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AIRBORNE PRECISION MAPPING SYSTEM

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ABSTRACT

The Aerial Profiling of Terrain System (APTS) was developed under a contract with the Charles Stark Draper Laboratory of Cambridge, Mass., for the U.S. Geological Survey. The APTS was designed to profile terrain from a relatively small aircraft, such as a Twin-Otter, and consisted of an inertial measuring unit, a laser tracker, a laser profiler, a video imaging system, a computer, and supporting electronics. The inertial measuring unit and laser tracker provided an accurate three-dimensional coordinate system referenced to the local datum through a calibration and alignment process. This accuracy was maintained by periodic update measurements using the tracker in flight. The profiler measured accurate ranges to the terrain from this reference platform. The navigation and profile data were recorded and later postprocessed to produce a survey data set. This data set consisted of the latitude, longitude, and elevation of the terrain profiled by the system. This large file of points (approximately one point every 2 meters along the flight path) has an accuracy of ±60 cm in the horizontal coordinates and ±15 cm in the vertical coordinate at the 90-percent reliability level.

The development and testing of the prototype APTS was completed in April 1987. The prototype system was dismantled and design specifications were developed for a production system, the Airborne Precision Mapping System. The new system is proposed to contain a commercial inertial measuring unit, a Global Positioning System receiver, and a laser tracker. A multimode laser profiler is proposed to measure terrain profiles, and provisions will be made for collecting data from other onboard sensors such as magnetometers, gravity gradiometers, and digital cameras. This new system is designed to provide precision navigation for a wider variety of earth science data collection activities.

INTRODUCTION

The Aerial Profiling of Terrain System (APTS), developed by the Charles Stark Draper Laboratory for the U.S. Geological Survey, has undergone field testing during the last several years to determine its effectiveness as a terrain measuring instrument. The APTS is an airborne inertial surveying system supplemented with laser instruments that provide measurements for transferring position and elevation coordinates to the ground. It consists of an inertial platform, laser tracker, laser profiler, and video imaging system. When performing profile surveys, the inertial navigation system provides continuous position and elevation information for the aircraft, and the laser profiler measures ground profiles relative to the aircraft. To control the accumulated errors of the inertial navigation system, the laser tracker periodically provides independent position information by measuring range and direction to retroreflectors prepositioned on the ground. During performance evaluation test flights, APTS demonstrated that it can perform terrain mapping tasks to accuracies of ±15 cm vertically and ±60 cm horizontally while flying at a height of

488 meters above mean ground at 100 knots if laser tracker update information is obtained at about 3-minute intervals. The APTS instruments are installed in a De Havilland Twin-Otter aircraft (figures 1 and 2).

During the last several years, APTS was used to perform a series of application tests, which included:

- A survey along a 28-mile stretch of the Charles River near Needham, Mass., to position water wells and to measure water surface elevations along the river within a project area.

- A map accuracy survey over four areas to determine the vertical and horizontal accuracy of corresponding 7.5-minute topographic maps.

- A surface elevation survey of over 100 kettle ponds near Plymouth, Mass. The data, collected during a 2-hour flight, were used to develop a computer model of the aquifer.

- A survey using the laser tracker to determine the positional accuracy of ground points marked by retroreflectors.

- A terrain survey at the north half of the Great Salt Lake Desert for production of a 1-foot contour interval map (figure 3) in support of a West Desert Pumping Project. The State of Utah jointly funded this project.

- Two flight tests (June 1985 and April 1987) to determine the accuracy in position and velocity as measured by an airborne Global Positioning System receiver.

The development and testing of the prototype APTS was completed in April 1987. The system was dismantled and the aircraft was returned to service.

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Airborne Precision Mapping System Concept

The concept of the APTS began with an engineering analysis study performed by the Draper Laboratory for the Geological Survey in 1975. The study addressed the application of an airborne laser profiler augmented by an inertial navigation system to measure ground profiles across stream valleys for flood-plain mapping. The optimistic conclusion of the study led to a series of contracts for system design (1975-78), component fabrication (1978-81), system integration (1982), aircraft installation (1983), flight testing (1984), and performance evaluation and application testing (1984-87). This development period of about 10 years was slow compared with the rate in which computers were improving and the rate in which new navigation systems were developing. By the time the APTS was ready for airborne testing, the computer and accessories were over 5 years old, and hardware failures became more frequent during the flight testing phase. During the final phase of application testing, the APTS was becoming more unreliable and the hardware was becoming out of date.

