Rapid geodetic survey system (RGSS) deflection of the vertical and gravity anomaly tests at White Sands Missile Range, 1980

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OCTOBER 1982

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ETL

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ETL – 0308	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RAPID GEODETIC SURVEY SYSTEM (RGSS) DEFLECTION OF THE VERTICAL AND GRAVITY ANOMALY TESTS AT WHITE SANDS MISSILE RANGE, 1980.		5. TYPE OF REPORT & PERIOD COVERED 1 April 1980 – 1 April 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mark Todd		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, VA 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Topographic Laboratories Fort Belvoir, VA 22060		12. REPORT DATE October 1982
		13. NUMBER OF PAGES 38
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Anomaly
Deflections
Densification
Gravity
Ground Vehicle
Helicopter
Inertial
Rapid Geodetic Survey System

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents the tests and results obtained with the Rapid Geodetic Survey System (RGSS) at White Sands Missile Range in 1980. The performance capability of the system in the ground vehicle and helicopter modes is statistically characterized.

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PREFACE

The U.S. Army Engineer Topographic Laboratories (USAETL) has been active in the development of inertial surveying for several years. A number of advances in hardware and techniques to recover the anomalous gravity vector components have been incorporated into the Rapid Geodetic Survey System (RGSS). This report presents the results of a series of tests of the RGSS at the White Sands Missile Range (WSMR) to determine its performance capabilities and areas for possible improvement. The testing was performed by Mark Todd from the Photo/Electronic Survey System Branch, Surveying and Engineering Division, Topographic Developments Laboratory, USAETL. Test and data reduction support was provided by Defense Mapping Agency Geodetic Survey Squadron personnel both at Cheyenne, Wyoming and WSMR.

COL Edward K. Wintz, CE was Commander and Director and Mr. Robert P. Macchia was Technical Director of the U.S. Army Engineer Topographic Laboratories during the report preparation.

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INTRODUCTION

SUBJECT • This report covers the results of tests conducted in 1980 with the Rapid Geodetic Survey System (RGSS) at the White Sands Missile Range (WSMR), New Mexico.

BACKGROUND • In early October 1979, the Defense Mapping Agency (DMA) contacted the Engineer Topographic Laboratories (ETL) for assistance in developing advanced surveying capabilities. DMA has the responsibility to provide large quantities of geodetic and gravimetric control. The large number of deflection stations and the precision required at each station created particular concern since first-order astronomic observations, combined with precision geodetic surveys, had to be made at each site. Because of the skill levels and labor-intensive methods required for astronomic observations, alternative, less demanding techniques to determine deflection of the vertical were needed.

Inertial survey systems, such as the RGSS, made by Litton, and the Inertial Positioning System-2 (IPS-2), made by Honeywell, provide an attractive possible solution to the deflection of the vertical problem. Previous tests conducted under special conditions with the RGSS indicated that inertial techniques can transfer deflections to the required order of accuracy and can provide them faster and more economically than conventional means. Therefore, DMA requested that ETL perform field tests to better establish the capabilities of RGSS.

OBJECTIVE • The objective was to perform a series of field tests with the RGSS to determine its current capabilities to measure changes in the deflection of the vertical and, if possible, to determine the hardware and software modifications required to improve accuracy.

INVESTIGATION

TEST SITE • Preliminary planning and organization for the project were presented by DMA in a draft test plan.[1] Subsequent planning sessions between DMA and ETL led to a slightly modified plan that was coordinated with DMA's Geodetic Survey Squadron (GSS) in Cheyenne, Wyoming. Field support was provided by GSS Detachment–2 personnel, who worked with ETL personnel on detailing traverse routes for the selected WSMR test area. WSMR was selected because:

- A very accurate and dense network of horizontal and vertical geodetic control, astrogeodetic control, and gravimetric control exists in the various test ranges.
- Numerous roads and trails are available throughout WSMR to accommodate multiple traverses across a 30–km–square area selected for the test.
- Significant changes in gravity vector anomalies occur across the test area.
- Excellent support in geodetic surveying and logistics is available at WSMR from DMA's GSS Detachment-2.

Field reconnaisance by ETL and Detachment–2 personnel was undertaken in December 1979 to check the existence and passability of all routes and to determine the locations of required monument offsets to insure accessibility by the RGSS land vehicle and helicopter. During the following weeks, Detachment–2 personnel performed the following tasks:

1. Monumented, precisely surveyed and computed new positions and heights for more than 50 offset survey points to be used in the tests.

