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Flight Testing the Aerial Profiling of Terrain System

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FLIGHT TESTING THE AERIAL PROFILING OF TERRAIN SYSTEM

By Edward J. Cyran and William H. Chapman

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FLIGHT TESTING THE AERIAL PROFILING OF TERRAIN SYSTEM (APTS)

Edward J. Cyran
William H. Chapman
U.S. Geological Survey
526 National Center
Reston, Virginia 22092
(703) 860-6203

ABSTRACT

The U.S. Geological Survey (USGS) has completed laboratory testing of the Aerial Profiling of Terrain System (APTS) and has installed the equipment in a DeHavilland Twin-Otter aircraft. The system has undergone a series of performance evaluation flights over a calibration range west of Boston, Massachusetts. The APTS was designed, constructed, and laboratory tested at The Charles Stark Draper Laboratory (CSDL) in Cambridge, Massachusetts. These performance evaluation flights demonstrated the accuracy of the APTS primary mission of terrain profiling. The results of the performance evaluation phase confirm that the APTS performed so as to achieve its positional design goal of ±60 cm horizontally and ±15 cm vertically.

INTRODUCTION

Since 1974, the USGS has been involved in the development and use of inertial surveying systems in support of mapping projects. The APTS is an airborne profiling system which has been designed, constructed, and tested by CSDL in Cambridge, Massachusetts.

The APTS, designed to be carried in a relatively small aircraft such as a Twin-Otter, consists of an inertial measuring unit (IMU), a laser tracker, a laser profiler, a video imaging system, supporting electronics, and a computer. The IMU and laser tracker provide an accurate three-dimensional reference frame based on the local datum. The laser profiler measures accurate ranges to the topography from the reference platform. The on-board computer serves as a system controller and a data collector and processor while navigating the aircraft during data collection activities. A video system records the ground image below the aircraft during profiling.

As a part of the design process, CSDL completed an engineering analysis of the proposed system concept. The results of the analysis indicated that absolute accuracies of 15 cm vertically and 3 m horizontally could be achieved 90 percent of the time for points along the profile. The horizontal specification was later changed from 3 m to 60 cm. The analysis established that the proposed accuracies could be obtained if state-of-the-art IMU components were used and if the system position estimate was updated or reset every

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200 seconds. To accomplish the updating, a precision laser tracking device was recommended. The tracker would lock on to surveyed retroreflectors in the operating area (fig. 1). The measured ranges and angles to known positions, which are referenced to the IMU, would be used to correct systematic errors. The engineering analysis led to a series of contracts with CSDL to refine the engineering analysis, fabricate and assemble hardware, and develop both inflight and postflight software.

The data collected by APTS is processed postmission by a mainframe computer program. This software edits, renavigates, compresses, filters, smooths, and recombines the flight data to provide a survey data set. This set consists of the latitude, longitude, and height of profile points along the flight paths and the latitude, longitude, height, and gravity for any retroreflectors not previously surveyed but encountered during the mission. This feature of point positioning retroreflectors allows flexibility in preparing for APTS profile missions since ground survey coordinates are not needed for all retroreflectors. In addition, this feature expands the APTS capability to include point positioning surveys such as used for geodetic control densification surveys.

The instrument package was installed in the aircraft in January 1983. The aircraft (a DeHavilland Twin-Otter) had been modified under a separate contract to include a viewing port in the belly, an auxiliary power unit, and an air-conditioning unit. The installed equipment was thoroughly tested on the ground. A series of flight tests to evaluate system performance were then conducted over a calibration range set up just west of Boston, Massachusetts.

CALIBRATION RANGE

Before the APTS was used for any operational missions, the performance of the system was tested over a calibration range in Massachusetts (fig. 2). Doppler satellite surveying techniques were used to establish the relative locations of the 15 retroreflector sites. Four Magnavox 1502 Doppler receivers were used to simultaneously observe satellite passes over the area. The four receivers were located at adjacent sites to form a quadrilateral. When sufficient data were collected at these four sites, two of the receivers were moved to the next two sites to form a new quadrilateral. The receivers were leapfrogged in this manner to collect a data set over a series of interlocking quadrilaterals that cover an area of 16 by 48 km extending from Framingham to Lowell. The satellite data were reduced by the National Geodetic Survey (NGS).

Conventional survey techniques were used to tie the Doppler sites to both the vertical and horizontal North American Datums (NAD). A sixteenth Doppler station was observed at Marlborough, Massachusetts. This site was not used as a retroreflector site, but provided an additional tie between the satellite datum and the NAD 1927. Second-order levels were run to each retroreflector site to provide accurate elevations.

Aerial photographs (1:4,800 scale) were taken of several of the sites selected because they contained large, relatively flat open areas. For three of these sites, Acton, Sudbury, and Nagog, orthophotomaps at 1:800 scale were compiled

