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APPLICATION OF THE AERIAL PROFILING OF TERRAIN SYSTEM

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ABSTRACT

The U.S. Geological Survey (USGS) has completed the performance evaluation flight testing of the Aerial Profiling of Terrain System (APTS) and is now performing a series of application tests to determine its effectiveness and efficiency as an Earth science data collection tool. These tests are designed to evaluate the APTS at such tasks as positioning water wells, testing reliability of maps, measuring elevation of kettle ponds, and profiling stream valleys for flood studies. The results of three application tests are discussed: positioning water wells and measuring elevations along the Charles River; measuring elevations of 100 kettle ponds near the Cap Cod Canal; and precise point positioning. The foliage penetration capability of the profiler is also discussed.

INTRODUCTION

Since 1974, the U.S. Geological Survey (USGS) has been involved in the development and application of inertial surveying systems in support of mapping projects. The Aerial Profiling of Terrain System (APTS) is an airborne inertial surveying and profiling system which has been designed, constructed, and tested by the Charles Stark Draper Laboratory (CSDL) in Cambridge, Mass., for the USGS.

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 coordinate system referenced to the local datum. The tracker measures precise ranges and angles to retroreflectors on known points relative to the datum. The system is calibrated and aligned over a point for which the coordinates and gravity are accurately known The laser profiler measures accurate ranges to the terrain surface from the reference platform. The onboard computer serves as a system controller and data collector, computing real-time estimates of the aircraft position. The data processed by this computer consists of the profiler ranges, the tracker ranges and gimbal angles, and the IMU gimbal angles and accelerations. A video system records the ground image below the aircraft during profiling.

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After the flight mission has been completed, the data are further processed by a post-mission software program installed in a mainframe computer. This software edits and provides estimates of system errors, such as IMU position and velocity errors, which are then combined with the real-time estimates of position and velocity. These improved positions are then combined with the profiler data to provide accurate latitudes, longitudes, and elevations of profile points along the flight path. This very large file of points (approximately one point every 2 meters) is then edited in a ground data editing system to the specifications of the user.

The APTS was designed to collect profile data accurate to ±60 cm (±2 ft.) in the horizontal coordinates and to ±15 cm (±6 in.) in the vertical coordinate 90 percent of the time. In January 1984 a series of performance evaluation tests confirmed that these accuracies were achieved. These tests were conducted over a calibration range in the Boston area. The range consisted of 15 retroreflector sites that were presurveyed with Magnavox 1502 Doppler receivers over an area of 10 by 30 miles (16 by 48 km). Orthophoto maps at 1:800 scale were made of three of the sites. These maps were contoured using 1-foot intervals and were used as ground truth to test the APTS-measured profiles.

After performance evaluation, the APTS system was made operational and a series of applications tests was initiated. These tests were designed to develop the procedures and field support by which the system would be operated and to demonstrate its ability to collect Earth science data.

APPLICATIONS TESTING

The initial application for which the system was designed was flood-plain mapping. This has been expanded to include the monitoring of ground subsidence, map reliability testing, control for topographic maps, and volcanic swelling. Eventually, the system will be applied to such survey problems as monitoring beach and slope erosion and to providing a reference platform for other sensors (such as aerial cameras, side-looking airborne radar, magnetometers, and infrared scanners). The system also appears capable of establishing geodetic control and three-dimensional gravity modeling.

The accuracy of APTS profile data depends on frequent (at least every 400 seconds) velocity and position updates from retroreflectors. As a result, the number of retroreflectors required for a project is proportional to the size of the area to be profiled.

A significant reduction in the amount of preparatory field survey work could be achieved if the number of retroreflectors required for large projects could be reduced. Global Positioning System (GPS) data collected simultaneously with inertial data could prove to reduce the number of surveyed retroreflectors required to provide position references. An application test to evaluate combined GPS/APTS data collection was completed in June 1985. In this test a five-channel GPS receiver collected velocity data which were later compared to post-processed APTS velocity data. The results of this test provided the sponsor, U.S. Army Signal Corps, with an estimate on the accuracy to which GPS can measure velocity.

Once an application test has been proposed by a principal investigator, a plan for execution of the test is developed and a field crew dispatched to the area to select retroreflector sites and establish geodetic control. Normally, the location of retroreflector sites is chosen based on the requirements of the project, the APTS flight plan, availability of geodetic control, and physical security. Both conventional and satellite survey techniques are used to establish the horizontal positions of these sites. The elevation of each site is measured using fly or higher order leveling techniques from benchmarks on the North American Vertical Datum. A minimum of three control points with retroreflectors, not in a line, is required by the system. Additional sites can be surveyed by the APTS during a data collection flight if the positions of these sites are known within 50 meters. While these points are not suitable for position updates, they can be used by the system to obtain velocity updates. Retroreflectors must also be spaced so that the system is never without a tracker update for more than 400 seconds; otherwise, the profile accuracy will be less than ± 15 cm vertically and ± 60 cm horizontally.

After the retroreflector sites have been surveyed, the flight details are planned, and the aircraft crew is briefed on the mission. Before the day of the flight, the field crew installs the retroreflectors at those sites where physical security is good. On the day of the flight, the remaining retroreflectors are installed for the period of data collection and then removed.

The Charles River Project

The first applications test completed was along a 28-mile stretch of the Charles River just west of Boston, Mass. The purpose of this project, proposed by the Water Resources Division of the USGS, was to survey several well sites along the river and to determine the elevation of the river near these sites. The level of the water in these wells is monitored by the USGS in conjunction with its studies of water use in the area.