[1] "Rapid Geodetic Survey System Free Air Gravity Anomaly and Deflection of the Vertical Capability Test." U.S. Army Defense Mapping Agency, Washington, D.C., January 1980.

2. Re–observed gravity at all 79 gravity stations involved in the tests.

3. Observed four new astrogeodetic stations to modified first–order quality.

4. Reobserved eight survey points that required upgrading.

5. Arranged for the grading and smoothing of seven miles of trails to provide better mobility.

6. Provided logistical support throughout the tests.

The test area is inclosed in a quadrilateral 32 by 30 kilometers, with the southwest corner of this tract adjacent to the WSMR post area as shown in figure 1. Eleven traverses crisscross the area, with three running in a SW–NE direction, two running in a N–S direction, five running in a E–W direction, and one running in a NW–SE direction. The traverses were 35 percent paved, 30 percent gravel, and 35 percent field road for ground vehicle missions. Eighty percent of the stations on each traverse were within a straightness parameter value of L/6.5 of a straight course.

Values for geodetic position and height are known for 61 interior stations on these traverses. Thirty of these stations are junction points of at least two traverses.

Free–air gravity anomaly values are known for 60 interior stations. Thirty gravity stations are junction points of at least two traverses.

Values for the meridian and prime vertical deflections are known for 29 interior stations. Twenty deflection stations are junction points of at least two traverses.

In addition to those listed above, 18 stations around the perimeter of the area have all geodetic parameters known and were used as initial and final fixed stations for traversing.

The estimated standard deviations associated with known geodetic values are 0.08 meter for latitude and longitude relative to the local WSMR datum origin, 0.03 meter for height relative to local first–order level lines, 0.25 arc–second for each deflection component in an absolute sense, and 0.1 milligal for the gravity anomaly in an absolute sense.

TEST DESIGN • The tests were performed using ETL's RGSS, which is a Litton Inertial Positioning System–1 (IPS–1) operating with modified software and hardware to provide optimal platform control with respect to deflection of the vertical determination.[2,3,4,5,6,7] Because level axis tilt errors tend to increase with mission duration, the system should not be operated for more than one or two hours after alinement without performing at least a partial realinement of the platform. This constraint dictates that traverses be run only in one direction following an initial 1–hour alinement process. At the end of a traverse, the system was updated by entering the coordinates of the terminal station. The system computer then smoothed the intermediate positions and elevations. Later, the anomalous gravity vector components were smoothed using an off–line computer. After positional smoothing, the system was realined and another survey mission run along the course in the opposite direction. A minimum of two passes, one in each direction, were made along each traverse. With 11 traverses crossing the area, this resulted in 22 missions in a complete data set. Complete data sets were collected with the RGSS in both a land vehicle and a helicopter.

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[2]"Feasibility Test Program For Measurement of Gravity Anomaly Changes Using 2–Micro–G Accelerometer in the Inertial Platform." Litton Guidance and Control Systems, Woodland Hills, California, Document No. 402373, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–CR–74–16, December 1974, AD–B001 553L.

[3]"Addendum to Feasibility Test Program For Measurement of Gravity Anomaly Changes Using 2–Micro–G Accelerometer in the Inertial Platform." Litton Guidance and Control Systems, Woodland Hills, California, Document No. 402414, April 1975.

[4]"Description of a Proposed Rapid Gravity Survey System." Litton Guidance and Control Systems, Woodland Hills, California, Document No. 13181, May 1975.

[5]G. Johnson and C. Asher, "Rapid Geodetic Survey System Final Report." Litton Guidance and Control Systems, Woodland Hills, California, Document No. 403273, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–0074, March 1976, AD–B014 577L.

[6]James R. Huddle, "The Measurement of the Change in the Deflection of the Vertical with a Schuler–Tuned North–Slaved Inertial System." Litton Guidance and Control Systems, Woodland Hills, California, November 1977.

[7]James R. Huddle and R.H. Lentz, "Post–Mission Smoothing and Analysis of the Measurements of the Change in the Deflection of the Vertical Obtained by the Rapid Geodetic Survey System (RGSS) at the White Sands Test Range." Litton Guidance and Control Systems, Woodland Hills, California, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–0065, September 1976, AD–A032 525.

