

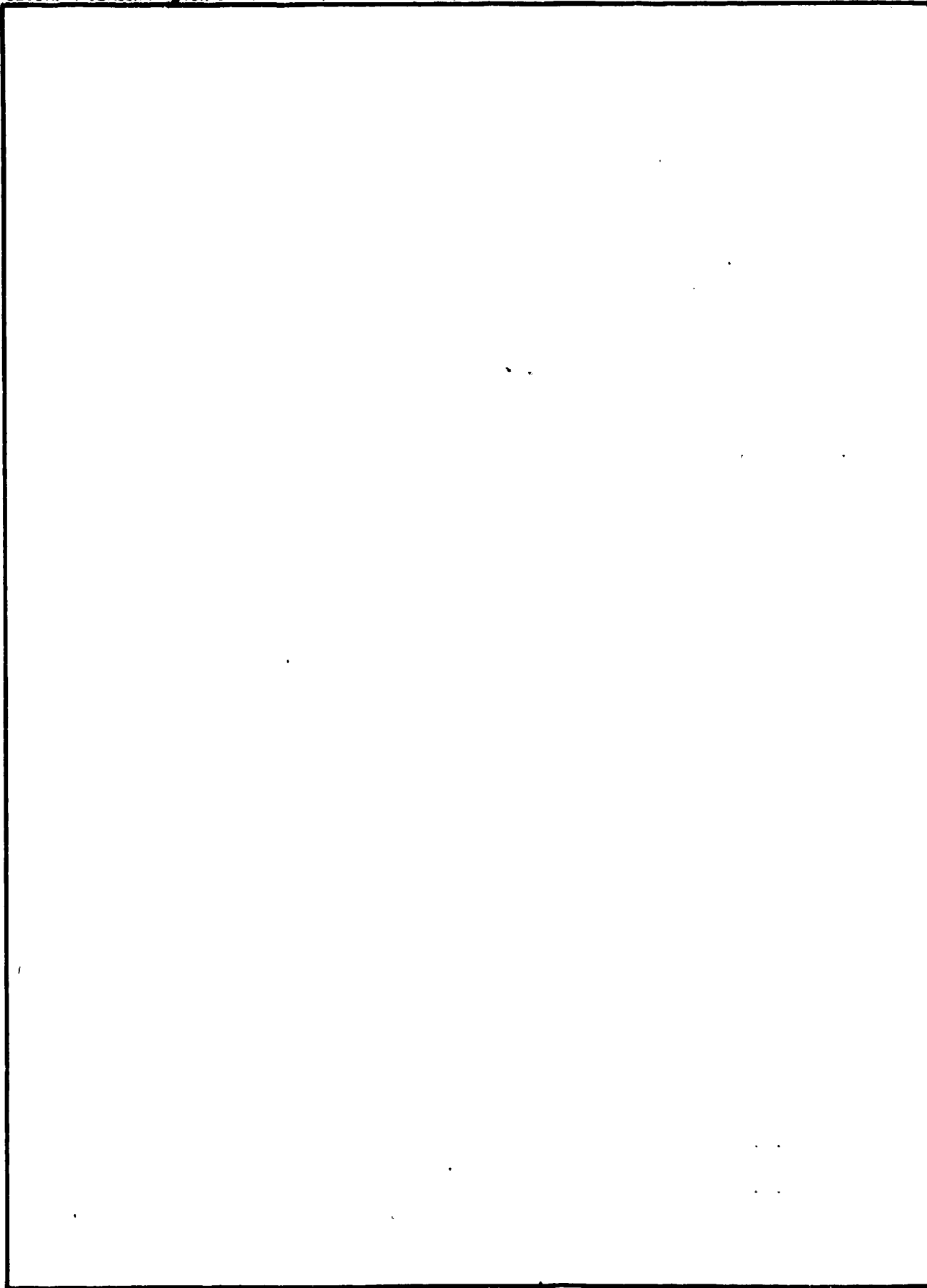
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EVALUATION OF THE POSITION AND AZIMUTH DETERMINING SYSTEM'S POTENTIAL FOR HIGHER ACCURACY SURVEY

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ABSTRACT

This paper reports on tests conducted to evaluate the accuracy potential of the U.S. Army Field Artillery's inertial survey system (Position and Azimuth Determining System AN/USQ-70). The tests were conducted by researchers at the U.S. Army Engineer Topographic Laboratories starting in the summer 1981. The test results reported include position, height and gravity anomaly. Also discussed is a post-mission least squares adjustment technique which was applied to the test results and which should have application to other inertial survey system missions.