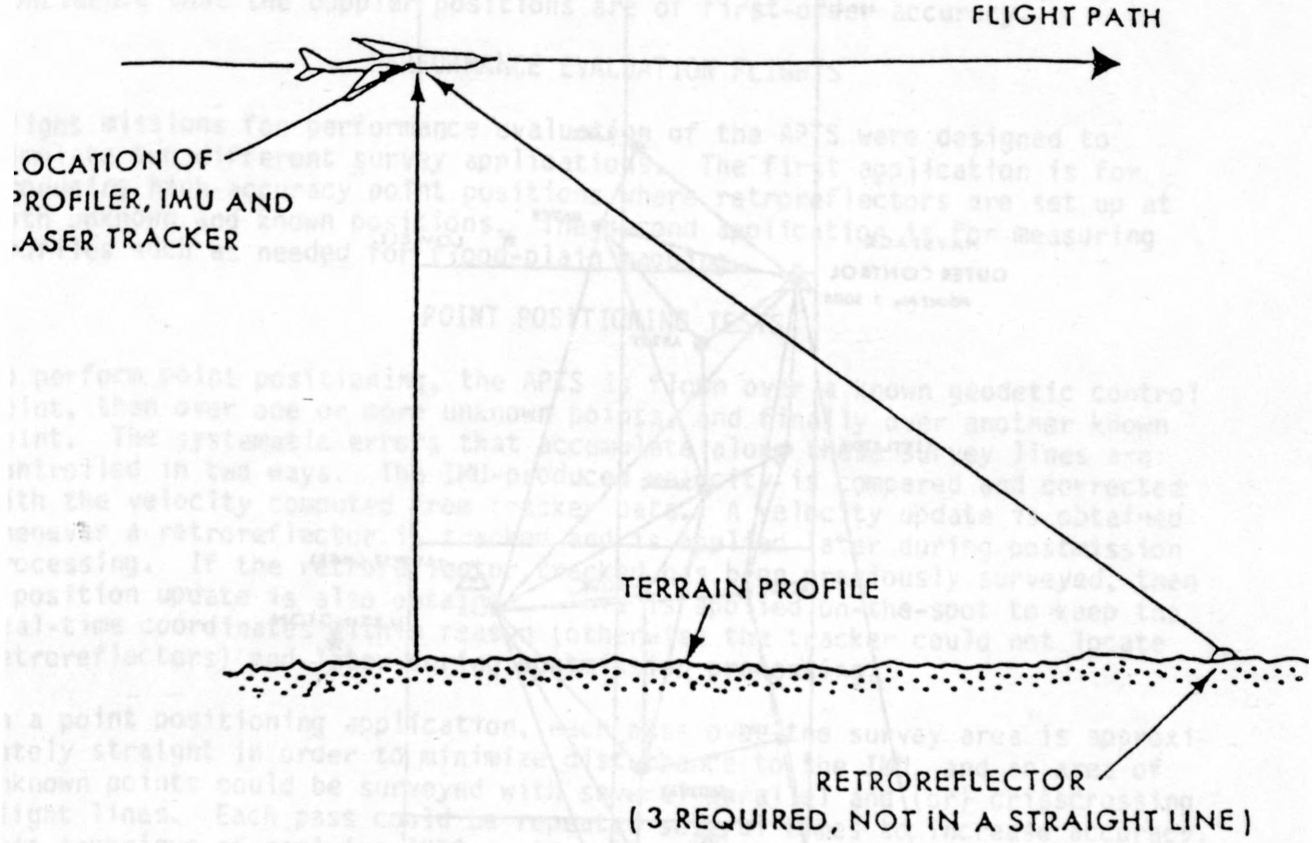

Figure 1.--Aerial Profiling of Terrain System

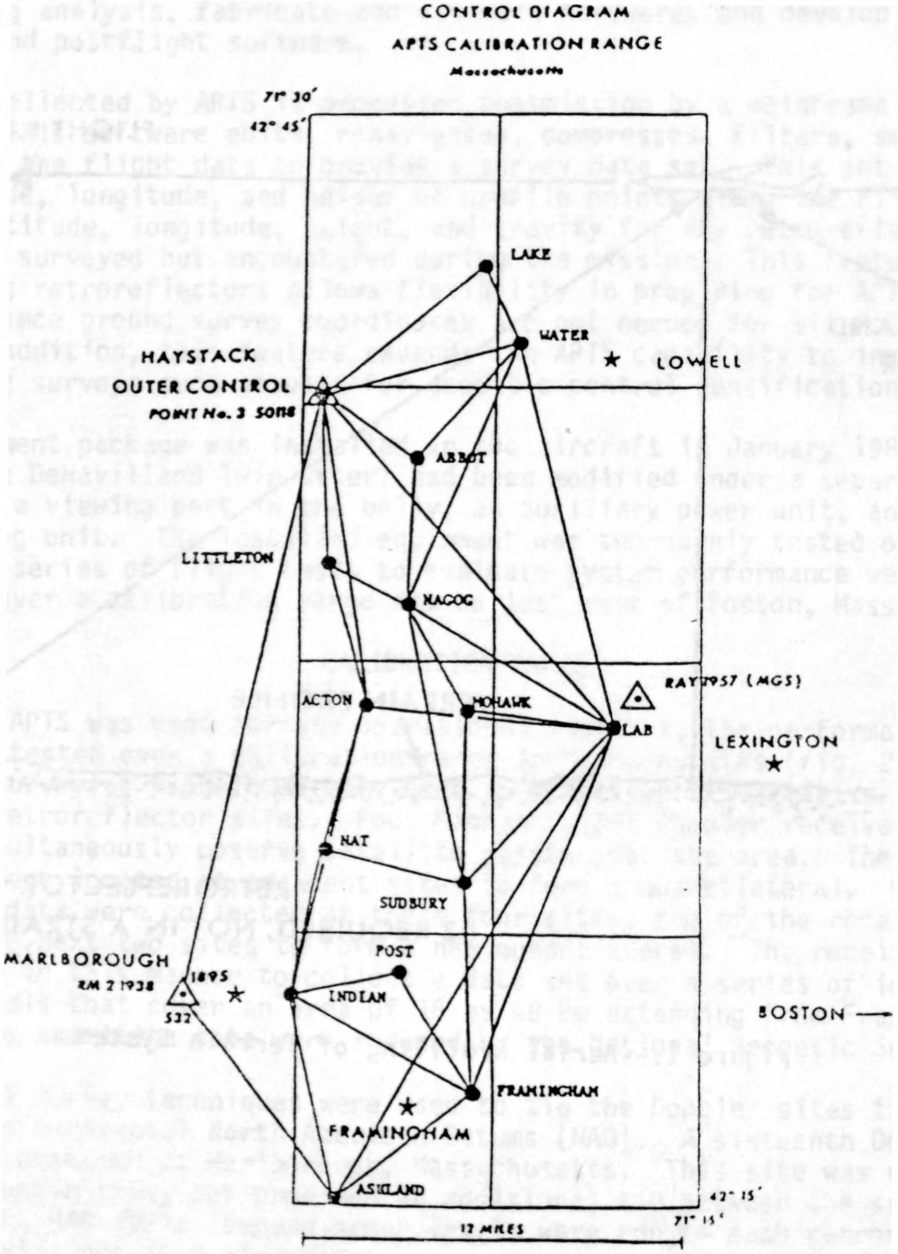

Figure 2.--APTS calibration range

using the Gestalt Photomapper and 1-foot interval contours were produced for these maps on the Kern PG-2. These sites were used as ground-truth to compare the APTS-measured profiles.