TEST PROCEDURES and SCHEDULE • Azimuth drift bias calibration, dynamic calibration, and other necessary operational procedures were followed in conducting the tests. The azimuth drift bias, left unchecked, has serious deteriorative effects on the positioning capability of the RGSS. Azimuth drift bias is compensated by statically measuring azimuth drift, entering the correction into the computer, and then verifying satisfactory performance of the system. Azimuth drift bias was corrected before performing dynamic calibration.

Usual IPS–1 operating procedures were used in conducting the actual area test missions. The system was warmed for approximately 1 hour before commencing with the pre–mission alinement. The pre–mission alinements were performed at the initial survey station with the IMU oriented approximately in the direction required to survey the particular traverse. Approximately 3.5–minute travel periods were used in each survey mode. The average travel period between system zero velocity updates (ZUPTS) was 3.5 minutes in both the ground vehicle and helicopter nodes. When a mark was performed, system data such as survey parameter estimates and covariances were stored on magnetic tape. Since system state parameters and covariances are corrected only at the ZUPTS, it is worthwhile to mark (record) at every ZUPT to have a complete record of system status for each mission. During the tests, marks were performed at all stops for ZUPTS, even when not over a monumented position. North and east accelerometer velocity corrections were manually recorded at every ZUPT. These are observable quantities used to correct or update the system state estimates during the mission. All required survey data (position, height, anomalous gravity vector component changes) were manually recorded to prevent loss should the recording unit fail and to provide a real time assessment of system performance. As a result of the hand recording effort at each stop, the duration of each ZUPT was extended from 45 seconds to approximately 70 seconds for the ground vehicle mode. The disadvantage of extending the mission duration is countered by the advantage of refined null velocity at the conclusion of the ZUPTS. The ZUPTS in the helicopter averaged 96 seconds in duration.

In January 1980, after calibrating the RGSS, a performance run was made in the Chevrolet "Suburban" 4–wheel drive vehicle over the survey course associated with the high–speed sled–test (HSST) track at nearby Holloman AFB. After a single, 1–hour alinement, direct (northerly) and reverse (southerly) passes were made over the course to compare the system's performance in deflection determination with its performance in the summer of 1978, when the system was run on the same course for acceptance from the manufacturer.

Thirteen land vehicle missions were completed from 16 through 25 January 1980. On 26 January, a malfunction was experienced during the 1-hour alinement process. After unsuccessful attempts to correct the problem in the field, ETL returned the system to the manufacturer for repair. The manufacturer found that a relay which controls the platform slew rate had stuck in one position. Also, loose wiring in the platform, which occurred during shipment or during investigatory work to diagnose the relay problem, was repaired.

After the hardware problems were corrected, the system was checked dynamically over the manufacturer's test course. The system was then sent back to WSMR where azimuth drift bias and dynamic calibrations were repeated, and the test missions resumed. Six additional missions were completed from 24 through 28 February 1980, after which the tests were interrupted to conduct a 1-week demonstration with the system in St. Louis.

During the St. Louis demonstration, difficulty was experienced in completing a satisfactory pre-mission alinement. After unsuccessful attempts to correct the problem, the system was returned to the manufacturer on 17 March 1980. The manufacturer found that the lower gyro in the platform was low on florolube, the liquid required to provide a bouyant medium for the gyro float assembly. This and other problems required extensive repairs.

The lower gyro was replaced by an available spare. During laboratory tests to compile new gyro bias heading tables, the A-1000 accelerometer in the vertical channel was damaged by excessive heat and was subsequently replaced. Precise heat compensation and heading tables were compiled for the new A-1000 accelerometer. The system was tested over the manufacturer's test course from 14 to 17 July 1980, to check calibration repeatability and to observe deflection change over a six-station traverse. Proper performance was verified. The system was returned to WSMR on 19 July, where azimuth drift bias and dynamic calibration were completed and missions resumed. The three remaining ground vehicle missions were completed by 24 July 1980.

On 27 July, four passes over the HSST track were made using a 1-hour alinement and a 25-minute alinement, running forward (northerly) and reverse (southerly) following each alinement period.

Since the helicopter was not immediately available for the next phase of tests, in late July and again in early September, the system was operated eight times over a V-shaped course and once over an L-shaped course. The V-shaped course was surveyed four times with the inertial measuring unit (IMU) hard-mounted in the vehicle as usual and four times with the IMU remounted onto a turntable to facilitate rotation of the IMU case independent of the vehicle.

