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GPS APPLICATIONS TO LASER PROFILING AND LASER SCANNING FOR DIGITAL TERRAIN MODELS

William B. Krabill, NASA Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, Virginia USA

GENERAL DISCUSSION

The use of airborne laser systems for terrain mapping has been demonstrated by a number of different groups over the past fifteen years. Lidar profiling applications have been reported by investigators from Australia [Penny, 1972], Canada [Schreier et. al, 1984], and the United States [Krabill et. al., 1984; Arp, 1982; Ritchie and Jackson, 1989; and McDonough et. al, 1980]. The relatively small foot print (several meters to less than one meter) coupled with the high signal to noise ratio afforded by pulsed laser systems yields a determination of the distance between the aircraft and ground targets to a precision of < 1 m and perhaps as good as 5 - 10 cm on some of the systems. These light detection and ranging (lidar) systems are especially effective over open terrain with a sparse vegetative cover. However, with the use of a waveform recording capability, a lidar system such as the NASA Airborne Oceanographic Lidar (AOL) can be used to survey through even forest covered areas with results roughly comparable to that which would be obtained using standard photogrammetric techniques [Krabill et. al., 1984]. The recorded temporal waveform also permits the recovery of information on tree height and canopy density [Nelson et. al., 1984; Nelson et. al., 1988; and Maclean and Krabill, 1986]. The use of a high pulse repetition rate laser and a scanning mirror assembly provides coverage over a swath beneath the aircraft [Krabill et. al., 1980 and Krabill et. al., 1987].

Although airborne lidar investigations have demonstrated that such systems have been capable of providing highly precise measurements between the aircraft and the ground since the early 1970's, laser altimeter systems are currently not in widespread use for precision topographic mapping for two related reasons. First, the vertical position of the aircraft must be known to a precision roughly comparable to the aircraft-to-ground measurement capability of the lidar system in order to make effective use of the lidar measurements. Second, horizontal positioning of the individual aircraft lidar footprint locations, while having perhaps a less stringent requirement, is likewise a major obstacle to the utilization of these systems for terrain mapping. These aspects are treated individually below.

Two approaches have been used to address the aircraft altitude problem in previously reported airborne lidar terrain mapping experiments. In his airborne lidar survey of a remote section of South America, Arp [1982] used recorded pressure data from a highly precise aircraft aneroid barometric altimeter to gauge changes in the aircraft altitude along the flight path. Altitude determinations from aircraft aneroid barometric altimeters, however are subject to error due to changes in local air pressure, vertical temperature, humidity and wind structure, as well as short term changes in aircraft velocity. Some of these effects can be partially compensated by the use of a second ground-based barometric altimeter located near or within the survey site. However, our evaluation of aircraft aneroid barometric altimeters (unpublished) showed that the short term altitude determinations are noisy and the resultant data are not within the submeter tolerance necessary to make full use of an airborne lidar altimeter for most survey purposes. In Arp's application in a remote section of South America, the aircraft aneroid barometric altimeter provided a relative altitude measurement that was acceptable for that application and it was certainly the best approach available at the time of that survey.

A second approach to resolving the aircraft altitude problem was demonstrated by Krabill et. al. [1984] in surveys conducted in the Wolf River flood plain near Memphis, Tennessee in 1978. During these surveys, the aircraft was instrumented with a vertical accelerometer, the output of which was recorded along with the lidar data. Krabill's approach was based on an earlier use of a vertical accelerometer by Walsh et. al. [1984] to remove aircraft vertical motion contamination from radar ocean wave profiling data. During post flight processing, the accelerometer data is doubly integrated to provide a relative vertical trajectory of the aircraft along the survey line. The vertical acceleration information however is subject to drift. To resolve this problem, the ground elevation of at least two (preferably three) laser measurement locations along a flight trajectory are used to remove the drift from the accelerometer measurements. Krabill found in this and later studies [Krabill et. al., 1987] that the technique was effective in removing aircraft motion to the subdecimeter level over distances of 6 - 10 km. However, obtaining independent ground elevation at two or more laser foot print locations in itself often presents difficulties. In Krabill's applications, available information from previous ground surveys of road crowns and other man-made structures was generally utilized. However, such circumstances are reasonably unique and are unavailable for many survey applications. Moreover, the recognition of the horizontal location of the lidar footprints on road surfaces is a time consuming operation and is especially difficult in data obtained in a scanning mode of operation.

Horizontal control for airborne lidar surveys has typically been performed post-flight using a combination of time tagged airborne photographs acquired with a boresighted camera, positional information recorded from an inertial navigation system (INS), and detailed survey charts showing local road systems and other man made structures. At best, this procedure has been a tedious process involving much time from an experienced technician. Under other circumstances, recognizable features in the airborne photographic records may not be available.

GPS AS APPLIED TO AIRBORNE LASER TERRAIN MAPPING

The use of information from Global Positioning System (GPS) receivers offers an attractive common solution to both the aircraft altitude and the horizontal positioning problems. A single GPS receiver on board an aircraft is capable of providing horizontal information at the 20-100 m level of accuracy, depending upon ephemeris quality. This level of accuracy would, of course, be of marginal value in providing vertical control. However, using a second ground-based receiver located over a known bench mark in the vicinity of the survey site greatly increases the potential precision of using GPS in combination with an airborne lidar system. In its simplest form, this differential GPS technique involves recording the real-time independently determined positions from both the airborne and ground-based receivers, typically obtained using a Kalman type filter. Here the apparent changes in the position of the fixed receiver are assumed to be systematic errors due to ionospheric refraction or ephemeris uncertainties, and are applied to the airborne receiver as corrections. This technique can be used to refine the aircraft position in horizontal and vertical coordinates to the ± 2 to 5 meter level. This may be acceptable for vertical positioning for some applications and for horizontal positioning for a larger number of applications.