Draper Laboratory was contracted during the last year of the program to develop design specifications for a new airborne surveying system, the Airborne Precision Mapping System (APMS). The contract specifications required a system with the following design characteristics:

- A commercially available inertial measuring unit;
- A Global Positioning System (GPS) receiver, which will be incorporated into the system to improve the operating capabilities and final position accuracy;
- A commercially available laser profiler with a scanning capability to improve the ground elevation gathering capabilities;
- A new laser tracker designed to fit the inertial measuring unit and with a wider field of view to improve the retroreflector acquisition capability;
- Microprocessors to direct the system through the various programs for calibration and profiling and for collecting and recording the observation data.

The specifications were based on Geological Survey experience in operating the prototype APTS.

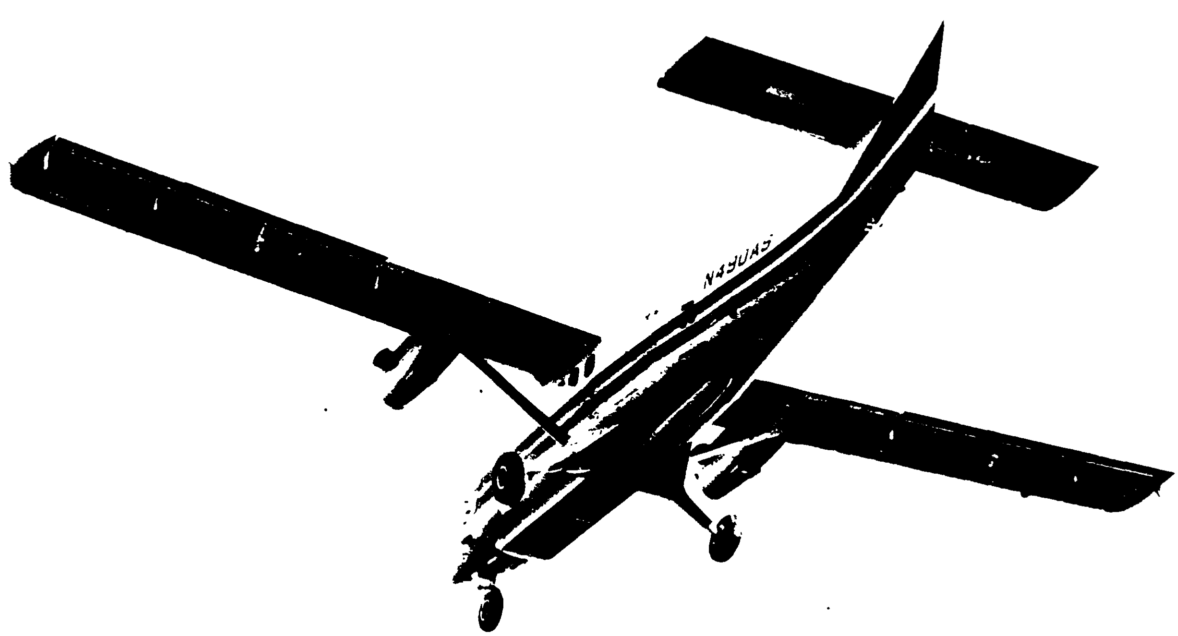

Figure 1.--APTS De Havilland Twin-Otter aircraft.