To test the accuracy of the Doppler satellite positions, three of the range stations were resurveyed using NGS Macrometer Global Positioning System (GPS) receivers. The three sites resurveyed were stations Haystack, Lincoln, and Ashland. The three lines agreed to better than 1:130,000 and provided confidence that the Doppler positions are of first-order accuracy.

PERFORMANCE EVALUATION FLIGHTS

Flight missions for performance evaluation of the APTS were designed to simulate two different survey applications. The first application is for producing high-accuracy point positions where retroreflectors are set up at both unknown and known positions. The second application is for measuring profiles such as needed for flood-plain mapping.

POINT POSITIONING TESTS

To perform point positioning, the APTS is flown over a known geodetic control point, then over one or more unknown points, and finally over another known point. The systematic errors that accumulate along these survey lines are controlled in two ways. The IMU-produced velocity is compared and corrected with the velocity computed from tracker data. A velocity update is obtained whenever a retroreflector is tracked and is applied later during postmission processing. If the retroreflector tracked has been previously surveyed, then a position update is also obtained. This is applied on-the-spot to keep the real-time coordinates within reason (otherwise the tracker could not locate retroreflectors) and later during postmission processing.

In a point positioning application, each pass over the survey area is approximately straight in order to minimize disturbance to the IMU, and an area of unknown points could be surveyed with several parallel and (or) crisscrossing flight lines. Each pass could be repeated several times to increase accuracy. This technique of applying APTS could be used to densify a geodetic network or to monitor ground-surface subsidence.

A test of this application is depicted in figure 3, which shows long north-south flights over the calibration range retroreflectors. The profiler was not used since the purpose of the mission was to establish positions for retroreflectors. Four survey lines were completed for each flight, station Lake to Ashland and return and station Lake to Framingham and return. The data were processed so that the surveying accuracy was determined for different control spacing. In the first solution, position data for alternate retroreflectors were held fixed and the others served as test points. In the second solution, every third point was considered fixed (end and midpoint stations in each line). In the last solution, only the end points (Lake, Ashland, and Framingham) were considered fixed.

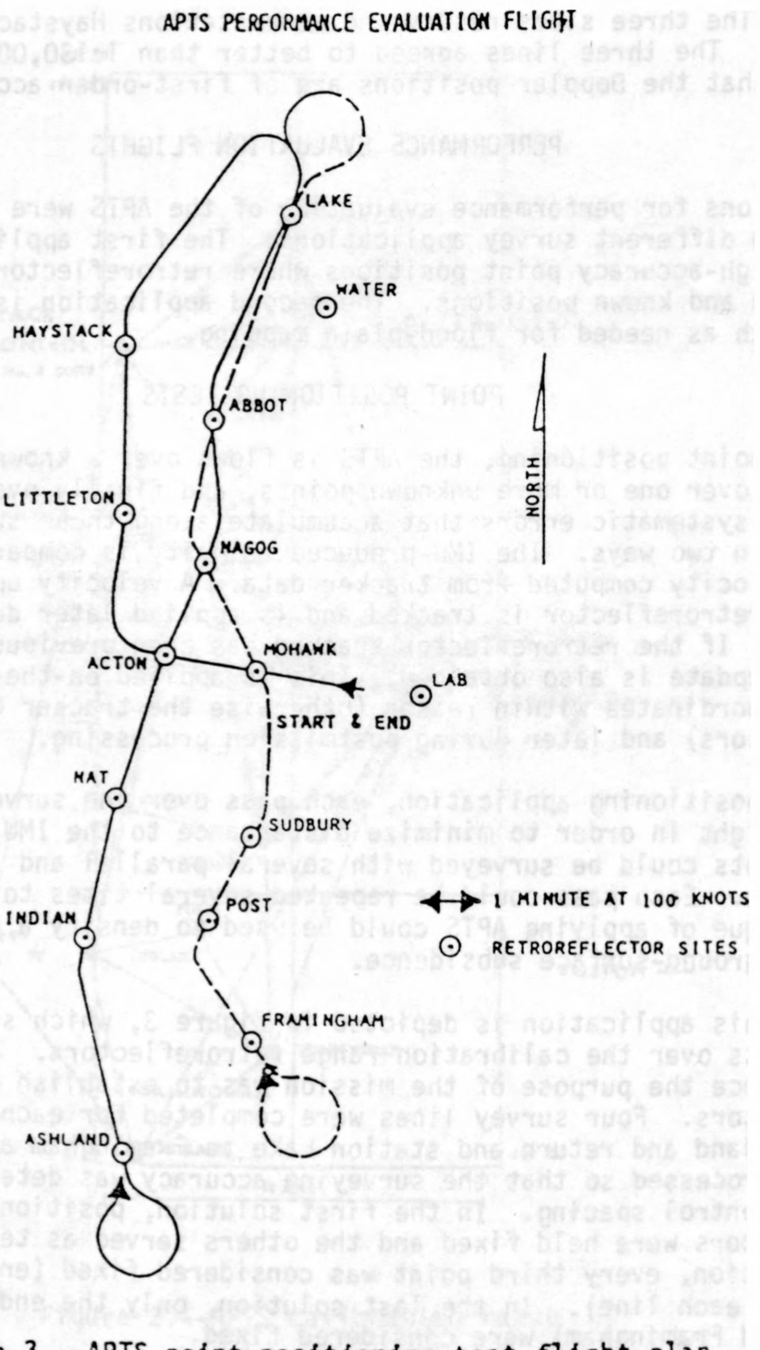

Figure 3.--APTS point positioning test flight plan

These tests were completed on January 26, 1984, when two missions were accomplished, one in the morning and one in the afternoon. All 38 retroreflectors were successfully tracked from a flying height of 610 m during both flights. This test demonstrated that almost all of the problems associated with the laser tracker had been solved.