A more precise extension of the differential GPS technique involves the recording and post-flight processing of pseudo- ranges derived from tracking the phase of the L-band carrier from both the ground-based and the airborne receivers. Tests using this technique were performed by NASA and NOAA in 1985 [Krabill and Martin, 1987], and demonstrated GPS relative height positioning accuracy for an aircraft at the 10-12 cm level under poor GPS tracking geometry using a pair of NOAA's TI4100 receivers.

A pair of Motorola Eagle GPS receivers were acquired by NASA/GSFC/Wallops Flight Facility (WFF) in 1986 and have been used successfully in a number of aircraft missions [Krabill et. al., 1989] for both single receiver positioning and in the differential mode. The Motorola units are single frequency four channel (an eight channel version is now available) receivers capable of providing raw measurements and present position at a once per second rate. Consequently they are potentially capable of providing suitably accurate relative positioning for airborne lidar missions where the aircraft is within a few tens to perhaps one hundred kilometers from the ground receiver. A very brief demonstration experiment applying the Motorola receiver to airborne laser topographic mapping was conducted in March 1989, and is described in the following sections.

GPS MEASUREMENTS AND AIRCRAFT TRAJECTORY ESTIMATION

The Motorola Eagle receivers provide raw measurements consisting of C/A code ranges, which are ambiguous at the 1 msec level with noise levels of several meters, and L1 carrier phase ranges, which are ambiguous at the L1 wavelength of 19 cm and have noise levels of approximately 3 mm. The receiver processes the code ranges with a Kalman filter to produce real-time estimates of the receiver's position, velocity, and timing error. Both the raw measurements and, optionally, the information from the Kalman filter are available to be recorded for post-flight processing. In the implementation used at WFF the Motorola receivers are interfaced to Compaq portable computers for command, control, and data capture.

The technique of performing differential carrier phase positioning requires a determination of the ambiguities in the measurements, thus obtaining for each satellite tracked a very accurate difference between the range from the aircraft to the satellite and the ground receiver to the satellite. These range differences have a common timing error associated with the separate clocks in the two receivers, but this bias can be estimated along with the three coordinates of the aircraft receiver from the measurements to the four satellites.

The basic tasks associated with performing differential carrier phase positioning of an aircraft are thus to: (1) collect sufficient data to provide for a post-flight estimation of the ambiguities on the phase data, and (2) maintain carrier lock during the flight without cycle slips. The latter cannot be guaranteed, but the probabilities can be maximized by tracking the four satellites with the strongest signals (maximum elevation angle) and by performing low bank angle turns with the aircraft. The typical procedures for calibrating the ambiguities include the following:

(1) Tracking the selected four satellites by both receivers before aircraft takeoff sufficiently long that the ambiguities can be estimated along with the initial position of the aircraft.

(2) Tracking the selected four satellites by both receivers after aircraft landing (and return to parked position) sufficiently long that the ambiguities can be estimated along with the aircraft position. (The positioning aspects of (1) or (2) need not be accomplished with the same four satellites as were tracked during the mission, provided that at least several seconds of data from the four satellites used in the flight are recorded while the aircraft is static.)

(3) The amount of time necessary to perform (1) or (2) can be substantially reduced by moving the antenna from the ground system to a precisely measurable position proximate to the aircraft antenna (typically within a meter) and tracking the in flight satellites for at least several seconds. The ground system must then be moved from the aircraft and transported to a fixed survey site while maintaining lock on the GPS carrier.

The operational difficulties associated with accomplishing the above tasks are in large part due to the limitations associated with using a four channel receiver and to the presently available number of GPS satellites. Using a receiver with more than 5-6 channels potentially should allow for in flight ambiguity resolution, improve geometry, accommodate a few cycle slips, and extend the operational time window.

INSTRUMENTATION

The NASA Airborne Oceanographic Lidar instrumentation was essentially configured as described by Krabill et. al. [1984]. The layout of the system for the terrain mapping experiment is shown in a schematic form in Figure 1. Basically, the sensor was configured with a pulsed nitrogen gas laser which was operated at 400 pulses per second. The laser has an output wavelength of 337 nm and ~100 kw peak pulse power making it well within American National Standards Institute (ANSI) standards for allowable eye exposure limits from the 300 m altitude at which the experiment was flown. The scan mirror assembly was set at

15 degrees off-nadir. In this configuration, the AOL produces a pattern of interlaced, nearly circular shaped scans beneath the aircraft as it is flown along the flight line. A sample of the pattern will be shown in the ensuing discussion of results.

During the terrain mapping experiment the AOL was also equipped with a Litton LTN-51 inertial navigation system (INS) and a Columbia model SA-100 vertical accelerometer. Data from both the INS and the vertical accelerometer were captured and recorded along with the basic laser ranging information. In addition, the two Motorola Eagle GPS receivers were used. One was operated on the ground as a fixed receiver over an existing bench mark embedded in one of the airport taxi strips. The antenna from the airborne system was located on a flat plate installed in an up-looking port of the aircraft. The information from both the fixed and mobile receivers was captured with Compaq 286 PC's and recorded on 1.2 megabyte floppy disks.