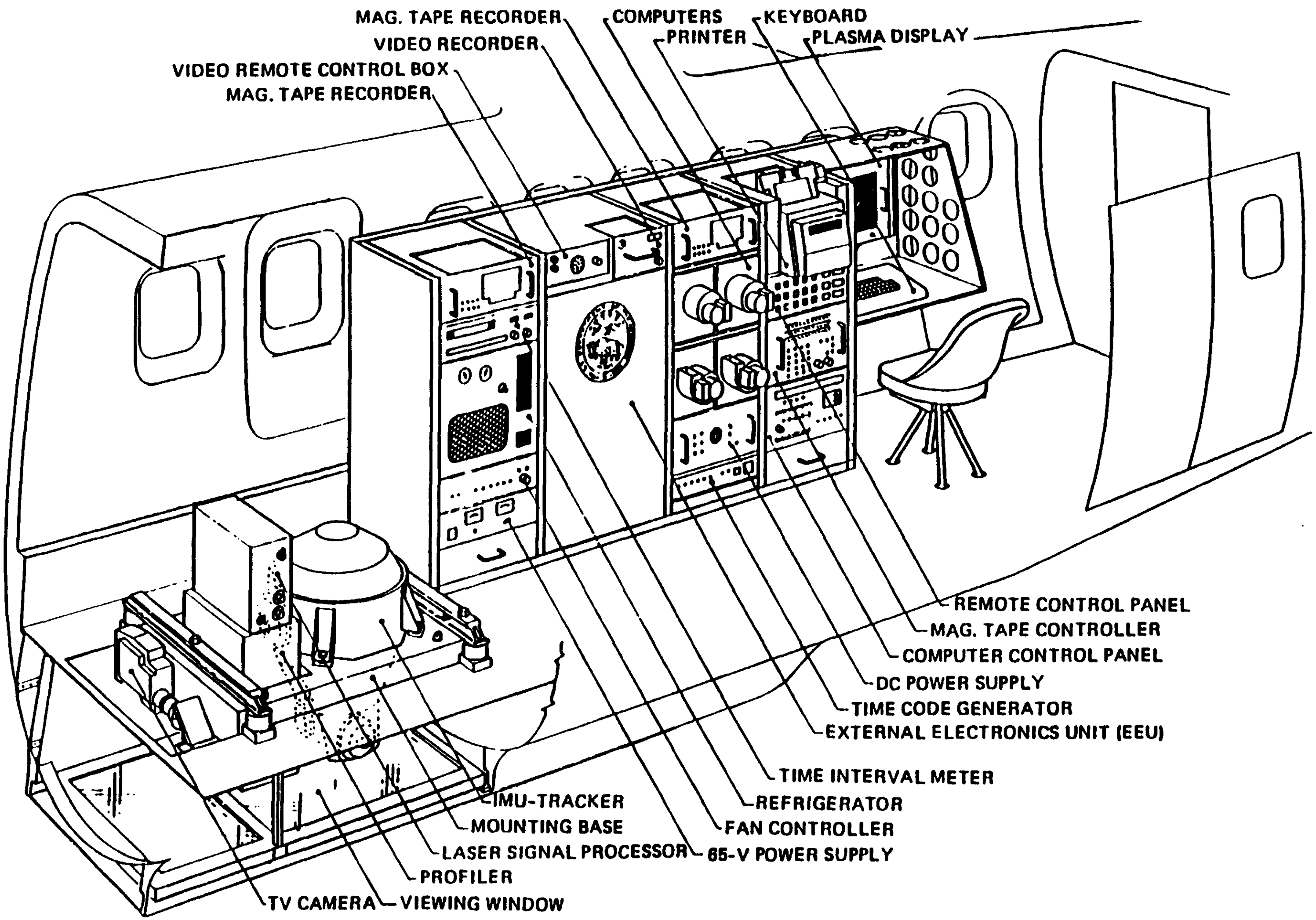

Figure 2.--Arrangement of APTS instruments in Twin-Otter aircraft.