The results of the point positioning performance evaluation flight are presented in table 1. Part A lists the errors in the APTS survey at each retroreflector for each of the two surveys when every other point was fixed. The average time interval between IMU updates was 5.2 minutes. The left three columns list the latitude, longitude, and elevation errors. The standard error in latitude was ±25 centimeters and in longitude was ±38 centimeters. The vertical accuracy was ±13 centimeters standard error. Some of the horizontal errors are due to noise in the Doppler surveys, which is estimated to be ±10-20 centimeters. The estimated vertical accuracy is probably not contaminated by ground survey since the elevations were established by second-order leveling.

The right three columns list the differences between the results of the two surveys in order to present the change detection capabilities. The change detection errors are, of course, independent of the calibration range coordinate values. The agreement between the two surveys is excellent and demonstrates strong change detection capability. It must be remembered that this is a very limited test since both surveys were done on the same day. These surveys will be repeated when an opportunity occurs. Also, the elevations of stations Abbot and Indian will be checked since the errors of both surveys and all three adjustments indicate that a bias exists.

Part B gives the results when the end and midpoints of each line were held fixed; Part C gives the results when only the end points were fixed. The results of these two adjustments indicate little degradation in accuracy as the update interval is increased to 7.8 minutes and to 15.7 minutes. We conclude that the velocity updates that are obtained all along the flight lines are sufficient to maintain this accuracy level. Higher accuracy could probably be obtained if additional retroreflectors are added to increase the frequency of velocity updates.

PROFILING TESTS

The second type of surveying is used for producing ground profiles, such as needed along a stream for flood-plain studies. Tight maneuvers of the APTS aircraft would be necessary to acquire successive closely spaced profiles. Instead, a circular path, about 2 miles in diameter, that moves up or downstream to acquire a new profile on each loop, was adopted for the flight plan. A retroreflector update would be obtained on each loop to control IMU errors. This type of data-gathering mission was simulated in the second group of APTS performance evaluation flights.

Table 1.--Results of APTS point positioning tests

A. Alternate points held fixed - 5.2 minutes between updates

SITE	FLIGHT	ERRORS (CM) ϕ	λ	ELEV	CHANGE (CM) $\Delta\phi$	$\Delta\lambda$	ΔE
Abbot	am	37	-19	-19			
	pm	38	-21	-27	- 1	2	8
Acton	am	- 1	-13	3			
	pm	- 7	-28	- 4	6	15	7
Mohawk	am	-23	-22	- 2			
	pm	-23	-31	3	0	9	- 5
Indian	am	34	37	-17			
	pm	28	80	-12	6	-43	- 5
Post	am	- 1	31	10			
	pm	-13	49	5	12	-18	5
Standard Error		±25	±38	±13	± 7	±22	± 6

B. End and midpoint positions held fixed - 7.8 minutes between updates

SITE	FLIGHT	ERRORS (CM) ϕ	λ	ELEV	CHANGE (CM) $\Delta\phi$	$\Delta\lambda$	ΔE
Abbot	am	49	4	-16			
	pm	63	35	-23	-14	-31	7
Nagog	am	11	33	4			
	pm	26	66	3	-15	-33	1
Natick	am	-58	26	-18			
	pm	-38	-72	- 2	-20	98	-16
Sudbury	am	- 2	5	-14			
	pm	23	-55	1	-25	60	-15
Indian	am	- 9	58	-29			
	pm	- 3	12	-16	- 6	46	-13
Post	am	- 3	36	- 2			
	pm	6	6	7	- 9	30	- 9
Standard Error		±32	±41	±14	±16	±55	±11

C. End points held fixed - 15.7 minutes between updates

SITE	FLIGHT	ERRORS (CM) φ	λ	ELEV	CHANGE (CM) Δφ	Δλ	ΔE
Abbot	am	41	37	-12			
	pm	73	50	-24	-32	-13	12
Nagog	am	3	68	8			
	pm	37	79	2	-34	-11	6
Acton	am	- 4	40	6			
	pm	20	11	- 6	-24	29	12
Mohawk	am	-22	27	2			
	pm	0	9	6	-22	18	- 4
Natick	am	-61	60	-11			
	pm	-23	-65	- 8	38	125	- 3
Sudbury	am	- 7	15	-15			
	pm	26	-51	2	-33	-66	-17
Indian	am	- 9	83	-23			
	pm	11	16	-23	-20	67	0
Post	am	- 5	43	- 1			
	pm	11	9	7	-16	34	- 8
Standard Error		±30	±48	±12	±28	±58	± 9

The plan for the first profiling test is given in figure 4. The flight was a box-like pattern with profiles measured at test sites Acton and Sudbury and retroreflector updates obtained at stations Mohawk and Nat. Flight time around the loop was about 11 minutes, and four counterclockwise loops were done first. An update at Indian was followed by four clockwise passes around the loop. The flights (shown in fig. 5) over the Nagog calibration site were similar, with four passes made in each direction. The flight time around this loop was about 4 minutes. By comparing the results of the two flights, the relationship between profile accuracy and time between retroreflector updates was to be determined.

The profiling test flights were completed on January 22, 23, 27, and 30. Retroreflectors had to be cleared of snow and frost almost daily during this period, and all test sites were covered with snow. The cleared areas were parking lots and roads, and at a 610-m flying height, the asphalt absorbed most of the laser energy so that few profiler returns were obtained in snow-free areas. Most of the vertical test points were on the frozen Nagog Pond or the Sudbury and Acton High School football fields. Also, the horizontal accuracy of the profile data could not be determined because the fine detail imagery (tennis court and playground lines) necessary for this test were snow covered.

The profiling test flights were repeated in May and June when detailed imagery could be obtained. The flights were made at 503 m above ground so that profile data could be acquired from asphalt surfaces. All test flights were flown at 100 knots.

The primary purpose of these tests was to determine the magnitude and characteristics of the vertical accuracy of the profile points. One source of vertical error is the heights measured by the profiler. Figure 6 displays this error for two different well-defined surfaces, Nagog Pond and the Acton High School football field. The results agree well with one another, ±5 cm for the grass field and ±6 cm for the water surface.