INTRODUCTION

The Position and Azimuth Determining System (PADS) is a self-contained surveying system which provides fourth- and fifth-order control for U.S. Army Artillery surveys. The PADS is essentially a velocity aided inertial navigation system which has been designed to provide positional accuracy to 20 meters circular error probable (CEP) and height accuracy to 10 meters probable error (PE) over a 6-hour mission which starts at a "known" survey control point.

In August 1981, researchers at the U.S. Army Engineer Topographic Laboratories (ETL) began testing the PADS in an effort to determine the system's potential to perform higher-accuracy surveys. These tests involve operating PADS over a controlled test course, with modified operating procedures, and adjusting the system's measurements in an off-line least squares adjustment. This paper reports on the test procedures and results to date (November 1981).

BACKGROUND

Studies conducted by the U.S. Army during the 1960's indicated that a vehicular mounted inertial navigation system using a gyroscopically stabilized platform and an onboard general purpose digital computer could provide a feasible technical approach for a self-contained surveying system. In 1969, the U.S. Army documented a requirement within the field artillery for such a system. A PADS prototype was designed and fabricated in 1971-72 and successfully tested in 1972-73. In 1975, the Army awarded a contract for the design, fabrication and testing of five engineering development prototype PADS. Testing on these models was initiated in 1977 with all tests including Arctic tests being completed in 1979.

PADS received classification as a standard field army system and a production contract for 102 systems was awarded in 1979. The first systems were received by the U.S. Army Artillery and Engineer Schools in 1981.

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Related to the PADS was the development of a higher-accuracy Inertial Positioning System (IPS) for the Defense Mapping Agency in 1975. The hardware was basically a repackaging of the original PADS prototype hardware. Accuracy improvement was obtained by modifying operating procedures, extending premission alignment, operating in a more benign environment and carefully selecting inertial instruments. Variants of the IPS have been produced under the names Autosurveyor, Rapid Geodetic Surveying System (RGSS) and others. These systems are not suitable for operation in a military environment.

In the future, it seems reasonable to base a high-accuracy system on the production PADS, thus taking advantage of the ruggedness, higher reliability, production base, test equipment and support facilities of the military system. The purpose of these tests is to assess the performance of a production PADS using modified operating techniques and off-line software which should improve accuracy.

SYSTEM DESCRIPTION

The major components of the PADS are the primary pallet, which contains the Inertial Measuring Unit (IMU), Computer, and Power Supply, the Control and Display Unit (CDU), and Battery Box.

The IMU consists of a gimbal-mounted stable element, which includes two, two degrees of freedom gyros, three perpendicular accelerometers, and interface electronics. The gyros maintain the stable element in a north-pointing and level orientation even though the case is rotating. The accelerometer outputs are twice integrated in the computer to obtain changes in distance from the starting point in the east, north and vertical coordinates. The computer also performs all the computations needed for navigation and coordinate transformation. Estimates for changes in the gravity vector also can be obtained.

The CDU provides operator interface with the PADS. Data input is via a keyboard and data is output on an alphanumeric display. System status is shown using a set of annunciator lights. Additional operator warning is provided by an audible alarm.

The battery provides power in case of a vehicle power outage. It also allows the system to continue in operation while being transferred from one vehicle to another. The system installs in an Army jeep (M151A2 1/4 ton truck) or helicopter (OH-58A).