DESCRIPTION OF THE EXPERIMENT

The purpose of the experiment was to demonstrate the potential for utilizing GPS receivers in a differential carrier phase mode to provide vertical and horizontal control for airborne lidar elevational measurements. The mission was viewed as an initial step toward a larger technology demonstration investigation where an area of 10 - 30 square kilometers would be surveyed with the technique and standard surveying products would be produced. The NASA Wallops Flight Facility located along the Eastern Shore of Virginia was selected for the initial demonstration for both convenience, since that is where the sensor and aircraft are maintained, and because previous survey information contoured at the 2 foot level was readily available to compare with the airborne results.

The mission was flown over a 70 minute period beginning at 00:50 Eastern Standard time on March 10, 1989. Conducting the mission at night was necessary because it was the only time that 4 GPS satellites were in continuous view at the locality of WFF during the mid-March time frame given the limited 7 satellite constellation at the time of the experiment. Prior to take-off the 4 visible satellites were tracked for a period of twenty minutes with the antenna from the ground GPS receiver positioned within a meter of the mobile antenna on top of the aircraft fuselage. This procedure was used in order to resolve ambiguities between the two receivers with a relatively minimum period of satellite tracking. The fixed GPS receiver was then moved to the nearby taxi strip and positioned above the reference bench mark as the aircraft taxied for take-off.

Following take-off, several passes were flown from east to west over the Runway 10/28. During maneuvering between passes, the aircraft was restricted to maximum bank angles of 10 degrees in order to maintain lock on all 4 of the satellites that were being tracked. Although all of the satellites were successfully tracked during the several passes, the mobile receiver lost lock on one of the satellites during landing. (At the time the loss of lock occurred, that particular satellite was down to 8 degrees elevation angle.) The loss of lock on landing did not adversely affect the results. However, problems encountered with the interface between the AOL sensor and the pitch/roll analog signal from the aircraft INS rendered all but one of the passes unsuitable for further processing and analysis. Figure 2 shows a map of the portion of the NASA Wallops Flight Facility where the mission was conducted. Labelled within the figure are (1) the location of the ground GPS receiver, (2) the location of the aircraft during pre-flight satellite tracking to remove the ambiguities between the two receivers, and (3) Runway 10/28 over which the survey passed.

During post-flight data processing the trajectory of the aircraft was determined from the pseudo-ranges derived by tracking the phase of the L-band carrier from both the ground-based and the airborne receivers. The aircraft elevational track for the pass which was analyzed is shown in Figure 3 as a profile plotted as a function of time. The knowledge of the aircraft altitude and horizontal positions allows the laser ranging measurements to be converted to elevation and to be registered in a standard coordinate system. The projection of the AOL scanning data in Figure 4 illustrates the initial form of the data after this registration process and also illustrates the sampling pattern produced by the AOL sensor. A 200 m segment of the flight line is shown in the figure as a east/west north/south projection in meters. The conical scanning pattern of the AOL sensor is very

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Although plots of spot elevations processed from the AOL scanning data are useful for illustrating the actual scanning pattern, the data in this form are not practical for most engineering purposes. Thus, the data are converted into an evenly gridded format and then contoured. An example is shown in Figure 5 for a 300 m portion of the flight line. The data have been contoured in feet to facilitate direct comparison with the available engineering charts that are contoured in two foot intervals.

The previously noted problems with the INS pitch/roll interface presented problems which prevented quantifying the results to the decimeter level that the high quality differential GPS data would warrant. Nonetheless, we were able to compare a profile derived from a section of evenly gridded AOL elevational data with corresponding elevational values extracted from the available engineering chart. The two profiles are shown plotted as a function of along-track distance (meters) in Figure 6. Both profiles appear to be fairly similar, however departures of 0.5 to 1.0 meters are evident. At this time we cannot be sure of the source of the differences although we strongly suspect the lack of reliable aircraft attitude data. Rather than waste additional effort on trying to refine the present data set we are planning another mission to be flown early this fall followed by a larger scale terrain demonstration survey which is planned for the November/December time-frame when the GPS constellation becomes visible from the Wallops Flight Facility locality during daylight hours.

REFERENCES

Arp, H., J. C. Griesbach, and J. P. Burns, Photogrammetric Engineering and Remote Sensing, 48, 1 (1982).

Krabill, W. B., J. G. Collins, R. N. Swift, and M. L. Butler, "Airborne Laser Topographic Mapping Results from Initial Joint NASA/U.S. Army Corps of Engineers Experiment," NASA TM-73287 (1980).

Krabill, W. B., J. G. Collins, L. E. Link, R. N. Swift, and M. L. Butler, "Airborne Laser Topographic Mapping Results," in American Society of Photogrammetry (1984).

Krabill, W. B. and C. F. Martin, "Aircraft Positioning Using Global Positioning System Carrier Phase Data," in Navigation: Journal of The Institute of Navigation, Vol. 34, No. 1 (1987).

Krabill, W. B., and R. N. Swift, "Airborne Lidar Experiments at the Savannah River Plant, June 1985" NASA TM-4007, DOE/SR/14075-1 (1987).

Krabill, W. B., C. L. Lennon, and E. B. Frederick, "GPS Differential Carrier Phase Applications to the Space Shuttle Landing System," in Proceedings of the Fifth International Geodetic Symposium on Satellite Positioning, Las Cruces, New Mexico (1989).