The project started in March 1984 and was completed in May 1984. The weather and several systems problems delayed the completion of the test. However, solution of the systems problems led to greatly improved performance. The two most significant improvements were (a) changes to the software controlling the laser tracker; and (b) better understanding of the parameters contributing to good retroreflector performance. Several of the retroreflector sites were close enough together to be visible nearly simultaneously during some of the flight paths. Since the software was designed to always track the nearest retroreflector, the desired retroreflector was not always tracked and, as a result, data were lost. To overcome this problem, the tracker software was modified to track retroreflectors according to a predetermined order or on command of the operator as well as tracking the nearest retroreflector automatically. After reviewing the records of retroreflector lock success rates, it was determined that retroreflectors which consistently had poor performance had corner reflector glass deviation angles greater than 30 arcseconds. As a result, only retroreflectors with deviation angles of less than 30 arcseconds are used on projects now.

The project was reflown on October 30, 1984, and was completed in a single flight, demonstrating how significantly the system had been improved. The project area for this test is shown in figure 1. The four control points were Morses Pond, Red Cross, Dedham, and Wheelock School. The well sites surveyed are numbered 1 through 18. Five of the sites in the original proposal were not surveyed by the system because their positions and elevations could be easily determined by conventional means.

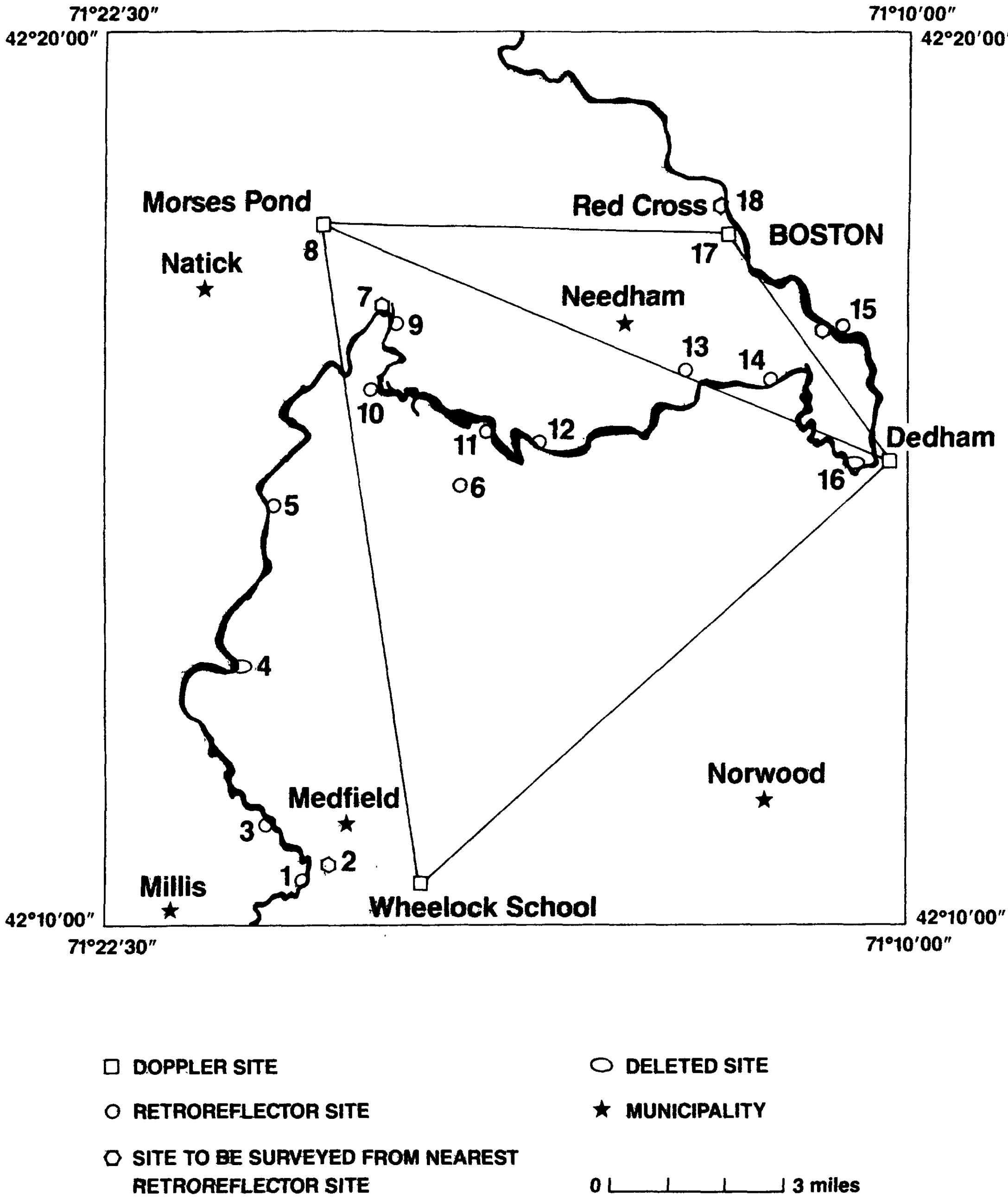

Figure 1.--Charles River Project area, Massachusetts, used for APTS application testing, October 30, 1984.