A typical mission sequence is:

- Turn on power and perform premission warm up and calibration under computer control.
- Drive (fly) the system to a known survey control point and enter the coordinates. This is known as an Update.
- Drive (fly) the system to the first location requiring measurement, stopping every 10 minutes for a velocity reference.
- Read out position coordinates. This procedure is known as a Mark.
- Continue mission to other points requiring survey.
- If the mission ends at a known survey control point or the start point, the PADS survey data can be adjusted for the closure error. This adjustment is performed by the system computer after an Update.

The PADS produces two measurements at the survey point. Raw

measurements are obtained at each survey point while marking the point. These raw measurements have been filtered by the on-board Kalman filter. At the end of a mission following an Update, smoothed values of the mark points are available. These smoothed values result from the closure adjustment by the system computer.

The PADS requires a 30- to 45-minute premission warm-up and alignment, which is performed automatically under computer control. During the alignment the system obtains a north reference by gyrocompassing and must remain stationary. During the mission the system obtains a velocity reference by stopping approximately every 10 minutes for a period of about 20 seconds. During this interval, the system has a known velocity of zero. Velocity errors can be measured and compensated. This procedure is known as a ZUPT (Zero velocity Update).

TEST PROCEDURES AND TEST COURSE

Two PADS have been used during the test: a production system with IMU serial number 019 and an engineering development prototype, IMU serial number 007. The essential difference between the two systems is the installation of an A1000 series accelerometer in the vertical channel of 019. An A200 series accelerometer is installed in the vertical channel of 007, as well as in the horizontal channels of both systems. The A1000 accelerometer is a more precise instrument than the A200.

The test course being used is shown at Figure 1. Two traverses were established. The "straight" traverse runs from station Welfare in an approximately northwest direction to station Mill, and is approximately 60 km long. The "L-shaped" traverse runs approximately north from station Horse, turns west at station Damascus and ends at station Mill. This traverse is approximately 40.6 km long. The control accuracy for the course is second-order. Gravity anomaly and deflections of the vertical are established at astronomic stations slightly offset from the main monuments. Gravity anomaly varies over the course from 32 milligals to 72 milligals with deflections of the vertical varying from -1.51 arc secs to 1.32 arc secs.

For the purposes of the test, a single mission consists of a forward traverse along either the straight or L-shaped course followed immediately by a reverse traverse of the same course. In the tests to date, the system has been updated at the end station of the forward traverse for five "straight" missions and four "L-shaped" missions. All updated missions have been performed with the 019 system. The end station has been marked but not updated for 12 "straight" missions and 12 "L-shaped" missions. Both systems have been used on these missions.

In addition to performing forward and reverse traverses for each mission, other changes to the standard operating procedures are performed. The interval between ZUPTs is decreased from 10 minutes to 3 minutes. For several of the missions a 2.5-hour premission alignment has been performed instead of the 30 minute standard alignment. For all missions residual bias estimates for each of the accelerometers are recorded at each mark. The horizontal accelerometer biases relate to deflections of the vertical and the vertical accelerometer bias to the gravity anomaly.

All data are hand recorded in the field. The data are then transferred to magnetic tapes back in the laboratories and adjusted using the techniques described in the next section.