The other source of vertical error appears as the bias in figure 6. This is the IMU elevation error and is caused by the accumulation of errors from the inertial instruments and the tracker. The accuracy of the IMU elevation is a function of the time between tracker updates and is proportional to the time interval squared for short time periods. A useful product of these tests is an equation that describes the vertical accuracy of an APTS profile. It will be used to design aerial surveys by providing an estimate of the retroreflector spacing needed to obtain a desired vertical accuracy.

The method employed to determine the IMU elevation accuracy was to measure the bias in each of the 54 profiles obtained. Three sources of information are used for this--the profile data from the postmission processor, the video tape, and the large-scale photomap.

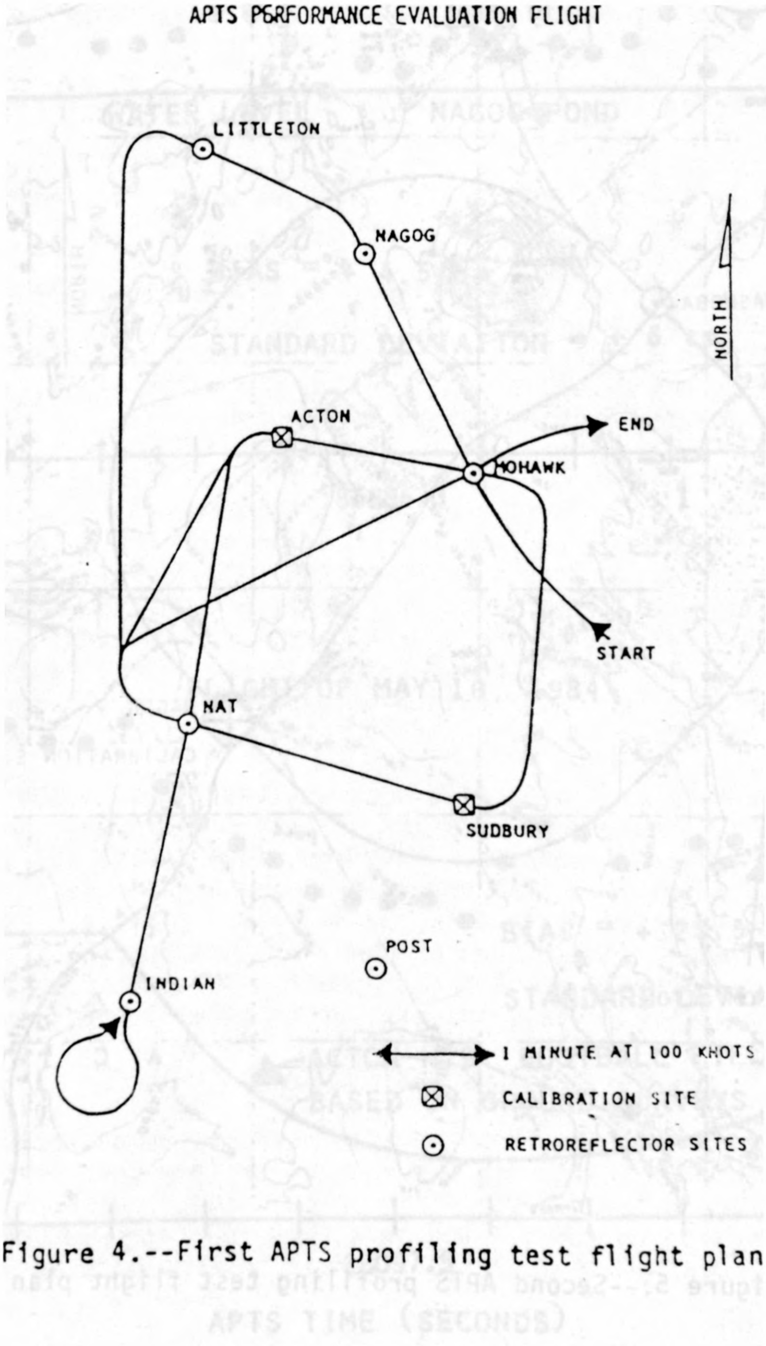

Figure 4.--First APTS profiling test flight plan

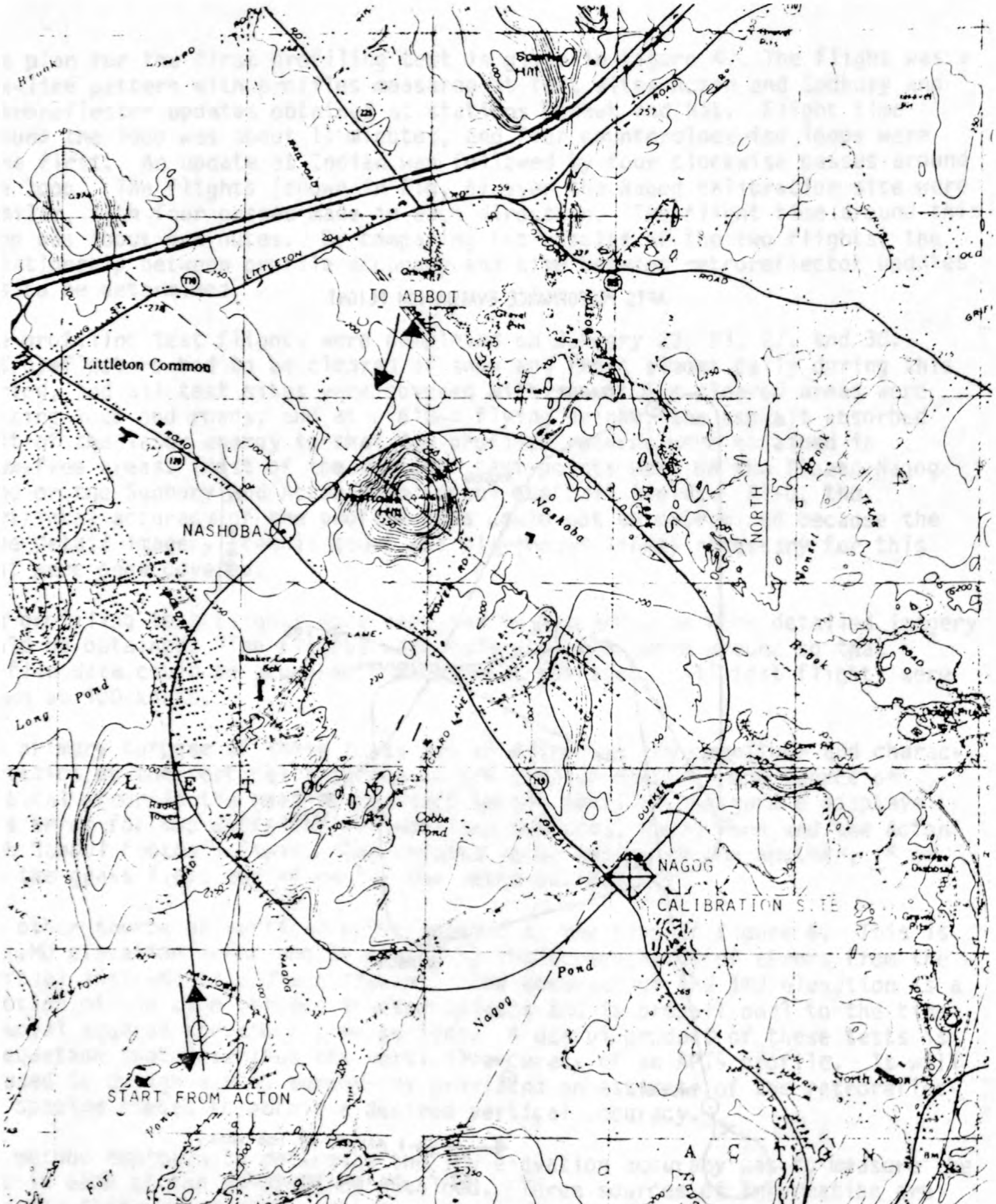

Figure 5.--Second APTS profiling test flight plan

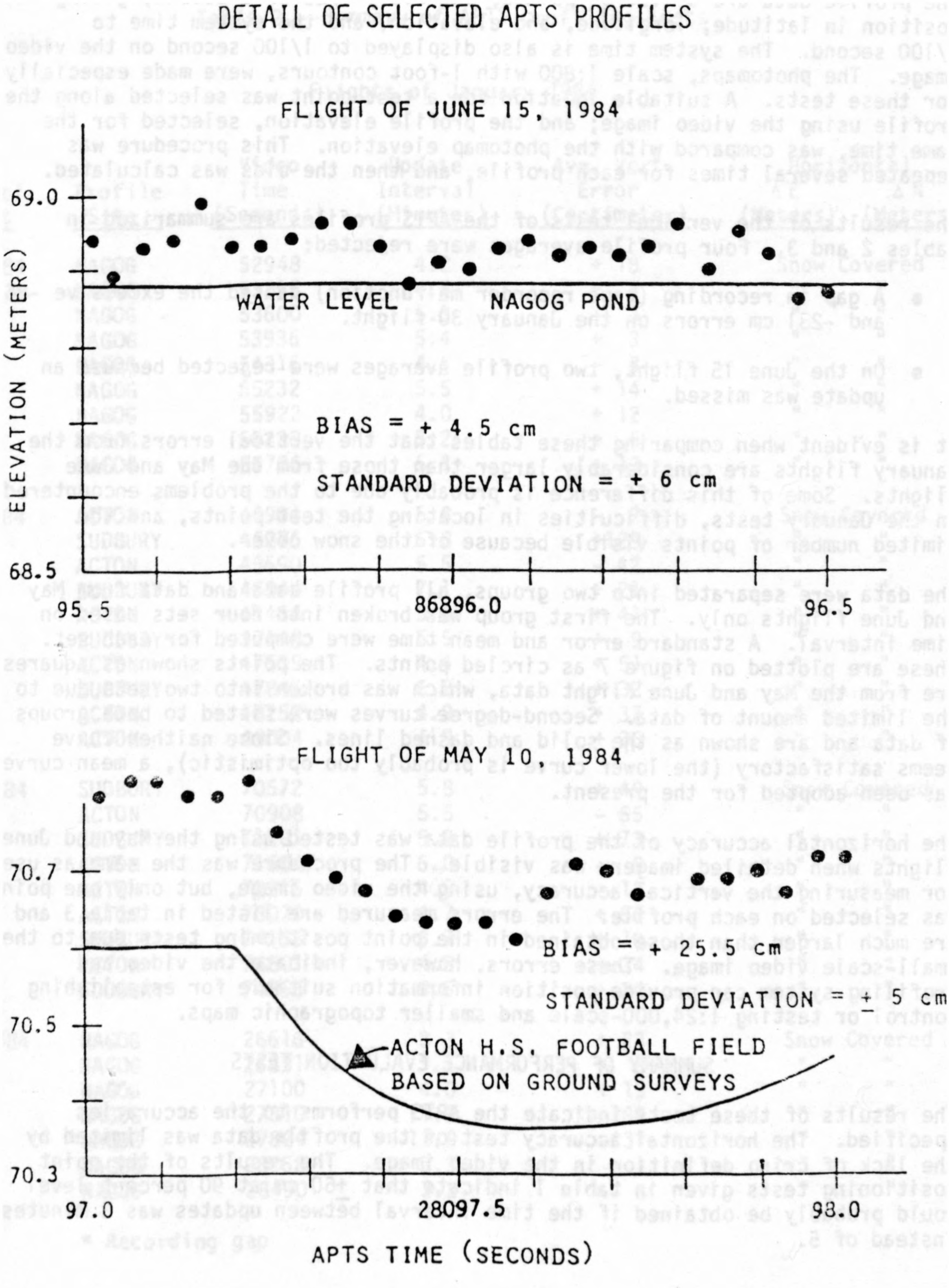

Figure 6.--Profiler accuracy

The profile data are a list of points, one every 1/25 of a second, giving position in latitude, longitude, and elevation, and the system time to 1/100 second. The system time is also displayed to 1/100 second on the video image. The photomaps, scale 1:800 with 1-foot contours, were made especially for these tests. A suitable location for a test point was selected along the profile using the video image; and the profile elevation, selected for the same time, was compared with the photomap elevation. This procedure was repeated several times for each profile, and then the bias was calculated.