During the four latter runs, an assistant kept the IMU at roughly a constant case heading to minimize the effects of the large heading changes in the V-shaped course. A single L-shaped run was completed in the same manner. On 9 September 1980, after the helicopter missions, another single L-shaped survey was completed with the IMU case maintained on a constant heading. These experiments were conducted under the premise that minimizing heading change of the IMU would improve deflection, anomaly, and height recovery. Using a simple turntable, accurate horizontal positioning was not possible because the relationship between the IMU reference point and the vehicle position point was not known.

On 16 August 1980, an Army UH-1 helicopter was made available for 2 weeks. The system was installed in the helicopter on 16 and 17 August. To minimize reference velocity noise, the operator removed the IMU from the helicopter and set it on the ground during all ZUPTS. Extended cables were provided by the manufacturer to facilitate removal.

Six dynamic calibration missions were conducted on the 18 and 19 of August with the RGSS in the helicopter. The north and east scale factors changed significantly. Sensitive axes alinement parameters did not change.

The 22 helicopter missions were completed by 5 September 1980. The helicopter was down for maintenance 4 days during this period. Maintenance on the ground vehicle, serving as a field APU, halted the operation for a day. The RGSS caused 2 days delay owing to problems in computer tray 4. A second spare was furnished by the manufacturer to finish the tests. The system's tape deck experienced intermittent problems throughout the project. Also, a spare fast-slew card was installed when the platform would not slew correctly to north during some alinements in mid-July.

TEST RESULTS ● The land vehicle and helicopter test results are reported for 22 missions in each mode of transportation, run on 11 traverses completed during January, February, July, August, and September 1980. All the statistics reported are average values resulting from combining independent observations made at many stations throughout the test area. Therefore, the statistics represent what may be expected anywhere over the area.

Unless otherwise noted, the average traverse time and distance for ground vehicle missions were 2.18 hours and 34.8 kilometers, respectively. The corresponding values for helicopter missions were 0.77 hour and 29.6 kilometers. In all the following tables, statistics for geodetic values are given with ϕ, λ, and H errors in meters, ξ and η errors in arc seconds, and Δg errors in milligals. The Average Error is the overall mean of the n–errors considered. The Average σ is the standard deviation of observed errors about the average error. This is a measure of precision or repeatability. The Average RMS is the root–mean–square (RMS) of all the individual errors and is a measure of accuracy if the known published values are considered to be very accurate. The Maximum Error is the largest deviation between a smoothed geodetic value estimate and the known published value. The n–observations line indicates the number of observed errors evaluated to compute the statistics. If this number is large, one can be more confident about the numerical values given for the various statistical parameter estimates.

The first category of statistics to be considered is the survey performance obtained when a single pass in any direction is completed with the RGSS in the ground vehicle. Table 1 shows the results of all 22 missions.

TABLE 1. Ground Vehicle, Single Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.00	0.12	–0.16	–0.6	0.5	–0.2
Average σ	0.45	0.38	0.18	1.4	1.1	2.1
Average RMS	0.45	0.40	0.24	1.5	1.2	2.1
Maximum Error	1.26	1.14	– .87	–4.6	5.3	7.3
n–observations	198	198	196	116	116	199

Although the average error (bias) levels for ϕ and λ in table 1 are within the noise levels for these axes, the −0.16 meter bias for H is higher than expected. This may result from not compensating for the influence of level gyro drift bias on the vertical axis. The algorithm to effect this compensation has been developed by the manufacturer but had not been implemented in the on-line, post-mission smoothing.

The corresponding results for all 22 missions in the helicopter mode are presented in table 2. These results are somewhat better than those achieved in the ground vehicle. The improved performance probably results from reduced systematic errors because traversing is speedier and straighter with the helicopter and reference velocity noise was reduced because the IMU was removed from the helicopter for every ZUPT. All reverse traverses in the ground vehicle followed 1-hour alinement periods whereas half of the reverse missions in the helicopter followed 1-hour alinement and half followed 25-minute alinements.

