updating features which are available on airborne systems can compensate for signal propagation anomalies at various locations.

The basic limitation on the accuracy of any radio navigation system is the velocity of radio signals, which travel at a rate of about one foot per nanosecond (McGuire, 1977). A nanosecond is one-billionth of a second. The system must be capable of measuring time down to 50 nanoseconds to get accuracies as low as 50 feet. The latest Loran-C equipment is capable of measuring time in these precise increments.

NAVIGATION DISPLAYS, STEERING, AND DATA OUTPUTS

The Loran-C receiver is about the size of a pack of cigarettes (about 10 by 5 by 3 cm). The Teledyne TDL-424 airborne navigation system (Figure 1)—including receiver, navigation computer, output interfaces, and display—weighs only nine pounds and measures 9.0 inches high by 5.7 inches wide by 6.5 inches deep.

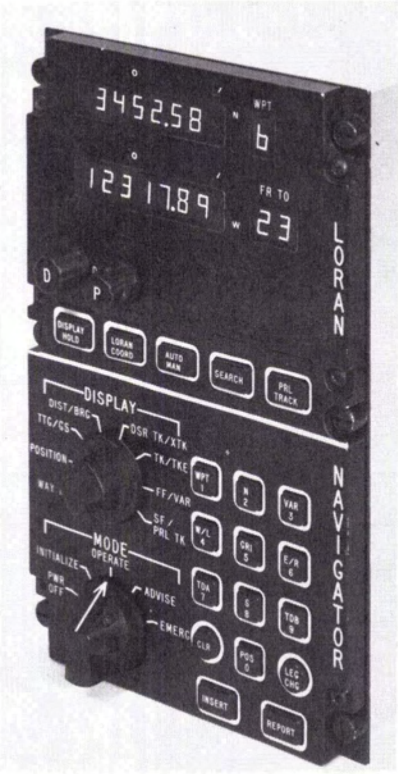

FIG. 1. TDL-424 Loran-C airborne navigation system.

The various navigation displays available on the receiver cockpit display are illustrated in Figure 2. The TDL-424 airborne navigation system can also perform the following functions: store nine waypoints and process them en route either manually or automatically; couple to an autopilot; transmit data on a one-way data link to a base station at specified intervals or record the data on a cassette tape; interface to a course deviation indicator (CDI) with a narrow (0.1 nmi) and wide (0.5 nmi) sensing deflection for a visual display of cross-track error; generate parallel track steering and prestored search patterns (Figures 3 and 4); display range to or from a waypoint on a horizontal situation indicator (HSI); and continuously monitor all critical parameters and warn the pilot of unsafe navigation displays or signal reception.

Loran-C enables the flight crew to fly extended flightlines more accurately, especially in areas with few landmarks. A major advantage of Loran-C is the reduced time needed to position the aircraft on a flight line prior to entering the target area. The increased accuracy of flying parallel flight lines also provides greater control of sidelap. Loran-C also helps control sequential photography for sampling loss assessment and trends over time. Using it reduces survey fatigue to the flight crew. Free from continually referring to the flight map, the pilot can direct his attention to the flight path, thereby increasing safety of the operation.

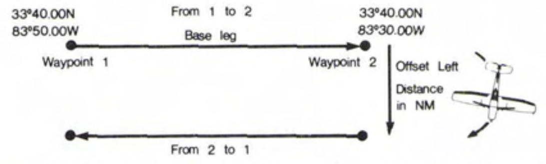

FIG. 3. Parallel track steering used during a typical aerial survey or photographic operation.

NAVIGATION ACCURACY EVALUATION

Loran-C flight tests were incorporated into operational photographic missions and aerial surveys. These flight tests have been divided into four different categories: (1) evaluations of flying parallel lines spaced at predetermined intervals; (2) comparisons of aerial photographic missions with and without Loran-C guidance; (3) measurements of return flight accuracy to previous flight lines; and (4) measurements of overflight accuracy of predetermined exposure stations. An assessment of total system error in aerial surveys was based upon the methodology previously developed (Adams, 1976; Hughes and Adams, 1977).