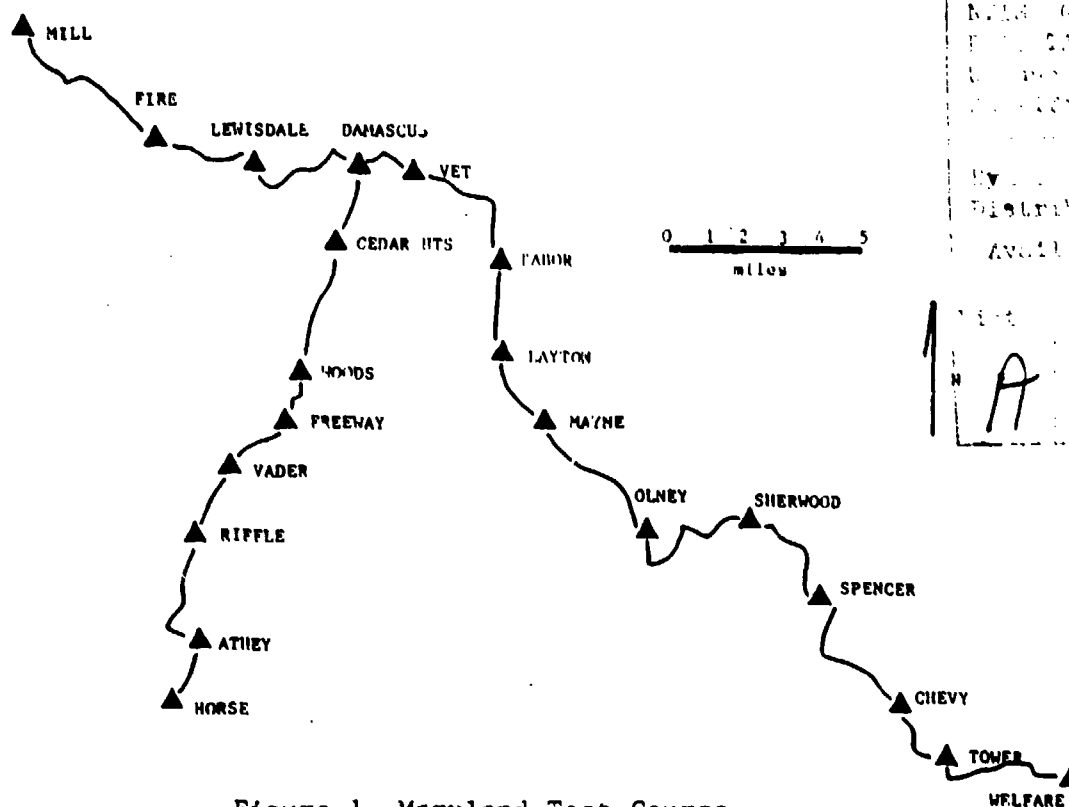


Figure 1. Maryland Test Course

OFFLINE DATA PROCESSING AND RESULTS

A computer program was developed to adjust the test data. This program was written in "basic" language to run on an HP 9830 desk top calculator. In this section the adjustment techniques used for positions, heights and gravity anomaly are discussed, along with the results of the adjustment.

Least Squares Formulation

A generalized weighted least squares method is used where all variables (observations and parameters) involved in the mathematical formulation are assumed to be observations. The following mathematical model is employed:

$$F(l_a, x_a) = 0 \quad (1)$$

where l_a and x_a are the true values of the observations and the parameters respectively. The linear equations in the above model are rewritten in the following form (using matrix notation):

$$A(l + v) + B(x + \Delta) - d = 0 \quad (2)$$

If there are c equations, n observations and u parameters then the following are defined:

- A is $c \times n$ matrix of observation coefficients
- B is $c \times u$ matrix of parameter coefficients
- l is $n \times 1$ vector of observations
- v is $n \times 1$ vector of residuals
- x is $u \times 1$ vector of parameters
- Δ is $u \times 1$ vector of parameter corrections
- d is $c \times 1$ vector of constants

Rearranging equation (2) gives:

$$Av + B\Delta - \epsilon = 0 \quad (2a)$$

where:

$$\epsilon = - (A1 + Bx - d) \quad (2b)$$

The weight matrix for the observations is the inverse of the variance-covariance matrix multiplied by the scalar reference variance σ_o^2 .

$$W = \sigma_o^2 \Sigma^{-1} \quad (3)$$

The parameters are also treated as observations with the following associated weight matrix:

$$W_{xx} = \sigma_o^2 \Sigma_{xx}^{-1} \quad (3a)$$

The least squares criterion requires minimization of the following expression:

$$\phi = v^t W v + \Delta^t W_{xx} \Delta - 2k^t (Av + B\Delta - \epsilon) \quad (4)$$

where k is the vector of Lagrange multipliers. This leads to:

$$(B^t M^{-1} B + W_{xx}) \Delta = B^t M^{-1} \epsilon \quad (5)$$

or:

$$(N + W_{xx}) \Delta = f \quad (5a)$$

where:

$$M = A W^{-1} A^t \quad (5b)$$

$$N = B^t M^{-1} B \quad (5c)$$

$$f = B^t M^{-1} \epsilon \quad (5d)$$

Estimates for the parameters result from:

$$\hat{x} = x + \Delta \quad (6)$$

where:

$$\Delta = (N + W_{xx})^{-1} f \quad (6a)$$

Estimates for the observations result from:

$$\hat{l} = l + v \quad (7)$$

where:

$$v = W^{-1} A^t M^{-1} (\epsilon - B\Delta) \quad (7a)$$

The Error Model

Equation (1) above represents an error model which is a combination of the inertial survey system's measurements (recorded raw values for positions, heights and gravity anomaly) and parameters which represent the primary system errors affecting a local-level inertial system. The

system errors included are level accelerometer scale factor errors, initial platform azimuth error following alignment, platform azimuth drift rate during the mission, and level accelerometer nonorthogonality for position (E,N). Errors modelled for height (H) include initial misalignment in the vertical, which also accommodates linear bias drift, and z accelerometer scale errors. Errors modelled for gravity anomaly (G) are the same as those for height. Note that the PADS system output is in the UTM coordinate system.

In the model, system raw measurements of the start and end points are compared to control coordinates. These control points are assumed to have $\sigma = .01$ meters, thus effectively constraining the solution at these points. For a double run traverse two smoothed values are available for each coordinate at each intermediate point. The average of the smoothed values at intermediate points on the traverse are assumed to have a $\sigma = 5$ to 10 meters and are used in the adjustment as a best approximation to the true values of these points. System raw measurements at the intermediate points are compared to these average smoothed values.

The following parameter notation for the position adjustment is defined:

α = azimuth misalignment
 β = nonorthogonality
 $\dot{\alpha}$ = azimuth drift rate
 $\tilde{S}_e$ = forward E scale error
 S_e = reverse E scale error
 $\tilde{S}_n$ = forward N scale error
 S_n = reverse N scale error

Note that by carrying 4 scale error parameters in the adjustment, accelerometer scale error asymmetry is acknowledged.

The error model for position has the following form:

$$\begin{aligned}\delta E_i &= \Delta N_i \cdot \alpha + \delta E_{\dot{\alpha}i} + \Delta E_i \cdot S_e \\ \delta N_i &= \Delta E_i \cdot (\alpha + \beta) + \delta N_{\dot{\alpha}i} + \Delta N_i \cdot S_n\end{aligned}\quad (8)$$

The azimuth drift terms are given by:

$$\begin{aligned}\delta E_{\dot{\alpha}i} &= \sum_{j=1}^i (N_j - N_{j-1}) \cdot \left[\dot{\alpha} \cdot t_{j-1} + \frac{\dot{\alpha}}{2} \cdot (t_j - t_{j-1}) \right] \\ \delta N_{\dot{\alpha}i} &= \sum_{j=1}^i (E_j - E_{j-1}) \cdot \left[\dot{\alpha} \cdot t_{j-1} + \frac{\dot{\alpha}}{2} \cdot (t_j - t_{j-1}) \right]\end{aligned}\quad (9)$$

Equations (9) are developed as an approximation to the integral of the PADS' trajectory along the traverse. These equations assume that the system's velocity is constant between coordinate measurements or mark points, and that azimuth drift is constant throughout the mission.

In equations (8) and (9) above, ΔE_i and ΔN_i are the change in coordinates and E_i and N_i are the control coordinates at end points, or the average smooth value coordinates at the intermediate points. Time, t_i , is the travel time from the initial point on the forward traverse to the i th mark point on the forward traverse.