The results of the vertical tests of the APTS profiles are summarized in tables 2 and 3. Four profile averages were rejected:

- A gap in recording (tape recorder malfunction) caused the excessive -86 and -231 cm errors on the January 30 flight.

- On the June 15 flight, two profile averages were rejected because an update was missed.

It is evident when comparing these tables that the vertical errors from the January flights are considerably larger than those from the May and June flights. Some of this difference is probably due to the problems encountered in the January tests, difficulties in locating the test points, and the limited number of points visible because of the snow cover.

The data were separated into two groups, all profile data and data from May and June flights only. The first group was broken into four sets based on time interval. A standard error and mean time were computed for each set. These are plotted on figure 7 as circled points. The points shown as squares are from the May and June flight data, which was broken into two sets due to the limited amount of data. Second-degree curves were fitted to both groups of data and are shown as the solid and dashed lines. Since neither curve seems satisfactory (the lower curve is probably too optimistic), a mean curve has been adopted for the present.

The horizontal accuracy of the profile data was tested using the May and June flights when detailed imagery was visible. The procedure was the same as used for measuring the vertical accuracy, using the video image, but only one point was selected on each profile. The errors measured are listed in table 3 and are much larger than those obtained in the point positioning tests due to the small-scale video image. These errors, however, indicate the video and profiling system can provide position information suitable for establishing control or testing 1:24,000-scale and smaller topographic maps.

SUMMARY OF PERFORMANCE EVALUATION TESTS

The results of these tests indicate the APTS performs to the accuracies specified. The horizontal accuracy test of the profile data was limited by the lack of crisp definition in the video image. The results of the point positioning tests given in table 1 indicate that ± 60 cm at 90 percent level would probably be obtained if the time interval between updates was 3 minutes instead of 5.

Table 2.--Summary of APTS profiling tests

Flights of January 1984

Date of Flight	Profile Site	Video Time (Seconds)	Update Interval (Minutes)	Ave. Vert. Error (Centimeter)	Horizontal ΔE (Meters)	Horizontal ΔN (Meters)
1/22/84	NAGOG	52948	4.2	+ 18	Snow	Covered
	NAGOG	53255	4.5	+ 3	"	"
	NAGOG	53600	5.3	- 3	"	"
	NAGOG	53936	5.4	+ 3	"	"
	NAGOG	54316	4.6	- 3	"	"
	NAGOG	55232	5.5	+ 14	"	"
	NAGOG	55922	4.0	+ 12	"	"
	NAGOG	56223	5.2	+ 5	"	"
	NAGOG	56736	5.3	- 13	"	"
1/23/84	ACTON	44904	5.8	- 7	Snow	Covered
	SUDBURY	45276	6.8	+129	"	"
	ACTON	45690	5.5	- 42	"	"
	SUDBURY	46044	7.1	+ 21	"	"
	ACTON	46464	5.3	+ 41	"	"
	SUDBURY	47148	5.5	+ 9	"	"
	ACTON	47535	4.4	+ 51	"	"
	SUDBURY	47846	6.2	+ 32	"	"
	ACTON	48252	4.8	+ 37	"	"
	ACTON	49004	4.9	+ 36	"	"
1/27/84	SUDBURY	70572	5.8	+ 49	Snow	Covered
	ACTON	70908	5.5	- 65	"	"
	SUDBURY	71281	5.2	+ 73	"	"
	ACTON	71604	6.0	- 9	"	"
	ACTON	72316	4.8	- 12	"	"
	ACTON	73070	4.7	+ 56	"	"
	SUDBURY	74165	6.7	+ 10	"	"
	ACTON	74501	4.6	+ 34	"	"
	SUDBURY	74865	6.6	+ 24	"	"
1/30/84	NAGOG	26616	3.3	+ 23	Snow	Covered
	NAGOG	26831	3.7	+ 6	"	"
	NAGOG	27100	4.0	+ 15	"	"
	NAGOG	27310	11.9	- 86	"	"
	*NAGOG	27824	11.9	-231	"	"
	NAGOG	28268	3.3	- 1	"	"
	NAGOG	28490	3.2	- 6	"	"

* Recording gap

Table 3.--Summary of APTS profiling tests

Flights of May and June 1984

Date of Flight	Profile Site	Video Time (Seconds)	Update Interval (Minutes)	Ave. Vert. Error (Centimeter)	Horizontal ΔE (Meters)	ΔN (Meters)
5/10/84	SUDBURY	26067	6.6	+10	-0.9	-0.3
	ACTON	26450	6.4	+22	-0.4	+0.9
	SUDBURY	26849	7.4	- 3	+0.2	-1.9
	ACTON	27266	6.3	+ 7	NO SUITABLE POINT	
	SUDBURY	27668	7.5	-15	+0.8	- 0.8
	ACTON	28098	8.0	+15	-0.8	+0.5
	ACTON	28949	4.8	0	+1.8	-0.4
	SUDBURY	29260	7.0	-20	+1.3	+0.3
	ACTON	29654	4.8	+16	-2.0	-0.7
	SUDBURY	29960	7.1	- 8	-1.6	0.0
	ACTON	30366	4.9	+ 3	+1.1	+0.9
6/15/84	NAGOG	84758	4.6	- 2	-0.7	+0.8
	NAGOG	85050	5.0	+11	+0.5	-0.6
	NAGOG	85361	5.3	+ 7	+0.6	0.0
	NAGOG	85673	3.9	-15	NO SUITABLE POINT	
	NAGOG	86006	3.9	+ 3	" "	"
	NAGOG	86611	9.3	-15	+0.6	-0.3
	*NAGOG	86900	9.3	+ 1	-1.0	+1.1
	NAGOG	87148	3.8	+ 4	-0.1	+1.2