Aerial operations utilizing the airborne navigator have been performed in 13 southeastern states and most of the northeastern states. The evaluation of the Loran-C system was based on aerial photographic measurements and flight log entries. An RC-10 camera mounted in an Aero Commander was used to obtain aerial photographic reference data. The principle points from a series of vertical aerial photographs were transferred to 1:24,000 scale USGS topographic maps to define the aircraft's true

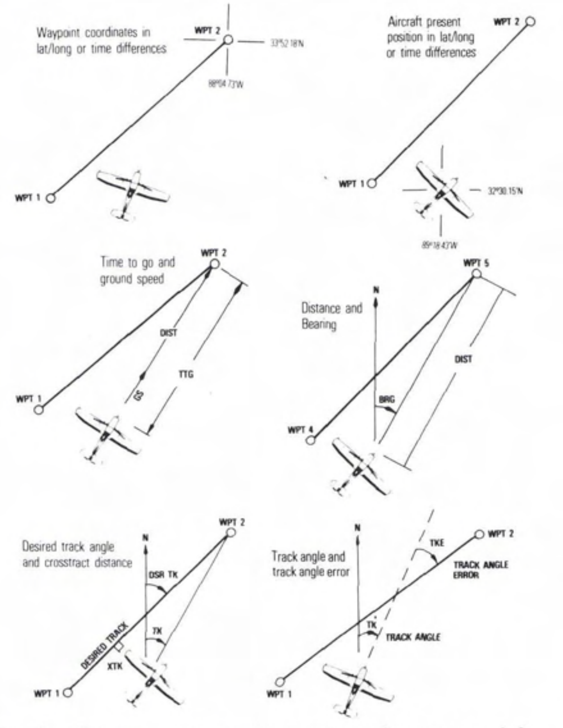

FIG. 2. Diagrammatic representation of navigational displays available from airborne Loran-C systems.

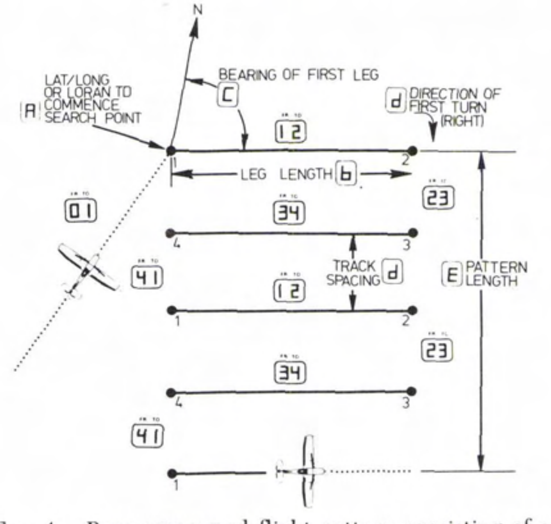

FIG. 4. Preprogrammed flight pattern consisting of a series of parallel flight lines.

ground track. The following is a partial list of data required for the aerial operational evaluation of the Loran-C airborne navigation system:

- Actual aircraft position (from aerial photographs).
- Loran-C indicated position (from digital readout or cassette tape via the data link system).
- Cross track deviation (CDI needle deflection and digital readout).
- Waypoint in use or digitized base leg end points.
- Desired track.
- From/to indication.
- Along track distance (nmi).
- Loran-C operation mode.
- Pilot workload (communications, weather, traffic, etc.).
- Status of equipment (aircraft, photographic, Loran-C system, etc.).
- Loran-C chain and secondaries utilized.

PARALLEL FLIGHT LINE NAVIGATION EVALUATION

The navigation requirements of parallel track steering are ideally suited to the TDL-424 system. Parallel track steering enables the pilot to fly along a course parallel to, and at a selected distance from, a given course. Once the offset distance has been entered into the system, all steering and other navigational data are referenced to the artificial destination (Anon., 1976). Given the scale, percent of end lap and side lap, and area boundaries, navigation coordinates used as input for the Loran-C system can be obtained by measuring latitude and longitude on 1:24,000 USGS topographic maps or other aerial survey maps. A base leg is then established within the survey boundary, with parallel flight lines positioned to accommodate side lap and scale requirements.

Direct navigation to the target area is provided by the Loran-C navigator. On the first photographic leg of the flight the pilot positions the aircraft on track prior to initiating photography. Loran-C steering is provided by the course deviation indicator, and distance to destination is shown by the horizontal situation indicator. The digital readout on the control indicator box provides the necessary navigational data along each flight line and indicates when to begin and terminate each sequence of photographs. After each flight line is completed, the Loran-C navigator is reprogrammed for the next parallel offset to provide steering directly to the next flight line.