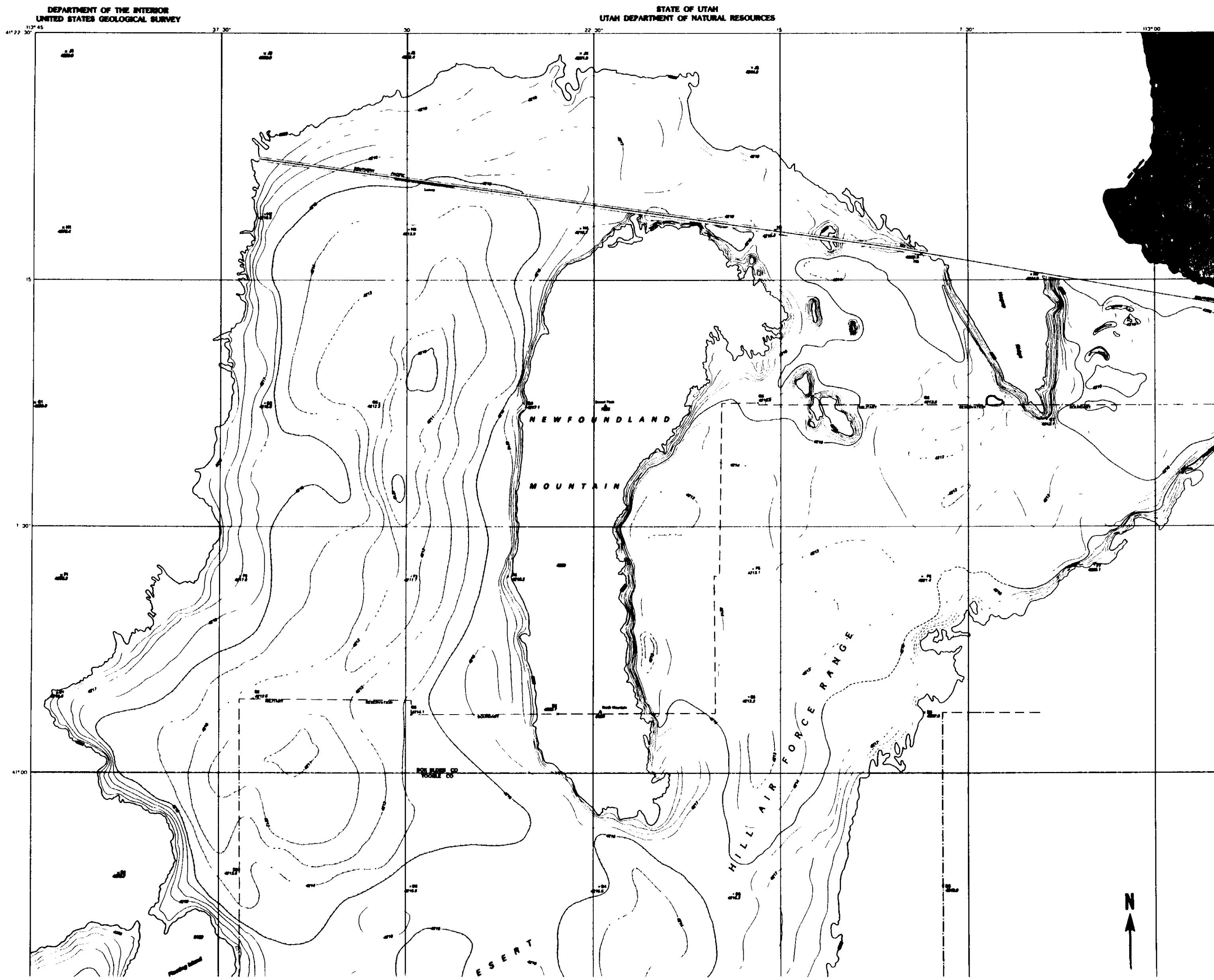

Figure 3.--One-foot contour interval map of a portion of the Great Salt Lake Desert based on APTS profile data.

Inertial Navigation System

The APTS inertial navigation system contained a unique inertial measurement unit, designed and fabricated by Draper Laboratory, which uses third generation gyros and accelerometers from a U.S. Air Force program. The unit is a three-gimbaled system designed to drift less than 0.1 nm/h unaided. The gimbal angles are encoded by two speed resolvers having an accuracy of 4 arcseconds RMS. The unit is contained within a chamber where the temperature is maintained at 39 ± 0.05 °C. All unit data are processed and stored in real-time by the APTS computer.

Because this inertial measurement unit is unique and very costly to replace, APMS will use a commercial unit in the navigation system. Commercial units suitable for use in APMS are available with the required position accuracy, with the addition of gimbal resolvers of greater angular resolution. Strap-down units are also available with the required performance and have the added features of low power consumption and rugged construction.

Three inertial measurement units have been analyzed and found to have the required performance characteristics. They are the Honeywell Ring Laser Gyro Navigator (RLGN), the Singer High Accuracy Inertial Navigation System (HAINS), and the Honeywell GEOSPIN.

The eligibility of these three systems was determined in a study performed by Draper Laboratory using actual flight data. The data were collected during an APTS/GPS test conducted for the U.S Army. The test course was arranged in the form of a race track with retroreflectors at the four turning points. The spacing between the retroreflectors averaged 6,500 meters or 200 seconds of flight time. To simulate using the three inertial measurement units, the plant and measurement noise parameters for the candidate systems were substituted for those of the APTS in the postprocessor. The flight data were then reprocessed for each system using the parameter set for that system. The postprocessor estimates of three-dimensional position error as a function of time were plotted and analyzed for each unit. It was concluded from the results of this study that any of the three would achieve APMS accuracy requirements as long as retroreflector updates were obtained every 160 seconds.

APTS used a single computer to perform all tasks needed for operating the system. APTS computer processing included computation of the navigation equations; editing, compression, and storage of all system data; solving the equations for determining the pointing angles for the laser tracker and interacting with the operator; and performing a calibration and alignment of the inertial measurement unit. However, use of a single computer severely hampered maintenance efforts. Maintenance of the APTS could not be done without powering down the whole system, thereby requiring a repetitition of the time-consuming effort to perform a calibration and alignment. APMS will use distributed microprocessors for its subsystem functions. A separate processor integrated with the inertial measurement unit will be used for all functions related to calibration and alignment and navigation. An advantage to processing in this manner is that calibration and alignment, and maintenance on other portions of the system, can be conducted independently without the need to power down the inertial measurement unit, thereby significantly reducing lost mission time.