The procedure followed in using the APTS was to first perform an overnight (12-hour) calibration and alignment at Hanscom Field. This process first measures the platform drifts, misalignments, and acceleration errors and then aligns the axes of the platform with north, east, and down. The APTS was then flown to the project area, approximately 10 minutes flying time. Upon arrival, the system was flown along a predetermined flight path (approximately 1.5 hours long) designed to optimize the survey data collection. The results of the initial May 7, 1984 survey for 11 of the retroreflector sites are shown in Table 1. Listed in this table are the latitude, longitude, and elevations of the station marks as measured by the APTS. The results from profiling the river to determine its elevation at various points are shown in figure 2. As expected, the river decreases in elevation in the direction of flow. The increases in elevation (bumps) plotted on the figure are a result of the APTS not receiving a tracker update in sufficient time to correct IMU errors.

Table 1.--Charles River, Mass., Project retroreflector coordinates measured by Aerial Profiling of Terrain System, May 7, 1984

Retroreflector	Latitude	Longitude	Elevation (m)
1	42° 10' 20.398"	71° 19' 03.750"	36.61
3	42° 11' 11.057"	71° 19' 54.451"	38.18
5	42° 14' 45.364"	71° 19' 46.006"	38.27
6	42° 14' 58.454"	71° 16' 52.190"	40.91
9	42° 16' 42.104"	71° 17' 50.800"	43.81
10	42° 16' 00.493"	71° 18' 12.433"	35.94
11	42° 15' 34.775"	71° 16' 25.143"	34.30
12	42° 15' 24.790"	71° 15' 32.539"	29.22
13	42° 16' 13.649"	71° 13' 19.392"	30.10
14	42° 16' 02.694"	71° 12' 13.036"	33.37
15	42° 16' 39.268"	71° 10' 58.390"	29.96

The Kettle Ponds Project

The Kettle Ponds Project area is located approximately 30 miles south of Boston, Mass., and includes six 7-1/2 minute quadrangles (North Plympton, Plymouth, Manomet, Sagamore, Wareham, and Snipatuit). This area is primarily used for cranberry growing because the ponds provide readily available water. The area contains approximately 600 ponds. Kettle ponds were formed when the North American glacier receded and large blocks of ice were left buried in the drift. When the blocks melted large depressions remained and became ponds. Because the bottoms of the ponds are below the level of the water in the aquifer, the level of the water in the ponds is a measure of the water table in the area.

The objective of this test was to measure the elevation of the water in as many ponds as possible in a single flight, providing a snapshot of the water levels throughout the area. This information is used by hydrologists to initialize and evaluate digital water models. These models provide information useful in planning ground water use.