* No update obtained

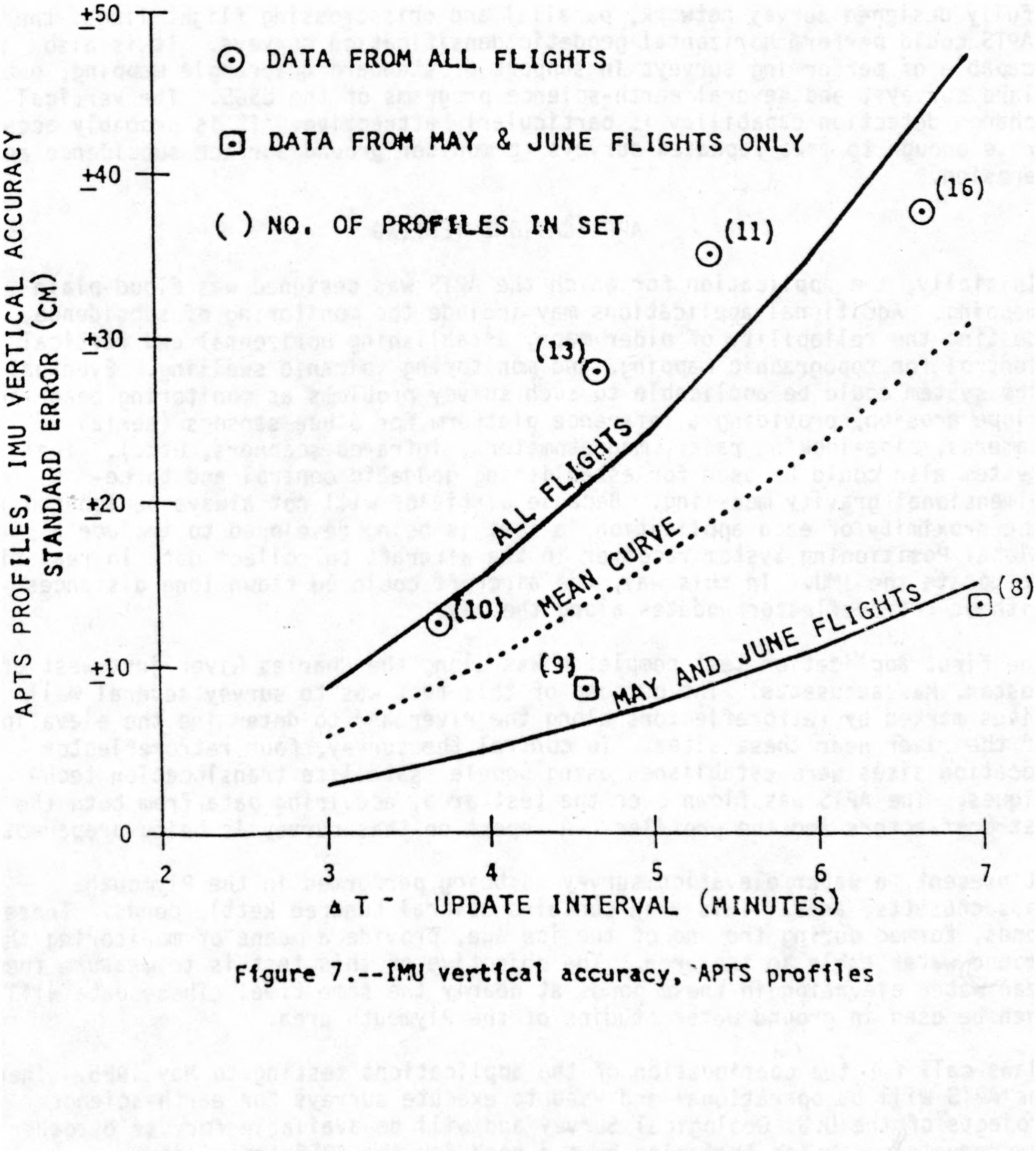

Figure 7.--IMU vertical accuracy, APTS profiles

The vertical accuracy of the profile data is considered more critical than the horizontal. It was believed that if the APTS can meet the ±15 cm accuracy requirement, then the horizontal accuracy will also be met. The profiling test data reduced to a standard error of ±6 cm at a 3-minute update interval (fig. 7). This, combined with the ±6 cm profiler noise (fig. 6), produces ±14 cm at the 90 percent level.

The results of the point positioning tests indicate that the APTS has accuracy capabilities suitable for low-order horizontal geodetic surveys. With a carefully designed survey network, parallel and crisscrossing flight lines, the APTS could perform horizontal geodetic densification surveys. It is also capable of performing surveys in support of standard quadrangle mapping, public land surveys, and several earth-science programs of the USGS. The vertical change detection capability is particularly attractive. It is probably accurate enough to make repeated surveys to monitor ground surface subsidence and erosion.

APPLICATIONS TESTING

Initially, the application for which the APTS was designed was flood-plain mapping. Additional applications may include the monitoring of subsidence, testing the reliability of older maps, establishing horizontal and vertical control for topographic mapping, and monitoring volcanic swelling. Eventually the system could be applicable to such survey problems as monitoring beach and slope erosion, providing a reference platform for other sensors (aerial cameras, side-looking radar, magnetometers, infrared scanners, etc.). The system also could be used for establishing geodetic control and three-dimensional gravity modeling. Because airfields will not always be located in the proximity of each application, a test is being developed to include a Global Positioning System receiver in the aircraft to collect data in real time to update the IMU. In this way, the aircraft could be flown long distances without retroreflector updates along the way.

The first application test completed was along the Charles River just west of Boston, Massachusetts. The purpose of this test was to survey several well sites marked by retroreflectors along the river and to determine the elevation of the river near these sites. To control the survey, four retroreflector location sites were established using Doppler satellite translocation techniques. The APTS was flown over the test area, acquiring data from both the retroreflectors and the profiler. A report on this survey is being prepared.

At present, a water elevation survey is being performed in the Plymouth, Massachusetts, area. This area contains several hundred kettle ponds. These ponds, formed during the end of the ice age, provide a means of monitoring the ground water table in the area. The objective of this test is to measure the mean water elevation in these ponds at nearly the same time. These data will then be used in ground water studies of the Plymouth area.

Plans call for the continuation of the applications testing to May 1985. Then the APTS will be operational and used to execute surveys for earth-science projects of the U.S. Geological Survey and will be available for use by other Governmental agencies that also have a need for the APTS capability.