Laser Tracker

The laser tracker serves two purposes in the navigation process of the APMS. First, the range and angle data it collects provide a very accurate (±3 cm), independent measurement of the aircraft's position during a mission. In the real-time mode of operation, this information is input to three (north, east, and down) four-state Kalman filters that compute estimates of errors in position, velocity, acceleration, and retroreflector position. These error estimates are used to maintain the real-time navigation sufficient to accomplish retroreflector acquisition during the mission. The difference between the tracker and inertial navigation system positions is used as input to the post processor, where a more complex Kalman filter is used to estimate inertial measurement unit errors during the time the inertial navigation system is interpolating position between retroreflector updates. Postprocessing provides the most accurate estimates of system errors, which when used to correct the navigation, provide the final survey data set. The second and equally important purpose is to provide a tie-in to the local geoid. Such a tie-in ensures that the profiles measured by the system accurately measure elevations in the project area. The development of this device is one of the significant accomplishments of the APTS.

However, in the APTS the successful operation of this device was dependent on achieving an accurate calibration and alignment of the inertial measurement unit and by periodic updates of the real-time navigation by the laser tracker. The acquisition of the retroreflector arrays is dependent on maintaining accurate navigation which is dependent on obtaining an accurate calibration and alignment and retro updates. The initial pointing angles are determined with respect to inertial measurement unit position, which usually is in error. If the error is large enough, then acquisition will fail. This dependence made testing and equipment failure determination more difficult, greatly reducing the chances of a successful mission.

In the study performed by Draper Laboratory of the requirements for an operational version of APTS, an analysis of the performance of the tracker was made to determine which tracker parameters could be changed to eliminate this dependence. The study concluded that a new design with a wider field of view would eliminate the dependence on accurate inertial measurement unit calibration and alignment and periodic navigation updates for retroreflector acquisition. A field of view of 4° with a suitable search strategy would permit independent acquisition as long as the plane was within 1,000 meters horizontally of the retro position. In effect, acquisition would occur as long as the pilot could fly the aircraft so that the retro could be seen through the aircraft bottom window.

To achieve the level of accuracy required for APMS profiles, the laser tracker must measure range with a RMS noise level of less than 3 cm and angles with a RMS noise level of less than 2 arcseconds when averaged over intervals of 0.1 second. This level of accuracy will be achieved while maintaining eye-safe operating conditions during a mission.

Global Positioning System

The Global Positioning System (GPS) will provide an alternative means for updating the APMS inertial navigation system. GPS will be used in two different ways: first in real-time to maintain navigation accuracy for retroreflector acquisition, and second in a differential mode with at least two receivers for a more precise navigation position accuracy.

The significant advantage of using GPS to provide navigation updates during a mission is that the navigation errors would never grow larger than the 10-meter level provided by GPS. Such an error level would guarantee retroreflector acquisition using the present APTS laser tracker design. Under some circumstances, missions of lesser accuracy could be accomplished using just GPS and the APMS inertial measurement unit.

The most precise application of GPS will be in the differential mode. In this mode two GPS receivers, one on board the APMS and the other on the ground located on a known position, will simultaneously collect data during a mission. The carrier-phase data collected by the two receivers will be processed and the vector difference between the aircraft position and the known ground position determined versus time. The difference between the GPS aircraft and inertial measurement unit positions will then provide the error vector used by the postprocessor Kalman filter.

With differential GPS measurements it should be possible to meet APMS accuracy requirements over a region several tens of kilometers on a side with as few as three retroreflectors to tie to the local geoid.

Data Postprocessor

A dedicated postprocessing system will be developed for APMS using suitable minicomputer or supermicrocomputer hardware. It will consist of the necessary central processing units, recorders, mass storage, and software needed to process the APMS raw data collected during a mission. It will provide a survey data set recorded in a standard format that is compatible with most equipment used by government and commercial agencies. The postprocessor will be an improved version of the APTS processor, updated to reduce mass storage requirements, and include other inertial measurement unit updating sources such as GPS. The facility will also be capable of processing differential GPS phase data as needed to satisfy mission requirements.