Maclean, G. A., and W. B. Krabill, "Gross-Merchantable Timber Volume Estimation Using an Airborne Lidar System," in Canadian Journal of Remote Sensing, Vol. 12, No. 1 (1986).

McDonough, C., G. Dryden, T. Sofia, S. Wisotsky, and P. Howes, in: Proceedings, International Symposium on Remote Sensing of Environment, 14th, San Jose, Costa Rica, 3:1171-1720 (1980).

Nelson, R., W. Krabill, and G. Maclean, "Determining Forest Canopy Characteristics Using Airborne Laser Data," in Remote Sensing of Environment 15:201-212 (1984).

Nelson, R., W. Krabill, and J. Tonelli, "Estimating Forest Biomass and Volume Using Airborne Laser Data," in Remote Sensing of Environment 24:247-267 (1988).

Penny, M. F., "WREMAPS II: System Evaluation," WRE-Technical Note 811 CAP, Department of Supply, Australian Defence Scientific Service, Weapons Research Establishment, Salisbury, South Australia (1972).

Ritchie, J. C., and T. J. Jackson, "Airborne Laser Measurements of the Surface Topography of Simulated Concentrated Flow Gullies," in Transactions of the ASAE, Vol. 32(2) (1989).

Schreier, H., J. Lougheed, J. R. Gibson, and J. Russell, "Calibrating an Airborne Laser Profiling System," Photogrammetric Engineering and Remote Sensing, Vol. 50, No. 11, pp. 1591-1598 (1984).

Walsh, E. J., D. W. Hancock, D. E. Hines, and J. Kenney, "Electromagnetic Bias of 36 GHz Radar Altimeter Measurements of MSL," Marine Geodesy (1984).

ABSTRACT

Problems historically associated with the application of airborne laser systems for routine surveying of topographic features are briefly reviewed. In particular, aspects regarding the vertical and related horizontal positioning are discussed. The potential solutions to these problems afforded by the use of mobile and fixed GPS receivers used in a differential mode are presented. Although, using the real-time C/A code derived positions in a differential mode can provide acceptable horizontal control, the post-flight processing of pseudo-ranges derived from tracking the phase of the L-band carrier from both the ground-based and the airborne receivers appears to offer superior results for resolving the vertical control problem. Finally the results from a preliminary flight test of the procedure over land are provided. Previous results using the system over water produced results in the decimeter level of precision for vertical control.

William B. Krabill
NASA Goddard Space Flight Center
Wallops Flight Facility
Wallops Island, VA 23337 USA

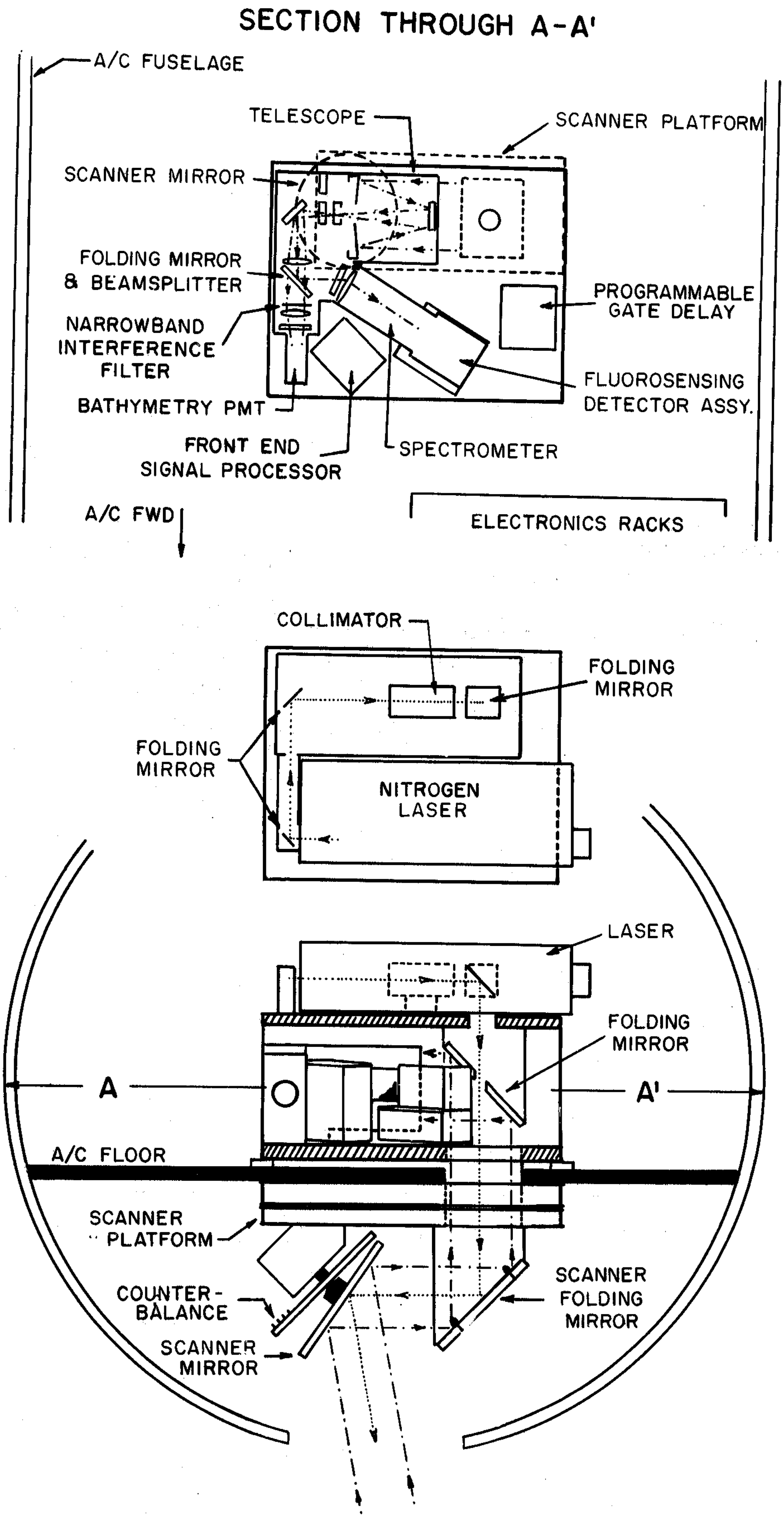
SECTION THROUGH A-A'
A/C FUSELAGE
TELESCOPE
SCANNER PLATFORM
SCANNER MIRROR
FOLDING MIRROR & BEAMSPLITTER
NARROWBAND INTERFERENCE FILTER
PROGRAMMABLE GATE DELAY
BATHYMETRY PMT
FLUOROSENSING DETECTOR ASSY.
FRONT END SIGNAL PROCESSOR
SPECTROMETER
A/C FWD
ELECTRONICS RACKS
COLLIMATOR
FOLDING MIRROR
FOLDING MIRROR
NITROGEN LASER
LASER
FOLDING MIRROR
A
A'
A/C FLOOR
SCANNER PLATFORM
COUNTER-BALANCE
SCANNER MIRROR
SCANNER FOLDING MIRROR