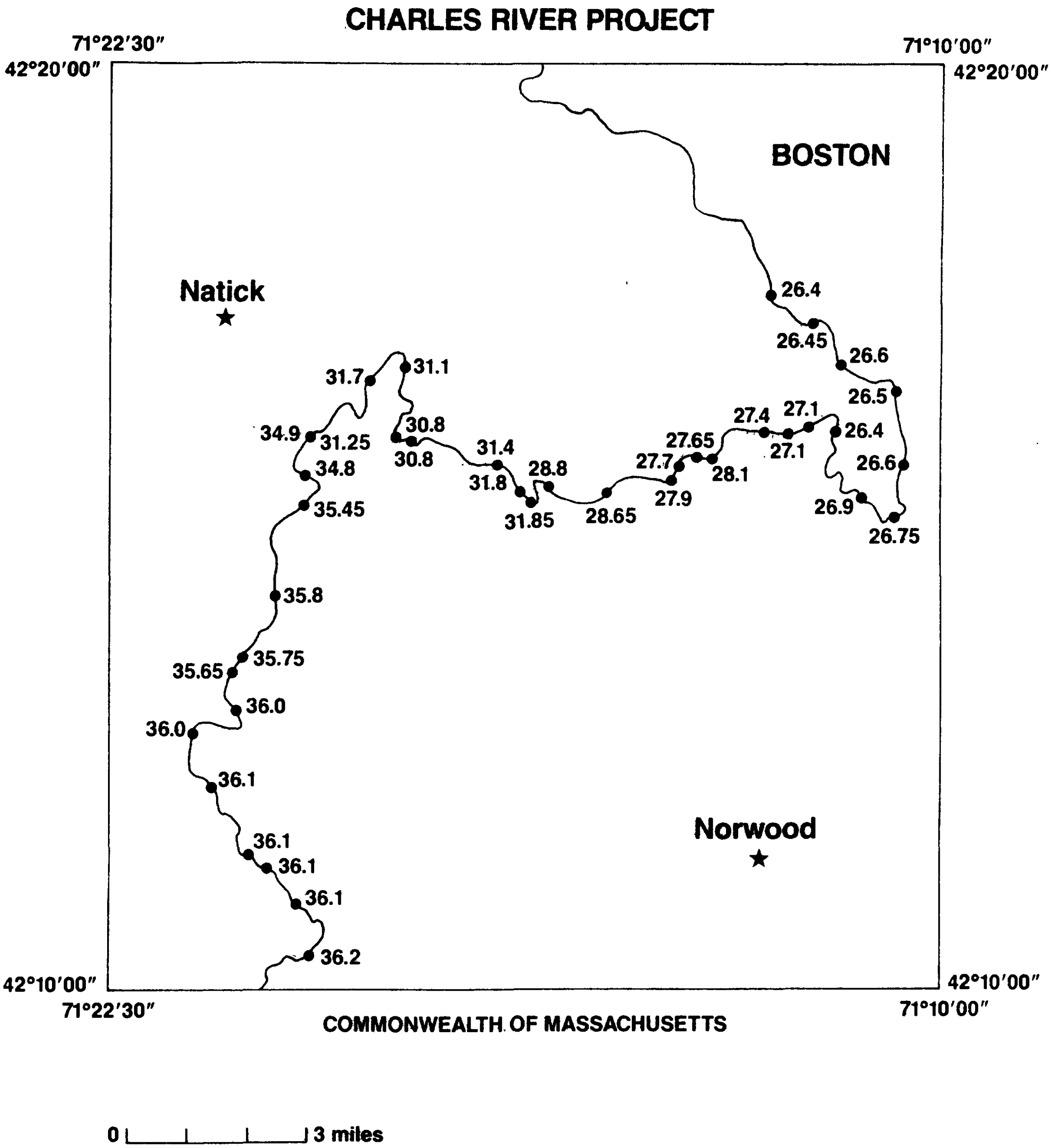

Figure 2.--Charles River, Mass., elevations (meters) derived from APTS profiling project, May 7, 1984.

Planning for this project provided a new challenge to project personnel. The arrangement of the ponds is random, shown in figure 3 . It soon became obvious that measuring all of the ponds in a single flight would be impossible. It was decided to measure those ponds that tend to be in line and to sample pond elevations in all six quadrangles. The 14 control sites were chosen accordingly and surveys performed during March 1984.

The horizontal survey for ground control was performed using high precision Global Positioning System (GPS) equipment in the translocation mode. This survey technique was chosen over Doppler because of the potential improvement in accuracy that the GPS would provide. The improved accuracy would be reflected in the APTS data.

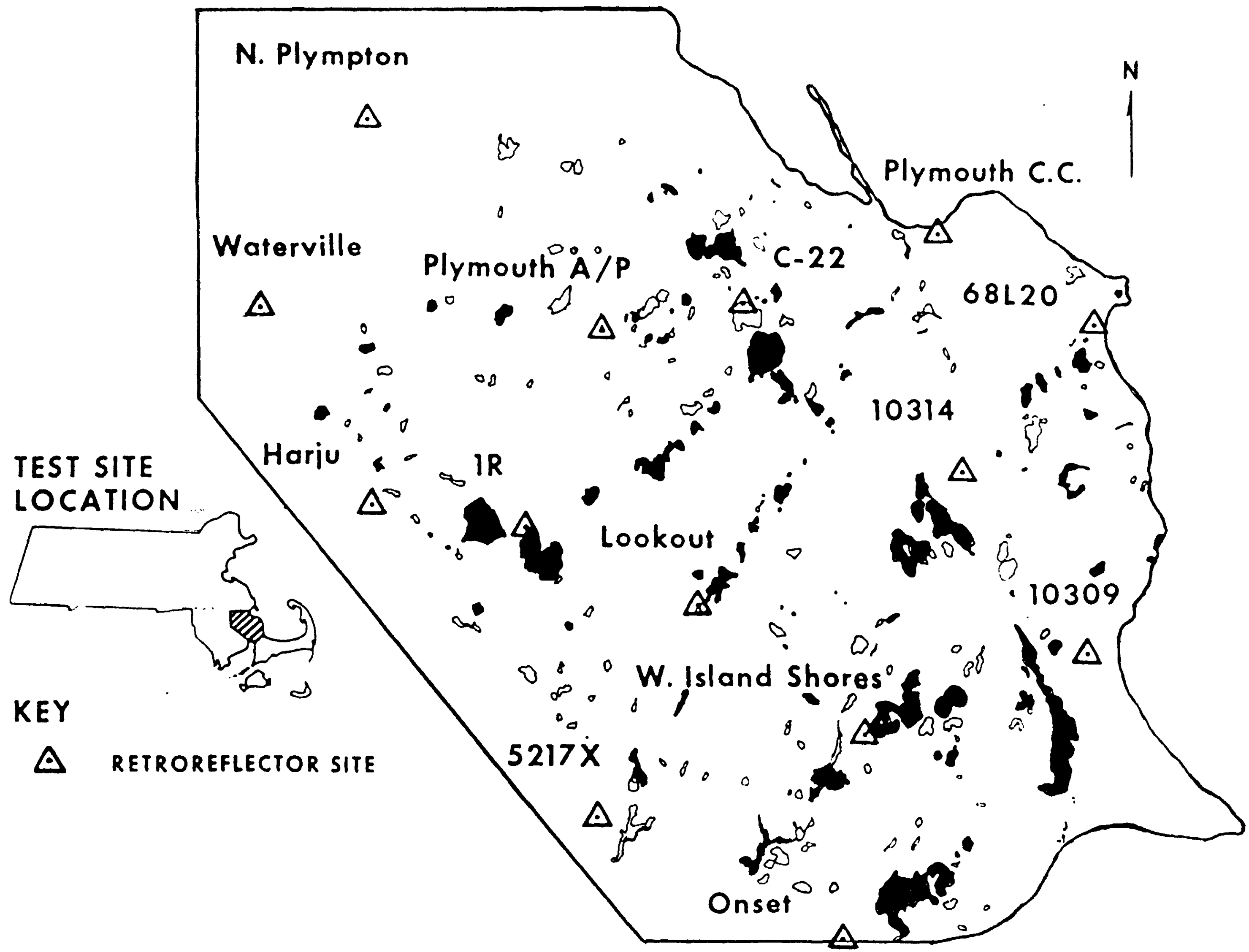

Figure 3.--Kettle ponds distribution in APTS project area, Massachusetts. Shaded ponds are those profiled.