The acceptable error budget for aerial photographic missions varies with the desired scale of the imagery and the desired percentage of sidelap. For this evaluation, maximum acceptable error was defined as the ground distance represented by one-half the desired sidelap. This is compatible with standard requirements for aerial photographic mapping missions (Thompson, 1966; Anon., 1979).

The desired ground track and the actual aircraft track, based on the principal points of successive photographs along each flight line, were plotted on 1:24,000 topographic maps. Cross track error was determined by measuring the distance between the actual and desired flight lines at 1.0 nautical mile (nmi) intervals. The distance between adjacent flight lines was measured at 1.0 nmi intervals and subtracted from the desired sidelap to determine sidelap error. Figure 5 illustrates the proposed flight line and the actual flight line as determined by plotting the principal points of the photographs.

In each of the photographic missions in this evaluation requiring parallel flight lines, navigation analysis was made of both the cross track error and the difference between actual gain per line and desired gain per line. A highly-trained three man flight crew was used in all the flight tests. These missions were conducted over extensively forested, remote areas where visual checkpoints for ground to map reference were lacking. The maps available for tracking were outdated.

Table 1 illustrates the guidance accuracy of the Loran-C navigation system during three aerial photographic missions. The Forest Pest Management Aerial Survey Team has conducted dozens of aerial photographic missions using Loran-C guidance for primary navigation and steering indications and obtained similar results.

The ability to fly parallel flight lines at specific offsets is one of the most critical demands of aerial surveys and aerial photographic missions. The results of the three missions in Table 1 illustrate that the Loran-C system performed within the error tol-

FIG. 5. Example of the proposed and actual flight lines with and without Loran-C guidance.

TABLE 1. PERFORMANCE EVALUATION OF LORAN-C GUIDANCE FOR PARALLEL FLIGHT LINE NAVIGATION IN OPERATIONAL AERIAL PHOTOGRAPHIC MISSIONS

	Mission		
	Oconee National Forest, GA	Linville Gorge Wilderness, NC	Great Smokey Mountains National Park, NC
Desired scale	1:8,000	1:20,000	1:12,000
Gain/line (nmi)	0.7	1.7	0.9
Number flight lines	65	7	16
Total linear flight line length (nmi)	605	152	193
Cross track error (nmi; metres)			
Mean	0.05; 90	0.13; 240	0.15; 280
Standard deviation	0.09; 170	0.15; 280	0.20; 370
Difference in distance (nmi; metres) between actual gain/line and desired gain/line			
Mean	0.06; 110	0.13; 240	0.07; 130
Standard deviation	0.07; 130	0.23; 430	0.14; 260
Tolerance	0.15; 280	0.37; 680	0.22; 410

erance limits for acceptable aerial photography. The punctual accomplishment of each mission, savings in flight time and film, and reduction of re-flights are additional benefits not directly reflected in the analysis of navigational accuracy. These factors, and limiting conditions mentioned previously, become increasingly important in areas where the flight time available for aerial photography is restricted.

COMPARISON OF AN AERIAL PHOTOGRAPHIC MISSION WITH AND WITHOUT LORAN-C

Aerial photographic coverage of the Oconee National Forest and the surrounding area in northeast Georgia was completed in the spring and fall of 1979. The same pre-determined flight lines were used on each mission. Two Aero Commanders, each equipped with a Wild RC-10 camera, flew simultaneously over a two-day period to acquire the photography. One aircraft was equipped with a Loran-C TDL-424 navigation system, while the other relied on visual lines of sight.

This test was designed to compare the parallel flight line navigation accuracy of visual and Loran-C guidance. The results obtained from the spring flight with Loran-C were compared with the results obtained when the same flight lines were flown without Loran-C in the fall. In the fall, the pilot relied solely on the Loran-C readout, as programmed by the navigator/tracker, to position the aircraft along the flight line. The pilot of the aircraft relying on visual navigation had ten years of experience in aerial photography. The results of this test are illustrated in Table 2. The Loran-C outperformed an experienced flight crew in both the cross track and gain per line analysis. The mean and standard deviations for Loran-C guidance in the cross track error analysis were less than one-half those for visual navigation. In the gain per line analysis, the

TABLE 2. COMPARISON OF PARALLEL FLIGHT LINE NAVIGATION WITH AND WITHOUT LORAN-C GUIDANCE, OCONEE NATIONAL FOREST, GA., 1979

	With Loran-C	*Without Loran-C*
Desired scale	1:8,000	1:8,000
Desired gain/line (nmi)	0.7	0.7
Area (acres)	175,800	175,800
Number flight lines	27	27
Linear flight line length (nmi)	234	234
Cross track error (nmi; metres)		
Mean	0.04; 60	0.08; 140
Standard deviation	0.06; 110	0.14; 250
Difference in distance (nmi; metres) between actual gain/line and desired gain/line		
Mean	0.05; 100	0.09; 170
Standard deviation	0.08; 160	0.16; 290
Tolerance	0.15; 280	0.15; 280

mean and standard deviation were again almost one-half the visual navigation values.