If there are $n-1$ intermediate points along a traverse with E_i^0 and N_i^0

as the raw measurements of the i th coordinate position along the forward traverse then the following forward traverse end point model equations are formed:

$$\begin{aligned} E_n^\circ - E_n - \delta E_n &= 0 \\ N_n^\circ - N_n - \delta N_n &= 0 \end{aligned} \quad (10)$$

If E_0, N_0 are the start point coordinates for the forward traverse, and therefore, the end point for the reverse, with E_i°, N_i° as the raw measurements of the i th coordinate position along the reverse traverse, then the following reverse traverse end point model equations are formed:

$$\begin{aligned} E_n^\circ - E_0 - \delta E_n &= 0 \\ N_n^\circ - N_0 - \delta N_n &= 0 \end{aligned} \quad (11)$$

where:

$$\begin{aligned} \delta E_i &= \Delta N_i \cdot (\alpha + \dot{\alpha}t) + \delta E_{\dot{\alpha}i} + \Delta E_i \cdot \tilde{S}_e \\ \delta N_i &= \Delta E_i \cdot (\alpha + \beta + \dot{\alpha}t) + \delta N_{\dot{\alpha}i} + \Delta N_i \cdot \tilde{S}_n \end{aligned} \quad (12)$$

The $\dot{\alpha}t$ term appears in the reverse traverse equations. It is azimuth misalignment due to azimuth drift during the forward traverse. The time t is the interval from the start of the forward traverse to the start of the reverse traverse. The azimuth drift rate terms ($\delta E_{\dot{\alpha}i}, \delta N_{\dot{\alpha}i}$) are the same as in equations (9) above with coordinate and time indices referenced to the start of the reverse traverse.

Model equations are formed for each intermediate mark point and take the following form for the i th point on the forward traverse:

$$\begin{aligned} E_i^\circ - E_i - \delta E_i - (\tilde{E}_{n-i}^\circ - \tilde{E}_{n-i} - \delta \tilde{E}_{n-i}) &= 0 \\ N_i^\circ - N_i - \delta N_i - (\tilde{N}_{n-i}^\circ - \tilde{N}_{n-i} - \delta \tilde{N}_{n-i}) &= 0 \end{aligned} \quad (13)$$

Since the i th point on the forward traverse is the same as the $n-i$ th point on the reverse traverse, $E_i = \tilde{E}_{n-i}$ and $N_i = \tilde{N}_{n-i}$ and equations (13) become:

$$\begin{aligned} E_i^\circ - \tilde{E}_{n-i}^\circ - \delta E_i + \delta \tilde{E}_{n-i} &= 0 \\ N_i^\circ - \tilde{N}_{n-i}^\circ - \delta N_i + \delta \tilde{N}_{n-i} &= 0 \end{aligned} \quad (14)$$

For the position adjustment there are $2 \cdot (n-1)$ intermediate point equations and four traverse end point equations.

Development of the error models for height and gravity anomaly is similar to that for position. For height:

$$\delta H_i = d_i \cdot a_h + Sh \sum_{j=1}^i \Delta H_j + Sh \sum_{j=1}^i \tilde{\Delta H}_j \quad (15)$$

For gravity anomaly:

$$\delta G_i = t_i \cdot \alpha_g + Sg \sum_{j=1}^i \Delta G_j + Sg \sum_{j=1}^{\sim i} \Delta G_j \quad (16)$$

where:

- d_i = distance from start to ith point
- t_i = time from start to ith point
- $\Delta H_i, (\Delta G_i)$ = change in height (gravity) increasing
- $\hat{\Delta H}_i, (\hat{\Delta G}_i)$ = change in height (gravity) decreasing
- $\alpha_h, (\alpha_g)$ = misalignment in vertical
- $S_h, (S_g)$ = scale error increasing H, (G)
- $\hat{S}_h, (\hat{S}_g)$ = scale error decreasing H, (G)

The end point and start point equations for the height adjustment are:

$$H_n^o - H_n - \delta H_n = 0 \quad (17)$$

$$\hat{H}_n^o - H_o - \hat{\delta H}_n = 0 \quad (18)$$

where the notation follows the convention established in the position adjustment development.