The system was calibrated and aligned at Hanscom Field prior to the data collection flight. It was then flown to the municipal airport at Plymouth, Mass., refueled, and updated over a survey mark at the airport parking ramp. This process took about 20 minutes to complete, providing a quick means to obtain an update before data collection. The flight plan for this application is shown in figure 4. Time required for the data collection portion of this flight was approximately 2 hours.

One hundred and five ponds were profiled during the flight. The distribution of the ponds profiled is shown in figure 3. The ponds that were profiled are shaded. Twelve ponds were profiled more than once. The average difference in repeated measurements was within 9 cm. The results of this comparison are shown in table 2.

The Plymouth Point Positioning Project

The survey for the kettle ponds area was performed using high-precision GPS techniques, so that a point positioning test could be done using some of the retroreflector sites as unknowns. The APTS-determined positions could then be compared with the GPS positions and with surveyed elevations. It was felt that better results could be obtained over that of the performance evaluation tests at the calibration range since the ground truth data were more accurate.

The data collection flight path for this test is shown in figure 5. Data were collected in two flights on December 4 and 7, 1984. The control points were North Plympton, Plymouth C.C., 68L-20, Onset, 5217ZX, and Waterville. The remaining stations were treated as unknowns by the postprocessor. The flight path was arranged so that the time between retroreflector updates was as short as possible. The longest time was 4.3 minutes, and the average time was 2.3 minutes. The flight took approximately 1.5 hours to complete. The results of the comparison are shown in table 3. Note that the system standard error of measurement is below the decimeter level in all three coordinates on the December 4th flight.

Foliage Penetration

The APTS laser profiler has been designed to maximize foliage penetration in wooded areas. Each time the laser transmits a pulse, multiple reflections are received from the foliage and the ground. In this test, a section of profile data, collected during the kettle ponds application test, was plotted to demonstrate the foliage penetration capability. This ability would be useful in such applications as measuring average tree height and determining the volume of wood contained in a forested area.

The reflected laser pulses can be processed in four different ways:

1. Leading edge of the last reflection;
2. Alternate transmitted pulses, trailing edge of the last reflection, leading edge of the last reflection;
3. Trailing edge of the last reflection;
4. Alternate transmitted pulses, leading edge of the last reflection, leading edge of the first reflection.