The means for cross track were significantly different at the 99 percent level. The mean values with and without Loran-C for the differences between actual gain per line from the desired gain per line were also significantly different at the 99 percent level.

RETURN FLIGHT ACCURACY FOR A PREDESCRIBED FLIGHT LINE

The objective of these tests was to determine if the Loran-C navigator could precisely direct an aircraft over a previously flown line. This capability is essential for accurate sequential aerial photography.

A flight line over the target was drawn on a map. The Loran-C indicated coordinates for the beginning and end points of the flight line were recorded in latitude and longitude following the first overflight. This flight line was then reflown utilizing Loran-C guidance.

The principal points of the aerial photographs obtained during these flights were plotted on 1:24,000 scale maps. Cross track error for each re-flight was measured from the maps for each frame. Therefore, the deviation from the original flight could be determined for each subsequent re-flight.

In this evaluation two separate tests were conducted to measure the re-flight accuracy of the Loran-C system. Test A measured the re-flight accuracy over the same flight line at various altitudes. Test B was a comprehensive evaluation of re-flying different flight lines at the same altitude. These two tests will be discussed separately.

Aerial photography in Test A was acquired at three different scales: 1:18,000; 1:6,000; and 1:2,400. Different film and filter combinations utilized in the test necessitated re-flying the flight line ten times at the various altitudes. One east to west oriented flight line 2-nmi long provided coverage for the target area at all altitudes.

Table 3 illustrates the mean cross track error for each of the ten subsequent overflights. A tolerance limit for error was defined as 15 percent of the negative width at each of the three scales. The standard deviation was also computed for each overflight. The mean was combined with the standard deviation and compared to the tolerance limit.

It can be inferred from these results that as you increase in altitude the greater the likelihood of remaining within the specified error tolerance limits. This can be explained due to the fact that as the scale gets smaller the corresponding tolerance for error gets larger, while the error of the airborne Loran-C navigation system would remain constant. Both re-flights at the scale of 1:18,000 were well within the tolerance limit.

An analysis of variance displayed significant differences among the means for cross track error. The greatest amount of variation between two flight lines occurred at the same altitude. This variation may have been influenced by atmospheric turbulence which would generally tend to increase the cross track error more at the lower altitude and become a more influential factor in relation to the tolerance for error.

A tolerance limit of 0.05 nmi (approximately 90 m) as specified at a scale of 1:2,400 would be very difficult to maintain on a single overflight. Errors greater than 15 percent of the area covered by the negative width should be expected at the larger scale.

Table 4 illustrates the navigational performance of adherence to a predetermined flight line in Test B. In order to obtain the maximum accuracy during subsequent re-flights, the same secondary stations must be in track. Previously utilized stations were not available during re-flights, due to a reconfiguration of the Loran-C chain during a subsequent flight. Therefore, data were obtained for 67 visually guided flights as opposed to 40 utilizing Loran-C guidance. The navigational performance of the aircraft using Loran-C allowed better adherence to a predetermined flight line.

TABLE 3. RE-FLIGHT ACCURACY OF A LORAN-C SYSTEM DURING AN AERIAL PHOTOGRAPHIC MISSION AT VARIOUS ALTITUDES

Line No.	Altitude ASL	Scale	Mean X-track Error (nmi)	Range X-track Error (nmi)	Standard Deviation (nmi)	Width of Neg. (nmi)	Calculated Error Tolerance Compliance	Tolerance Limit (nmi)
1	9500	1:18,000	0.04	0.01–0.09	0.09	2.25	0.13	0.34
2	9500	1:18,000	0.09	0.06–0.13	0.08	2.25	0.17	0.34
3	3500	1:6,000	0.07	0.03–0.10	0.06	0.74	0.13	0.11
4	3500	1:6,000	0.14	0.13–0.15	0.03	0.74	0.17	0.11
5	3500	1:6,000	0.14	0.10–0.17	0.07	0.74	0.21	0.11
6	3500	1:6,000	0.15	0.11–0.19	0.07	0.74	0.22	0.11
7	3500	1:6,000	0.03	0.01–0.04	0.03	0.74	0.06	0.11
8	3500	1:6,000	0.09	0.03–0.11	0.07	0.74	0.16	0.11
9	1700	1:2,400	0.05	0.00–0.05	0.04	0.30	0.09	0.05
10	1700	1:2,400	0.09	0.05–0.11	0.03	0.30	0.12	0.05