Figure 1

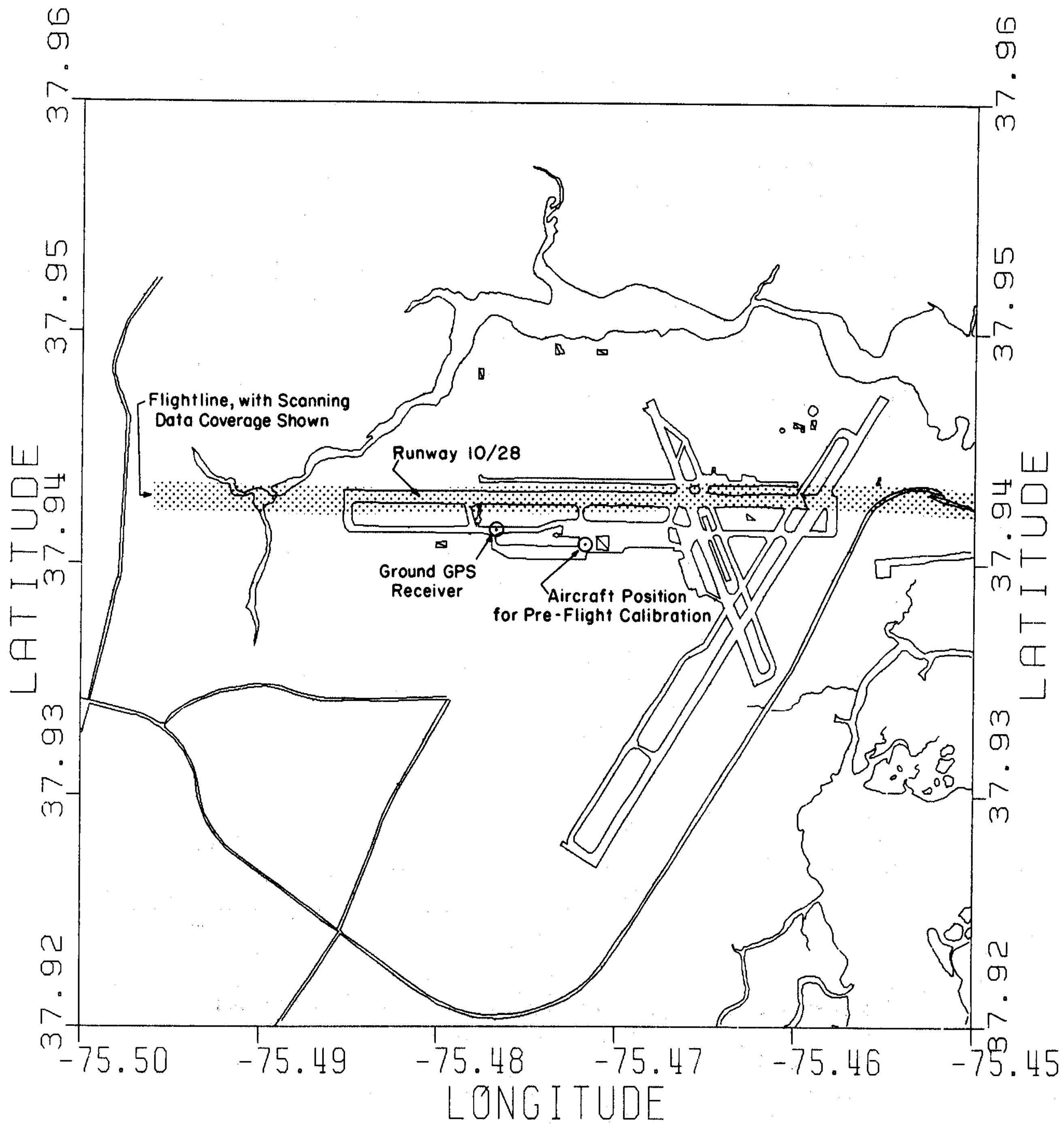
Flightline, with Scanning Data Coverage Shown
Runway 10/28
Ground GPS Receiver
Aircraft Position for Pre-Flight Calibration
LATITUDE
LATITUDE
37.96
37.95
37.94
37.93
37.92
37.96
37.95
37.94
37.93
37.92
-75.50
-75.49
-75.48
-75.47
-75.46
-75.45
LONGITUDE