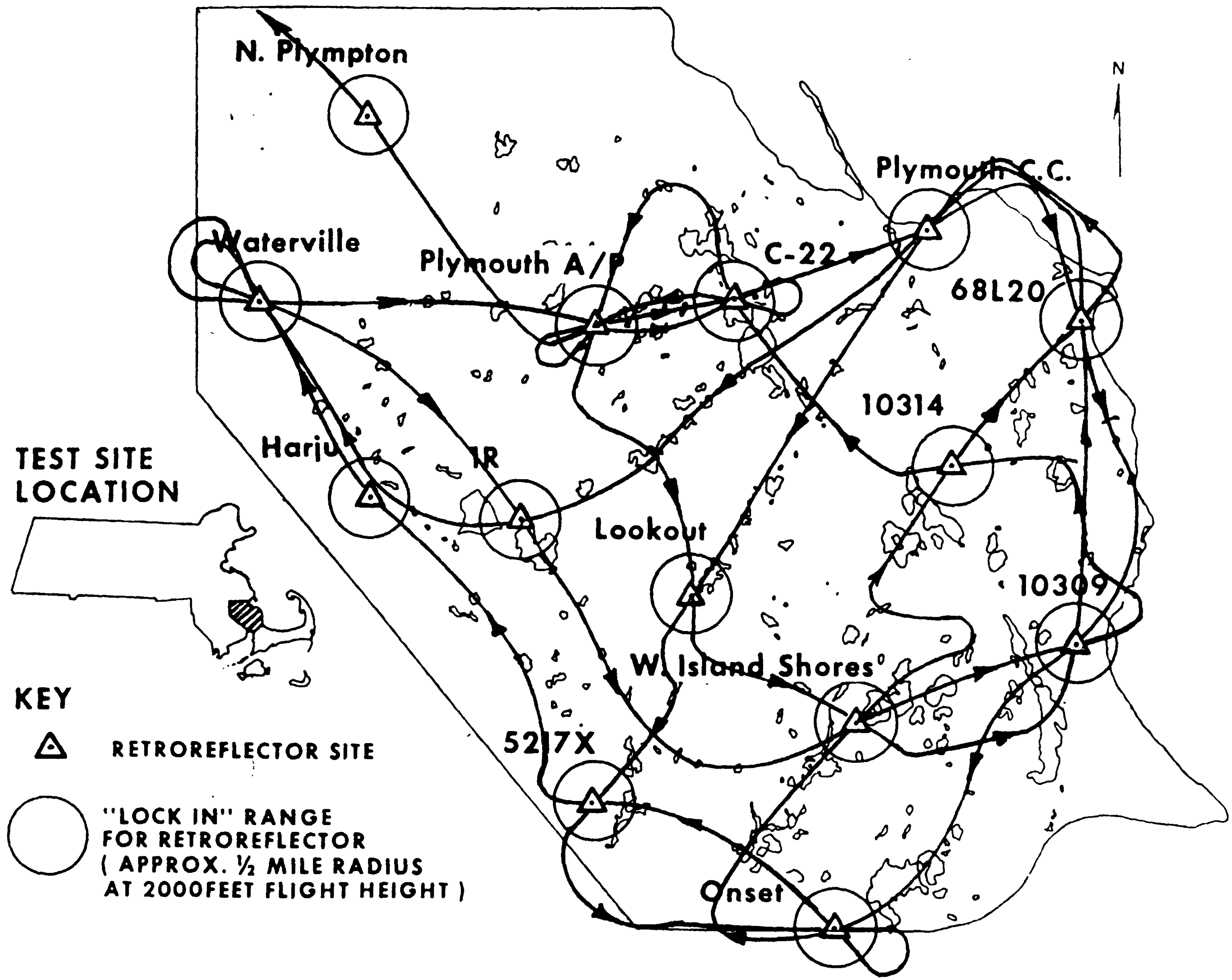

Figure 4.--Flight plan for kettle ponds area, Massachusetts, APTS test.

Table 2.--Water levels from repeated profiles, kettle ponds APTS application test

Pond	Water Levels (meters) 1	2	3
Macajah	32.99	33.02	
Little South	30.60	30.60	30.63
Fresh	4.47	4.61	
Shallow	9.51	9.61	
Tiangle	11.65	11.55	
#1	29.03	28.91	29.20
White Island	14.85	14.92	14.85
Russell Millpond	15.79	15.85	
Pond at Atwood Boggs	27.16	27.18	
Great South	30.56	30.41	
Federal	30.30	30.18	
Hodges	10.22	10.15	

Processing mode 4 provides the means of demonstrating the ability of the profiler to measure the elevation of the topography in wooded areas where multiple returned pulses are received for each transmitted pulse. The profiler signal processor splits the processing of the reflected pulses, providing simultaneous measurements of the tree tops and the topography. Every other measurement cycle is referred to as the A profiler and the others as the B profiler. In mode 4, therefore, half the data will be measured using the leading edge of the last reflection while the other half, B, will be measured using the first reflection. The theory behind this technique is that the first reflection will be from the tree tops, while the last will have come from the ground.

A 4-second segment of profiler data taken from the November 30, 1984 kettle ponds flight was used to demonstrate this woodland penetration capability. These data were plotted in figure 6 and are from the area of the pond named The Arm. Each point plotted on this graph is a first or last pulse measurement determined by measuring eight of the longest or shortest ranges measured. The solid dots (A profiler) are last pulse measurements while the "+" (B profiler) are first pulse measurements. The first pulse measurements are more scattered in the wooded areas, as expected. The last pulse measurements tended to penetrate the trees to measure the terrain surface. The elevations measured on the pond are nearly identical except for a constant 10 cm bias between the two profile modes. Four of the last pulse measurements over the pond are not identical in elevation. The cause of these outliers is under investigation.