TABLE 2. Helicopter, Single Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.04	0.09	0.13	0.2	0.1	−0.2
Average σ	0.28	0.23	0.23	0.8	0.7	2.0
Average RMS	0.28	0.25	0.27	0.8	0.8	2.0
Maximum Error	−1.16	1.03	1.31	2.1	−1.9	6.6
n–observations	220	220	219	120	120	210

To examine the performance resulting from shorter missions, statistics were computed for a subset of five ground vehicle missions averaging 1.71 hours in duration. Minimum and maximum mission durations were 1.50 and 1.88 hours, respectively. The results are given in table 3.

TABLE 3. Ground Vehicle, Five Single Short Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	−0.14	0.04	−0.08	0.1	0.6	−0.0
Average σ	0.28	0.22	0.17	0.5	0.6	1.6
Average RMS	0.32	0.22	0.19	0.5	0.9	1.6
Maximum Error	−0.78	−0.54	−0.60	1.3	1.5	−3.4
n–observations	45	45	45	33	33	45

The indication is that missions averaging about one–half hour shorter significantly reduce the variability in the anomalous gravity vector components. Also, there is a significant reduction in maximum error levels. The average distance covered by these missions was 32.2 kilometers with the shortest mission being 23.1 kilometers and the longest 40.8 kilometers. The critical difference between these five missions and the rest of the missions is reduced mission time due to operator familiarity, no delays, straight traverses, and smoother routes. These advantages were not available on all ground vehicle traverse missions.

To further examine gravity vector errors due to still shorter single passes, 17 missions were created by terminating longer missions before the end point and smoothing the anomaly components. The average mission time was 1.05 hours, the shortest and longest being 0.53 hour and 1.52 hours, respectively. The average distance was approximately 15.7 kilometers (table 4).

TABLE 4. Ground Vehicle, Short Single Passes

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	−0.2	0.4	0.2
Average σ	0.7	0.9	2.0
Average RMS	0.7	0.9	2.0
Maximum Error	−1.9	2.5	6.4
n–observations	38	38	71

The five full–length missions used in table 3 were shortened about 40 minutes and included in this 17 mission group. The results in table 4 are no better than those in table 3.

In the above 17 mission group, the smoother, straighter missions of average duration 1.71 hours were terminated near the middle and both halves were adjusted in the usual linear manner. The average mission time then became 0.85 hour, with minimum and maximum durations of 0.53 hour and 1.34 hours, respectively. The average mission distance was approximately 16.1 kilometers (see table 5).

TABLE 5. Ground Vehicle, Single, Short, Straight, Smooth Passes

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.1	0.2	–0.0
Average σ	0.4	0.7	1.6
Average RMS	0.4	0.7	1.6
Maximum Error	–0.8	1.3	–3.1
n–observations	27	27	40

Thirty–three short helicopter missions were created from 8 traverses. The average mission time and distance were 0.38 hour and 15.0 kilometers respectively. The results are shown in table 6 which corresponds to the ground vehicle statistics in table 4.

TABLE 6. Helicopter, Short Single Passes

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.0	0.1	0.1
Average σ	0.6	0.6	1.4
Average RMS	0.6	0.6	1.4
Maximum Error	–1.8	1.6	3.7
n–observations	76	76	131

This category further illustrates the advantage of short, straight, smooth missions by a significant reduction in bias errors. A reduction in the variability of errors is expected when multiple observations of the same parameters are combined. Perhaps the simplest and most often used scheme of this type is to average the results obtained from forward and reverse passes over a traverse. The mean value of the two passes through a given station is taken as the best estimate of the stations geodetic parameters. The error statistics for the same ground vehicle missions presented in table 1, but computed as double–run traverses, are contained in table 7.

TABLE 7. Ground Vehicle, Double Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.00	0.12	–0.15	–0.6	0.5	–0.2
Average σ	0.30	0.28	0.01	1.0	0.6	1.9
Average RMS	0.30	0.30	0.15	1.1	0.8	1.9
Maximum Error	–0.80	0.82	0.45	–3.5	2.4	5.7
n–observations	94	94	93	58	58	96

Average mission duration and distance were, as before, 2.18 hours and 34.8 kilometers, respectively.

The error statistics for double–run traverses in the helicoptor are presented in table 8. The average mission time and distance were 0.77 hours and 29.6 kilometers, respectively.