Laser Profiler

The laser profiler for the APMS will be capable of three modes of operation: point always to the nadir, scan perpendicular to the flight path with a scan width of $\pm 14°$, and profile a predefined path over the topography. The new profiler will continue to use a pulsed gallium arsenide laser diode with a power output of 75 watts. The method of scanning is yet to be determined. Several techniques have been studied, but no particular method has demonstrated a superior advantage.

The laser profiler designed and built for APTS is physically attached to the aircraft frame and therefore moves away from the nadir according to the angular motion of the aircraft. Since the angular motion of the aircraft has a random component, the spot on the ground also deviates from the desired location randomly.

This condition proved to be undesirable for many of the applications for which the system could be used. It is very difficult to maneuver a fixed-wing aircraft with the precision required, for instance, to measure profiles spaced 100 meters apart. In many applications, a scanning profiler would be more suitable since it would provide a swath of data covering the desired profile line. In addition, if the pointing of the profiler could be directed to follow a predefined path, then the aircraft maneuvering requirements would not be as difficult to achieve. The aircraft can be flown so that the area to be profiled is visible through the bottom window.

Non-Profiling Sensors

APTS was designed solely to perform terrain profiling. However, once the system became operational, it was recognized that an airborne platform with an accurate navigation system could be used for many remote sensing applications where the location and orientation of the sensor must be known. APMS will contain the hardware and software necessary to collect data from these sensors.

The laser profiler could be modified to measure terrain reflectivity in the near infrared region of the spectrum and to collect passive thermal imagery. Reflectivity data would be obtained by measuring the amplitude of return pulses. Thermal imagery data could be collected by installing a separate detector in the focal plane of the receiver optics.

APTS used a color television camera bore sighted with the profiler to assist in editing the profile data. Newer, shuttered television cameras are now available that can provide high-resolution, motion-distortion-free images of the terrain.

APMS could also be used to provide accurate camera-station parameters for photogrammetric cameras, especially for those mapping projects were ground access to survey control is difficult.

Mission Computer

Computer technology has made great strides since the selection of the PDP-11/70M for the APTS. Cost, power consumption, weight, and software expertise were the factors that were influential in the selection of this computer as the single means for processing data and controlling the system. However, in practice the use of a single computer proved impractical from the standpoint of ease of both hardware and software maintenance. The dependence of every subsystem on the continuous, error-free operation of a single computer required that the computer be extremely reliable. In practice, the computer was never reliable enough, and as a result projects took longer to accomplish than planned. Distributed processors will be used in APMS. The many recent advances in microcomputer technology have made this approach very practical in all respects. As was indicated previously, the inertial measuring unit will have its own processor capable of performing calibration and alignment and navigation tasks. The laser profiler and tracker will also contain microprocessors to perform most control and raw-data processing functions. Similarly, a high-speed data processor will be available to control and process data from the other sensors on board.

Overseeing these individual processors will be the mission computer. This computer will be responsible for coordinating the operation, collection, and storage of the data from all of the separate devices in concert with an overall mission plan. It will interact with the APMS operator and aircraft pilot to provide the necessary status and heading information needed by both to ensure a successful mission. Another new innovation will be the graphic displays to be used by both the operator and the pilot. A cathode-ray tube will display a map showing retroreflector locations, planned flight path, and current aircraft location. Additional operator graphic displays will allow the operator to monitor tracker gimbal operation and inertial measuring unit gimbal and platform orientation during calibration and alignment. Based on past experience with the APTS, the addition of these aids will greatly improve the chances of completing a mission successfully.

SUMMARY

The U.S. Geological Survey has completed the accuracy and application testing of the APTS, a prototype aerial surveying system. Based on the experiences gained in operating the system through about 3 years of flight testing, the Survey has developed the design specifications of an operational system, the Airborne Precision Mapping System. The new system would require less power and be lighter and less costly than the present prototype model. It would consist of a commerially available inertial measuring unit, a laser profiler, and microprocessors. A GPS receiver would be incorporated into the system to improve the operating capabilities and final position accuracy. A scanning capability would be developed for the laser profiler to improve the ground elevation gathering capabilities from a line of elevation data to a swath. The laser tracker design would need to be modified to have a greater field of view, and more precise angular resolvers would be needed in the inertial measuring unit. The system envisioned could be installed in a much smaller aircraft, such as an Aero Commander, would operate with a two-man crew, would provide better data for creating digital terrain models than the prototype system, and would cost much less to operate.

Because of budgetary constraints, the Geological Survey is unable to continue this line of research alone. The Survey is interested in working with other Federal agencies who have a need for an airborne surveying system capability and who can share in the costs.

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