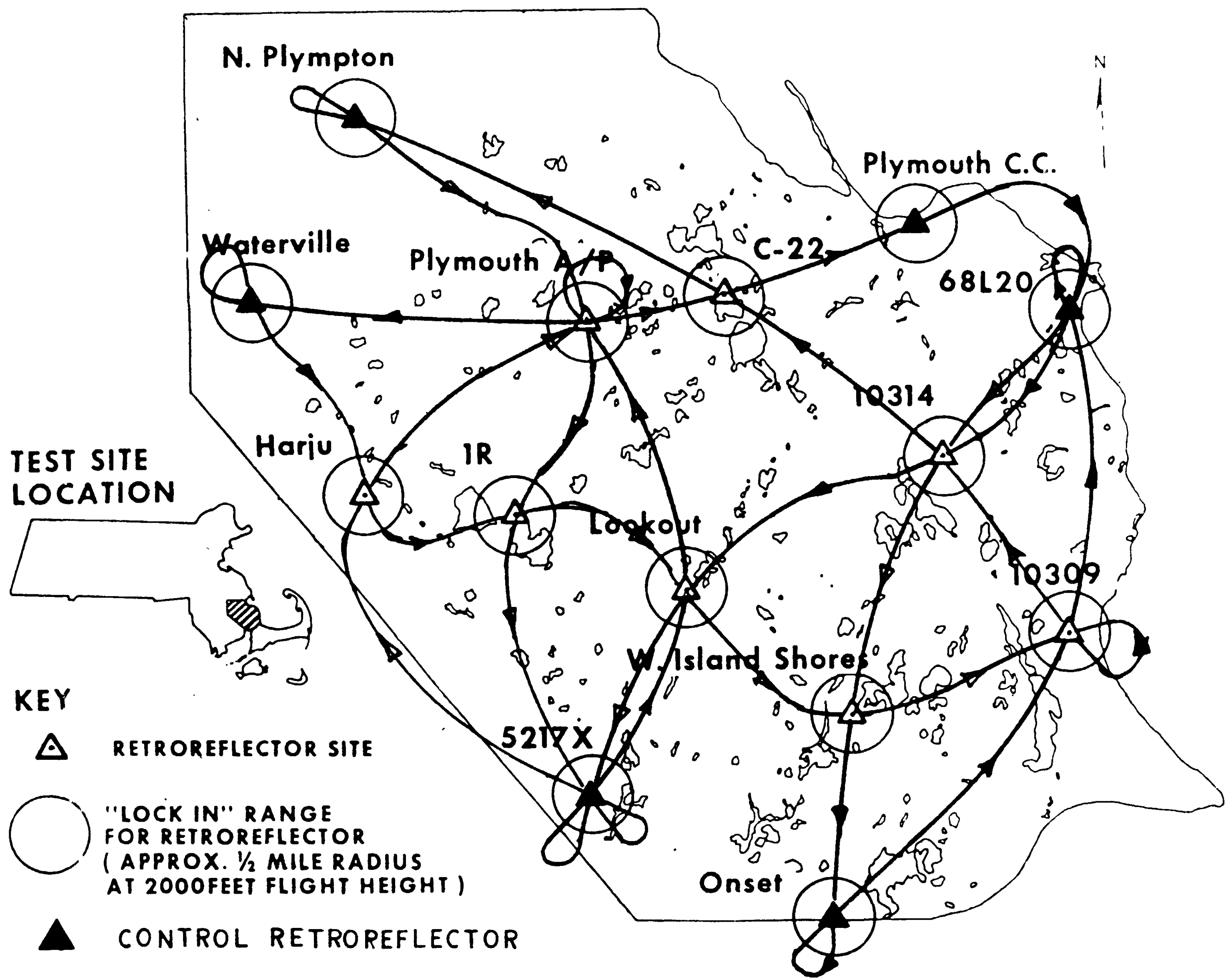

Figure 5.--Flight plan for Plymouth point positioning APTS test.

Table 3.--APTS positioning errors, in centimeters (inches), Plymouth, Mass., Point Positioning Project, December 1984

Retroreflector		Flight of December 4		Flight of December 7	
		cm	in	cm	in
10314	Lat.	10.0	(3.9)	-7.5	(-2.9)
	Long.	15.4	(6.1)	11.6	(4.6)
	Elev.	-5.6	(-2.0)	6.8	(2.7)
1R	Lat.	-1.6	(-0.6)	-9.8	(-3.9)
	Long.	3.4	(1.3)	-7.2	(-2.8)
	Elev.	2.9	(1.1)	1.6	(0.6)
Airport	Lat.	14.4	(5.7)	-1.8	(-0.7)
	Long.	15.3	(6.1)	-4.7	(-1.8)
	Elev.	-4.3	(-1.7)	2.9	(1.1)
Harju	Lat.	-12.3	(-4.8)	-16.6	(-6.5)
	Long.	7.1	(2.8)	7.8	(3.1)
	Elev.	-4.3	(-1.7)	-21.5	(-8.5)
Lookout	Lat.	-1.9	(-0.7)	-12.5	(-4.9)
	Long.	0.5	(0.2)	-12.8	(-5.0)
	Elev.	2.0	(0.8)	6.3	(2.5)
White Island Shores	Lat.	-0.9	(-0.3)	-6.7	(-2.6)
	Long.	2.3	(0.9)	-6.9	(-2.7)
	Elev.	-4.0	(-1.6)	-3.6	(-1.4)
C22	Lat.	-3.2	(-1.3)	-9.8	(-3.9)
	Long.	11.1	(4.4)	-7.2	(-2.8)
	Elev.	-6.1	(-2.4)	3.3	(1.3)
10309	Lat.	9.3	(3.7)	-25.5	(-10.0)
	Long.	-9.6	(-3.8)	-28.9	(-11.4)
	Elev.	7.8	(3.1)	3.7	(1.5)
STANDARD ERRORS	Lat.	± 8.4	(±3.3)	±13.1	(±5.2)
	Long.	± 9.7	(±3.8)	±13.1	(±5.2)
	Elev.	± 4.9	(±1.9)	± 8.6	(±3.4)