For the intermediate points:

$$H_i^o - H_i - \delta H_i - (\hat{H}_{n-i}^o - \hat{H}_{n-i} - \hat{\delta H}_{n-i}) = 0 \quad (19)$$

As before $H_i = \hat{H}_{n-i}$ and equation (19) becomes:

$$H_i^o - \hat{H}_{n-i}^o - \delta H_i + \hat{\delta H}_{n-i} = 0 \quad (20)$$

The gravity anomaly adjustment follows the same development as the height adjustment. For both the height and gravity anomaly there are n-1 intermediate point equations and two end point equations.

Deflection of the vertical data are not considered in this paper. The accelerometer biases which relate to deflections are being investigated at the present time.

Results

In the following tables preliminary results from the adjustment of 31 missions are presented. A priori estimates and weights chosen for the parameters are not necessarily optimum. They represent values which appear to be realistic based on the past experience of researchers at ETL. A more finely "tuned" adjustment based on a different a priori parameter estimation and weighting scheme may produce better results. Work will continue in this area.

Table 1 summarizes the pertinent statistics for the adjustment parameters. The values shown are a simple average of the adjustment results for 31 missions (30 missions, in the case of gravity anomaly).

TABLE 1 - PARAMETER STATISTICS

<u>Parameter</u>	<u>A Priori Estimate</u>	<u>A Priori σ</u>	<u>Mean Adjusted Results</u>	<u>σ</u>
POSITION				
α	0.0	50 sêc	39.4 sêc	48.9 sêc
β	0.0	10 sêc	17.4 sêc	19.8 sêc
$\dot{\alpha}$	0.0	20 sêc/hr	-14.9 sêc/hr	21.2 sêc/hr
$\dot{\beta}$	0.0	25 ppm	3.3 ppm	23.6 ppm
$\dot{\gamma}$	0.0	25 ppm	62.9 ppm	65.4 ppm
$\dot{\delta}$	0.0	25 ppm	16.8 ppm	20.2 ppm
$\dot{\epsilon}$	0.0	25 ppm	-15.3 ppm	59.4 ppm
HEIGHT				
α_h	0.0	10 sêc	-5.29 sêc	21.8 sêc
β_h	0.0	50 ppm	-6.1 ppm	42.0 ppm
γ_h	0.0	50 ppm	6.1 ppm	42.0 ppm
GRAVITY				
α_g	0.0	50 sêc	-24.2 sêc	108.4 sêc
β_g	0.0	100 ppm	-0.28 ppm	1.40 ppm
γ_g	0.0	100 ppm	0.15 ppm	0.8 ppm

ppm = parts per million

sêc = arc seconds

The accuracies of adjusted values for position, height and gravity anomaly are summarized in Tables 2 through 5 below. Data are grouped into the following categories:

- I - IMU 019, 30 min align, straight traverse w/end point update
- II - IMU 019, 30 min align, L-shaped traverse w/end point update
- III - IMU 019, 30 min align, straight traverse w/o end point update
- IV - IMU 019, 30 min align, L-shaped traverse w/o end point update
- V - IMU 019, 2.5 hr align, straight traverse w/o end point update
- VI - IMU 019, 2.5 hr align, L-shaped traverse w/o end point update
- VII - IMU 007, 30 min align, straight traverse w/o end point update
- VIII - IMU 007, 30 min align, L-shaped traverse w/o end point update
- IX - IMU 007, 2.5 hr align, L-shaped traverse w/o end point update

On the straight course there are 12 intermediate points and on the L-shaped there are nine. For each mission the adjusted results for the intermediate points were compared to the control course values and a root mean square error (RMS) was calculated. The numbers reported in Tables 2 through 4 represent the mean and standard deviation of the mean for the compared RMS values. The number of missions in each category is also shown.

In Table 4 below, Category III, the results shown are based on one less mission than are reported in the previous tables. This is due to missing gravity anomaly data for one of the missions in this category.