Figure 2

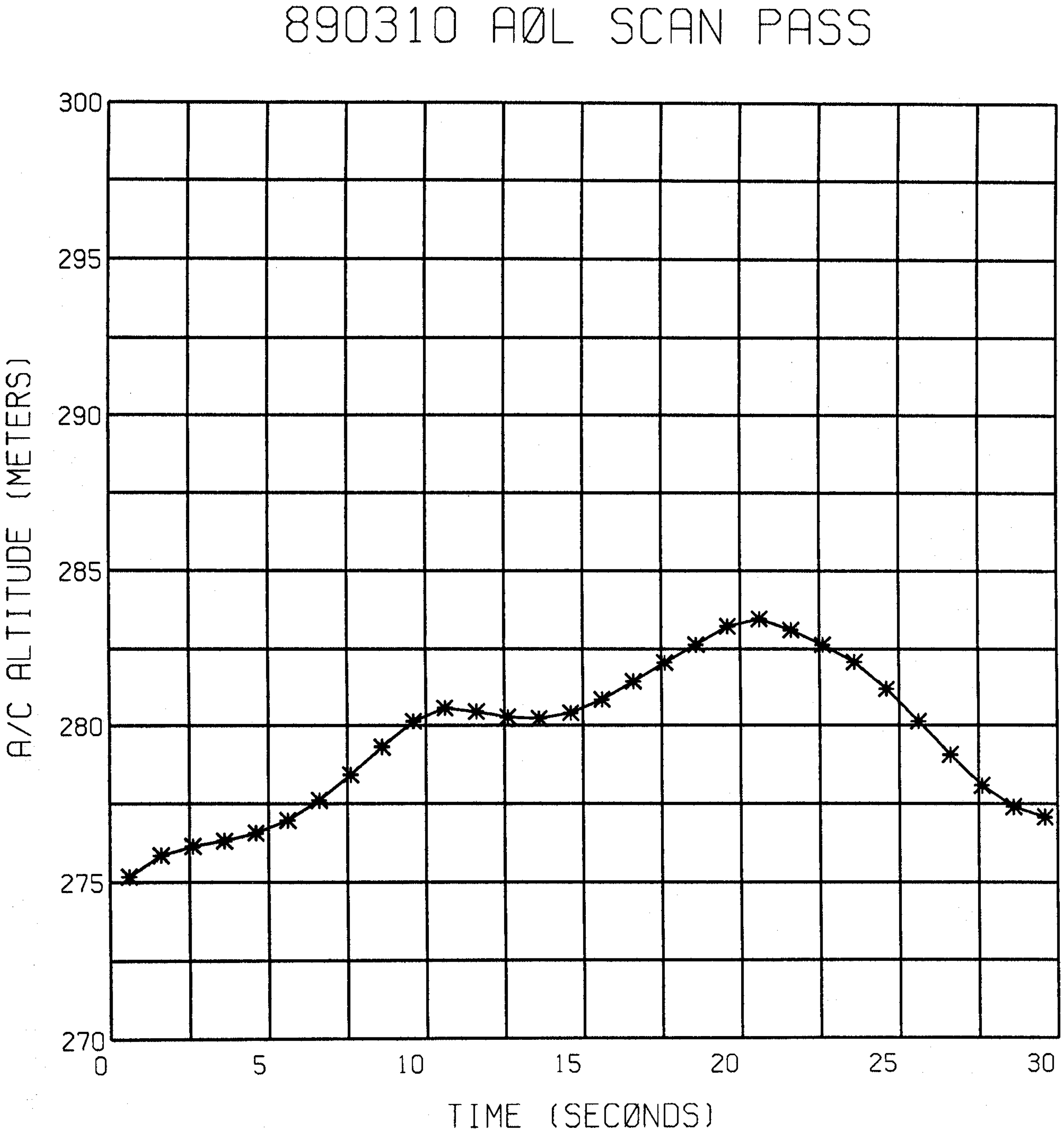
890310 AØL SCAN PASS
A/C ALTITUDE (METERS)
300
295
290
285
280
275
270
0
5
10
15
20
25
30
TIME (SECØNDS)