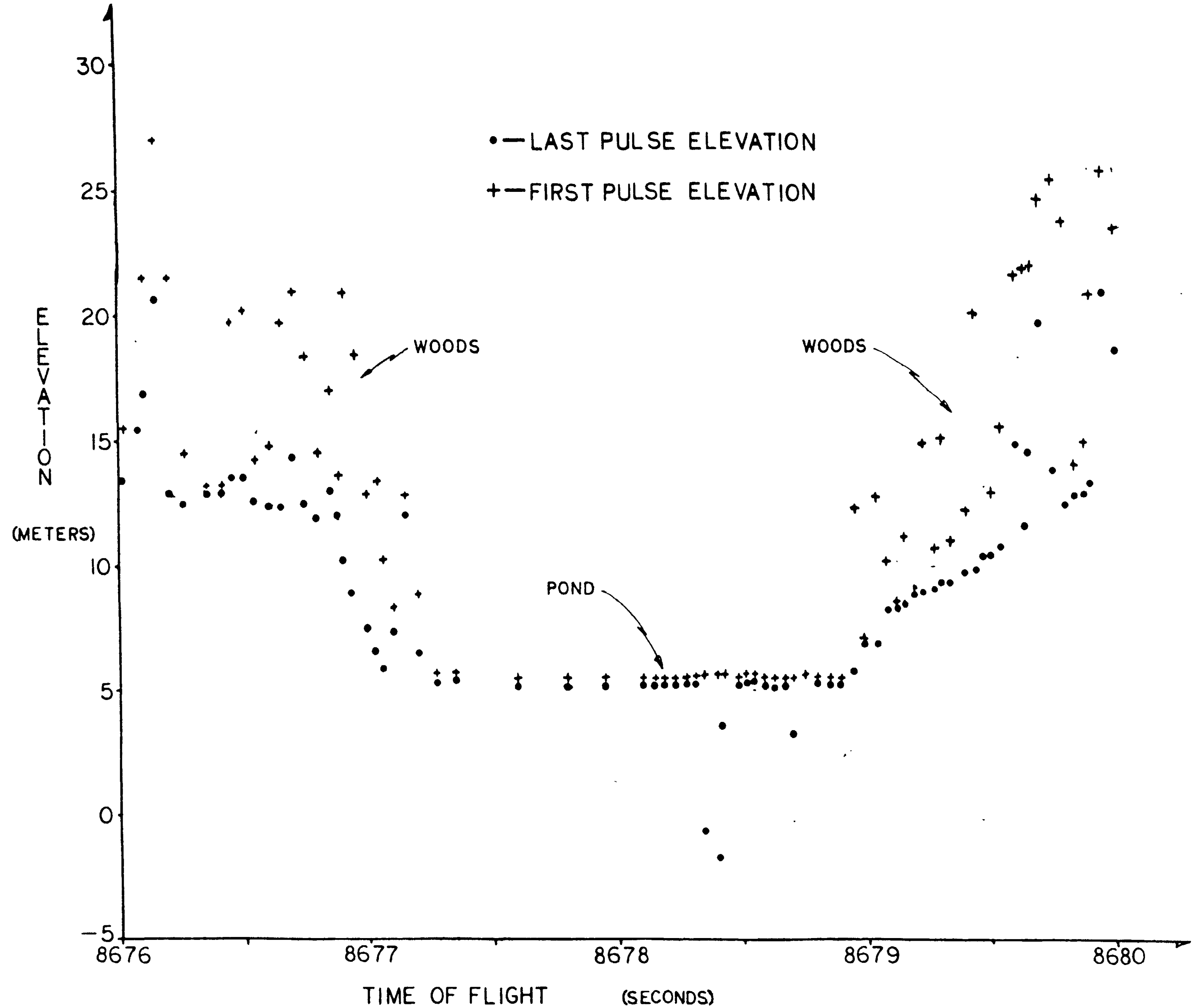

Figure 6.—Profiler plot used for foliage penetration test, the Arm pond, Mass., Nov. 30, 1984.

FUTURE APPLICATION TESTS

Application testing of the APTS is nearing completion; additional projects are in the planning stages or in progress. These tests will further expand the range of applications for the system by providing a variety of conditions under which the system will be operated and tested. The tests presently in progress or in the planning stages are as follows:

<u>Scheduled Applications</u>

*APTS/GPS Relative Positioning Test
*Plymouth Map Accuracy Testing
*Nashoba DEM
*Farmington River Flood Plain Project
*Lebanon, Hew Hampshire Profiling Project
*Control for Mapping

<u>Proposed Applications</u>

*Salt Lake Desert Profiles
*James River Digital Elevation Model (N. Dakota)

The National Geodetic Survey (NGS) will participate in a relative positioning test using two Texas Instrument 4100 GPS receivers. One GPS receiver will be installed in the APTS aircraft, while the other receiver will be located near a known point on the ground. The APTS will then be flown over a prescribed course collecting data simultaneously with the GPS receivers. Preliminary tests conducted by the NGS have demonstrated the possibility of performing relative positioning of an aircraft to decimeter accuracies.

The data for a map accuracy test have been collected. Four 7-1/2 minute quadrangle map sheets from the Plymouth, Mass., area are being tested to determine their reliability. The topography for these sheets was measured in the 1930's using planetable surveys. Approximately 20 points will be selected from each sheet and used in the comparison.

The other tests listed are planned for 1986. The Nashoba digital elevation model (DEM) will consist of a series of closely spaced profiles of a ski slope hill near Hanscom Field, Mass. These profiles will be compared to those obtained from a special orthophoto map of the hill with contours overlayed to be used as ground truth. The purpose of this application will be to determine if APTS can be used to develop accurate high-resolution DEM's of specific terrain features.

The Lebanon, New Hampshire Project was initiated by the Geologic Division of the U.S. Geological Survey. The APTS will be used to collect profile data along lines spaced 1 km apart along which points will be positioned to be used in a gravimeter survey.

The Control for Mapping Project will be conducted in cooperation with the Mid-Continent Mapping Center of the National Mapping Division. The project area is near Springfield, Mass. Twelve 7 1/2-minute quadrangle sheets are scheduled as new mapping projects.

Two other proposed projects are The Great Salt Lake Desert Profile[1] project in Utah and the James River Drainage Basin in North Dakota. The Salt Lake Desert Project will consist of a series of profiles spaced at 2 miles over approximately 1,600 square miles of desert. This area is bounded on the north by the Southern Pacific Railway and on the south by Interstate 80. The profile data will be used to design a drainage system for controlling Great Salt Lake flooding. The James River Project will be conducted for the Bureau of Land Management (BLM). The BLM will use the profile data collected in a DEM of the prairie pothole country to determine rainwater runoff. This information is vital to the design of a dam spillway on the James River.

CONCLUSIONS

The prototype APTS has successfully completed performance evaluation testing and several application tests. The results of these tests confirm that APTS performs at the desired level of accuracy and can collect data to satisfy a wide range of applications. Further testing during 1985 will further expand the range of applications. Following completion of these tests, the APTS will be used in a production mode on selected earth-science projects.

[1] The Great Salt Lake Project was completed in August 1985.