TABLE 2 - POSITION (in meters)

<u>CATEGORY</u>	<u>MEAN RMS EASTING</u>	<u>σ RMS E</u>	<u>MEAN RMS NORTHING</u>	<u>σ RMS N</u>	<u>MISSIONS</u>
I	0.87	0.28	1.33	0.55	5
II	0.63	0.20	1.10	0.36	4
III	0.95	0.31	1.24	0.38	6
IV	1.28	0.32	0.93	0.29	2
V	2.02	0.48	2.75	0.68	2
VI	1.86		1.26		1
VII	1.16	0.29	1.47	0.48	4
VIII	1.84	0.44	0.83	0.26	4
IX	1.53	0.65	0.71	0.06	3

TABLE 3 - HEIGHTS (in meters)

<u>CATEGORY</u>	<u>MEAN RMS HEIGHT</u>	<u>σ RMS H</u>	<u>MISSIONS</u>
I	0.20	0.06	5
II	0.45	0.17	4
III	0.31	0.08	6
IV	0.15	0.05	2
V	0.20	0.01	2
VI	0.13		1
VII	0.51	0.10	4
VIII	0.69	0.23	4
IX	0.93	0.11	3

TABLE 4 - GRAVITY ANOMALY (milligals)

<u>CATEGORY</u>	<u>MEAN RMS GRAVITY</u>	<u>σ RMS G</u>	<u>MISSIONS</u>
I	2.05	0.33	5
II	1.77	0.23	4
III	2.00	0.44	5
IV	2.15	0.43	2
V	1.71	0.05	2
VI	2.41		1
VII	7.46	2.75	4
VIII	7.18	1.45	4
IX	8.45	2.66	3

In Table 5 the position adjustment values are compared to distance traversed for each of the categories. Reported in this table are the ratios of the average RMS error to the one way distance traversed. Recall that the straight traverse was approximately 60 km long and the L-shaped 40.6 km.

TABLE 5 - RMS : DISTANCE

CATEGORY	E (RMS)	N (RMS)	$((E^2+N^2)/2)^{1/2}$
I	1:69000	1:45000	1:53500
II	1:64500	1:37000	1:45000
III	1:63000	1:48500	1:54500
IV	1:31500	1:49000	1:37500
V	1:29700	1:22000	1:25000
VI	1:22000	1:32000	1:25500
VII	1:52000	1:41000	1:45500
VIII	1:22000	1:49000	1:28500
IX	1:26500	1:57000	1:34000

To summarize the results reported in the tables, it can be generally noted that the 019 PADS produced higher accuracies than the 007 PADS. A direct comparison of the systems can be made by comparing results in categories III and IV to categories VII and VIII. In particular the 019 system is much more accurate in heights and gravity anomaly. This is directly attributable to the installation of the more precise Al000 accelerometer in the vertical channel of 019. Recall that 019 is the production system and should be representative of the fielded PADS.

Category V and VI results which represent 019 missions preceded by a 2.5-hour alignment prove to be worse than missions preceded by a 30-minute alignment. This is contrary to what was expected and probably indicates a time dependent gyro stability problem. An examination of all 019 missions reveal large uncompensated errors following adjustment for the last several points of the reverse traverse, giving further indication of the instability problem. The gross nature of this instability is probably an individual system dependent problem and may not occur in other PADS. It should be pointed out, though, that time dependent error growth appears to be an inherent characteristic of inertial survey systems. Generally, shorter (time wise) missions produce better results. Relatively speaking, the missions conducted for these tests take a long time: an average of 4.8 hours for the straight course and 3.6 hours for the L-shaped, following alignment.

CONCLUSION

PADS was designed to produce fourth- and fifth-order control accuracy surveys (relative accuracies of 1:2500 and 1:1000 respectively). These tests provide evidence that PADS does have a much higher accuracy potential. The preliminary results reported here indicate that by modifying normal operating procedures and processing the system's measurements in a simple off-line, adjustment program, positional accuracies obtainable are in the 1-meter range, with relative accuracies better than 1:40000. Height accuracies of approximately .30 meter and gravity anomaly accuracies of approximately 2 milligals also appear obtainable with the production system.

Upon completion of the ETL PADS testing program, a final report will be published. It is anticipated that in addition to reporting the final position, height and gravity anomaly results, deflections of the vertical data will also be considered and reported.

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