TABLE 4. RETURN FLIGHT ACCURACY UTILIZING LORAN-C NAVIGATION DURING AN AERIAL PHOTOGRAPHIC MISSION

	Without Loran-C	With Loran-C
No. flight line plots flown	67	40
Mean cross track error (nmi)	0.12	0.10
Standard deviation	0.20	0.13
Maximum cross track error (nmi) (average per flightline plot)	0.48	0.30
Standard deviation + mean for tolerance compliance (nmi)	0.32	0.23
Error tolerance limit (nmi)	0.15	0.15
Photographic scale	1:8,000	1:8,000
Width of negative (nmi)	0.98	0.98

At a scale of 1:8,000, the width of a negative is 0.98 nmi. With Loran-C guidance, means for cross track error were below the tolerance level. However, the calculated error for tolerance compliance (standard deviation plus the mean) was above the error tolerance limit for flights with and without Loran-C guidance.

In this test the Loran system relied upon previously recorded coordinates for subsequent flights. The first flight performance was compared to the predetermined flight lines. All subsequent flights were analyzed in reference to previously flown lines over the same coverage area. The amount of flight time required to obtain coverage of the photo sample plots was reduced by 40 percent using Loran-C guidance. Loran-C navigation allowed direct navigation to each site with electronic guidance along each flight line.

OVERFLIGHTS OF PREDETERMINED EXPOSURE STATIONS

Aerial photography at a scale of 1:12,000 was acquired on 40 sites in west central South Carolina. Each site covered only one acre. The center location for each site was plotted on 1:24,000 scale USGS topographic maps. A digitizer containing software capability to determine latitude and longitude for each site was used to obtain the coordinates. These coordinates were used to program the Loran-C system to obtain overflight guidance on each site at a 360° bearing. An Aero Commander 500B equipped with a Wild RC-10 camera and a TDL-424 Loran-C system was used to acquire the imagery.

The mean distance measured from the plot center to the principal points of the vertical aerial photographs was 220 metres (0.12 nmi) with a standard deviation of 220 metres.

In this evaluation the pilot positioned the aircraft over each site using only Loran-C guidance. The camera operator obtained the exposure only when the Loran system indicated arrival over the site. All 40 plots fell within 20 percent of the frame width from the principal point of the photograph. Reflights were not required for any of the sites.

CONCLUSIONS

Loran-C systems ranging in price from $12,000 to $31,000, have been evaluated for accuracy and utility during operational aerial photographic missions. (New systems, with similar operating characteristics, are currently available at greatly reduced prices.) Thousands of aerial photographs from a variety of missions with various objectives have been reviewed. The results of these evaluations indicate that the Loran-C navigation system is an ideal aid to aerial photographic operations. Navigation accuracy was acceptable at scales of 1:6,000 and smaller for parallel track navigation. Sequential aerial photography at scales of 1:12,000 and smaller, obtained using Loran-C for primary navigation, were acceptable.

The total system accuracy presented in this evaluation illustrates Loran-C utility in actual photographic missions. These results include several sources of error: airborne equipment error, which includes Loran-C signal propagation anomalies, and signal filtering, processing, computational, and output and display errors; flight technical error, or the quantitative assessment of manual or auto-pilot steering performance; and errors associated with aircraft tilt at the time of exposure. The methodology used to assess the Loran-C system accuracy in these evaluations included all of the error sources mentioned above and reflected constraints present in most aerial photographic missions. The Loran-C system provided navigational accuracy within an error tolerance specified in conventional photogrammetric mapping contracts.

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Aerial Photography/Aerial Photo Interpretation Workshop

University of Idaho, Moscow, Idaho
6-10 February 1984

This course—sponsored by the College of Forestry, Wildlife and Range Sciences and the Office of Continuing Education, University of Idaho—is for those land resource managers who have not had or who need a refresher on such topics as obtaining aerial photography; small format camera systems; preparing and viewing aerial photos stereoscopically; determining scale, distances, heights, slopes, and area; making simple maps; and interpreting vegetation and landform. The cost of the Workshop is $265.

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