Figure 3

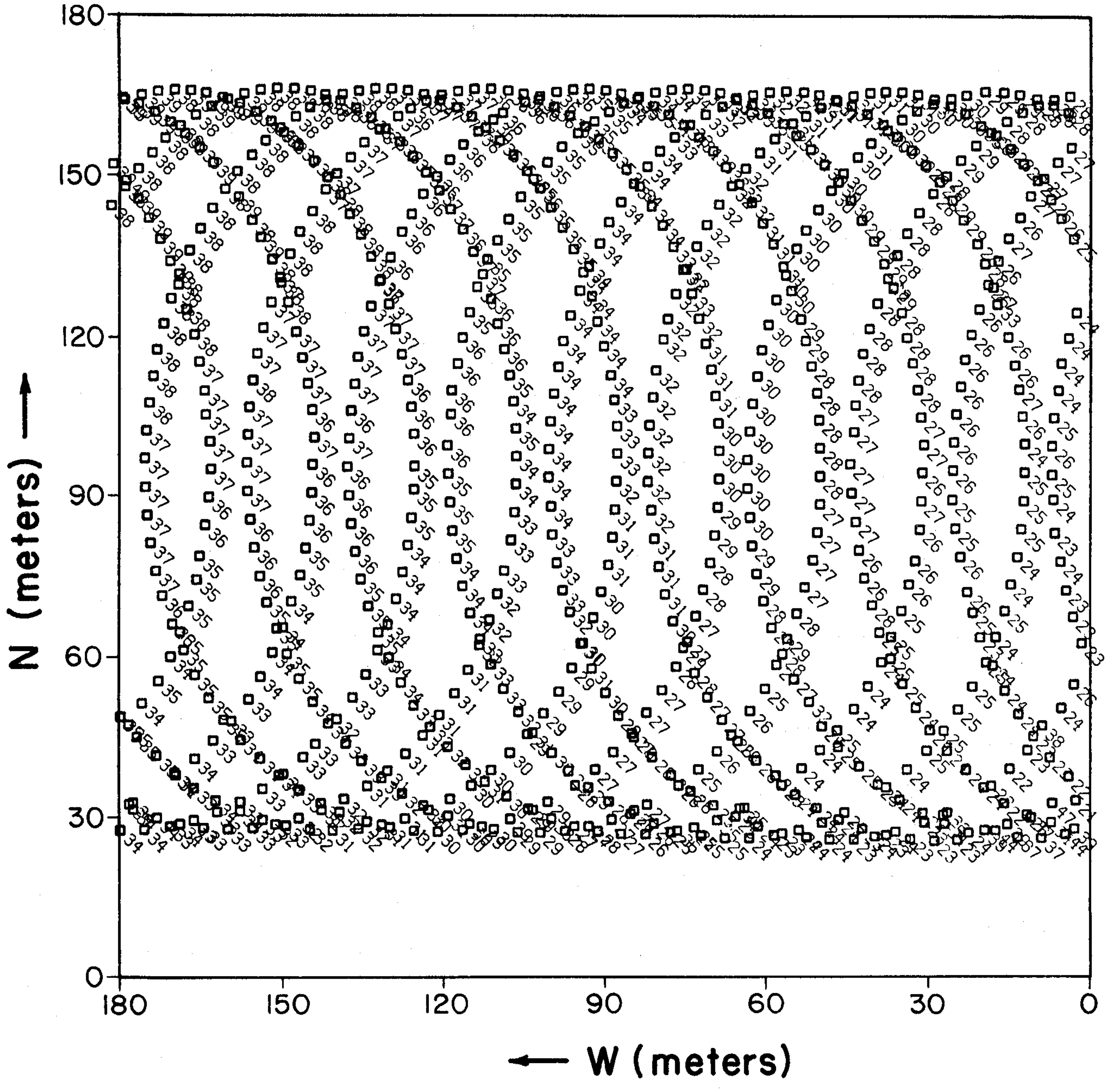

Figure 4

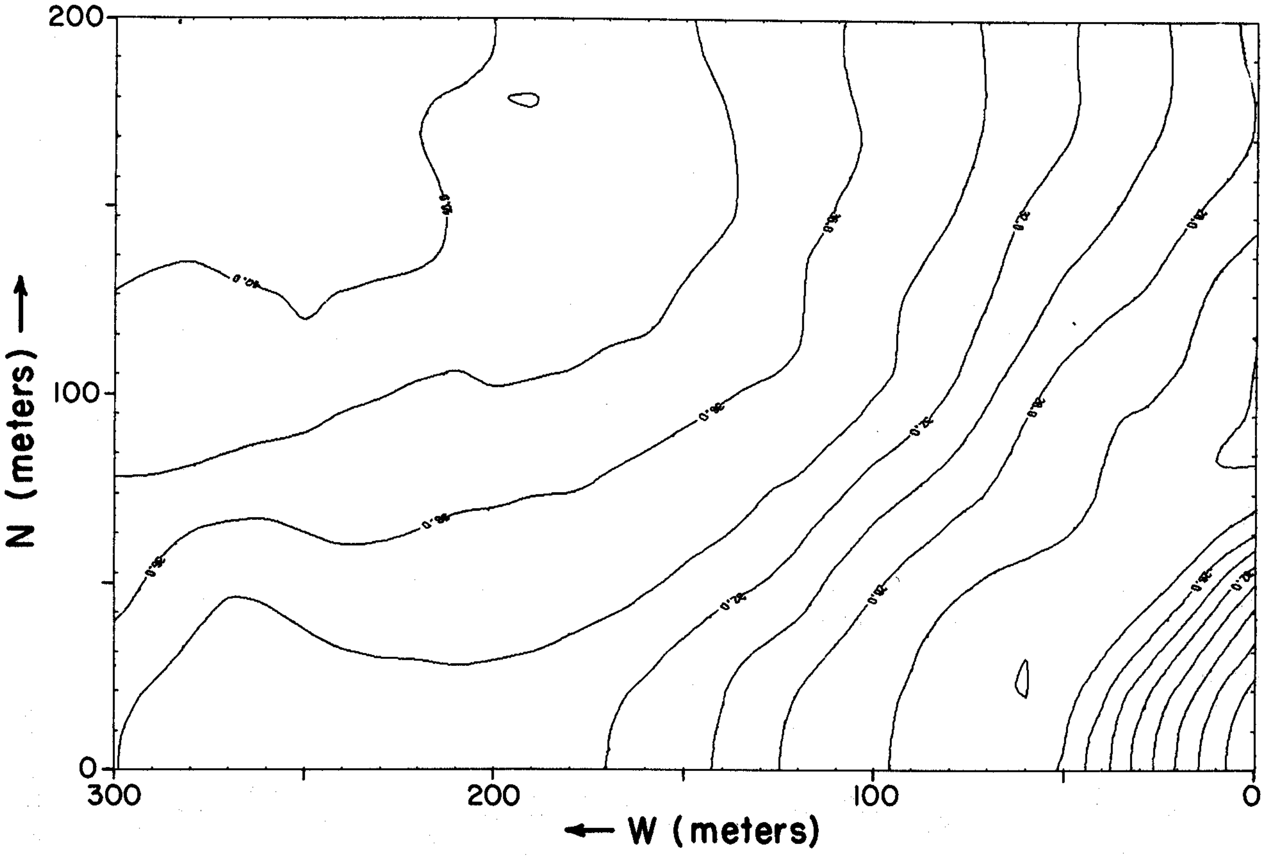

Figure 5

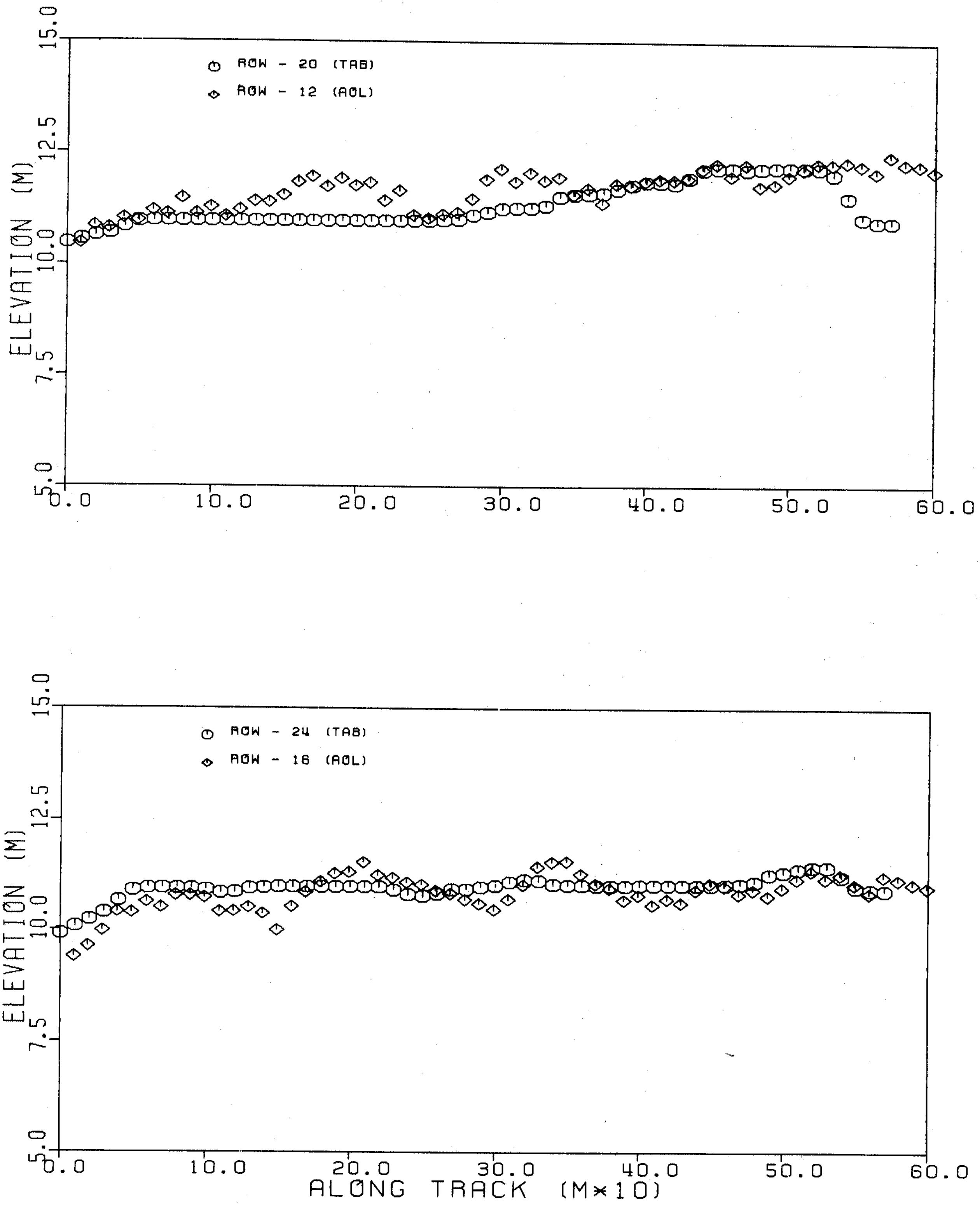
ROW - 20 (TAB)
ROW - 12 (AOL)
ELEVATION (M)
5.0
7.5
10.0
12.5
15.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
ROW - 24 (TAB)
ROW - 16 (AOL)
ELEVATION (M)
5.0
7.5
10.0
12.5
15.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
ALONG TRACK (M*10)

Figure 6