TABLE 8. Helicopter, Double Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.04	0.09	0.14	0.2	0.1	–0.2
Average σ	0.15	0.20	0.17	0.5	0.6	1.6
Average RMS	0.16	0.22	0.22	0.5	0.6	1.6
Maximum Error	–0.48	0.97	0.67	–1.3	1.5	–4.2
n–observations	110	110	109	60	60	105

To examine the effects of shorter double–run traverses on gravity anomaly determinations, nine full–length traverses were terminated in the middle and the data smoothed for each segment. Each half was meaned with the corresponding half run in the opposite direction. Missions generated in this manner had an average duration of 1.08 hours and an average distance of 17.4 kilometers (see table 9).

TABLE 9. Ground Vehicle, Short Double Passes

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.00	0.3	–0.00
Average σ	0.5	0.5	1.4
Average RMS	0.5	0.6	1.4
Maximum Error	1.2	1.3	4.9
n–observations	40	40	72

The corresponding results for data acquired in the helicopter are contained in table 10.

TABLE 10. Helicopter, Short Double Passes

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.1	0.1	0.1
Average σ	0.5	0.5	1.1
Average RMS	0.5	0.6	1.1
Maximum Error	−1.5	1.3	−2.6
n–observations	37	37	63

The average duration and distance of these created missions were 0.38 hours and 15.0 kilometers, respectively.

Another method of providing redundant observations, when surveying an area, is to traverse the area in a grid pattern. That is; survey the area with a series of approximately parallel single passes and then run a second series of intersecting passes approximately perpendicular to the first. The error statistics for the ground vehicle missions analyzed in this fashion are shown in table 11. The mean values of the parameters at each intersection were taken as the best estimates.

TABLE 11. Ground Vehicle, Grid Single Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.06	0.15	−0.17	−0.5	0.4	−0.2
Average σ	0.32	0.31	0.12	1.1	0.8	1.4
Average RMS	0.33	0.35	0.21	1.2	0.9	1.5
Maximum Error	−0.95	1.03	−0.56	−3.5	3.4	−4.0
n–observations	242	242	242	184	184	256

Again, the average mission time and distance were 2.18 hours and 34.8 kilometers, respectively.

The results for the data obtained in the helicopter, when processed in the same manner, are shown in table 12.

TABLE 12. Helicopter, Grid Single Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.01	0.10	0.13	0.3	0.2	0.0
Average σ	0.23	0.19	0.15	0.6	0.5	1.4
Average RMS	0.23	0.22	0.20	0.7	0.6	1.4
Maximum Error	−1.03	0.75	0.75	2.0	1.4	4.3
n–observations	276	276	274	180	180	276

The average time and distance for these helicopter missions were 0.77 hour and 29.6 kilometers, respectively.

For even more redundancy, the grid pattern might be traversed with double–run missions. The geodetic parameter estimates at each grid intersection will be the mean of the data from 4 passes through the point. The error statistics for the ground vehicle and helicopter missions are shown in tables 13 and 14, respectively.

TABLE 13. Ground Vehicle, Grid Double Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.07	0.15	−0.18	−0.5	0.5	−0.2
Average σ	0.21	0.22	0.03	0.7	0.6	1.2
Average RMS	0.22	0.27	0.18	0.9	0.8	1.2
Maximum Error	0.47	0.82	−0.36	−2.5	1.8	3.0
n–observations	55	55	55	46	46	63

TABLE 14. Helicopter, Grid Double Passes

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.01	0.10	0.13	0.3	0.2	0.0
Average σ	0.11	0.17	0.12	0.4	0.4	1.1
Average RMS	0.12	0.20	0.17	0.5	0.5	1.1
Maximum Error	−0.30	0.60	0.47	1.0	1.2	−2.6
n–observations	68	68	67	45	45	69

Again, the average mission duration and length were 2.18 hours and 34.8 kilometers in the ground vehicle, and 0.77 hours and 29.6 kilometers in the helicopter.

Adjustment of the data using techniques to maximize the use of available information should reduce errors. To examine this, simple least–squares adjustments were performed on both the ground vehicle and helicopter data sets. This adjustment, performed at the GSS, minimizes with the least–squares criteria the difference between forward– and reverse–smoothed geodetic value estimates, and simultaneously minimizes the differences at traverse crossing points. Error modeling to determine and remove systematic errors was not implemented in this adjustment. The adjustment program did not fully constrain the perimeter end–point stations, which were treated as observations with small a priori variances.

The error statistics, after the least–squares adjustments, are shown in tables 15 and 16 for the ground vehicle and helicopter missions, respectively.

TABLE 15. **Ground Vehicle, Least–Squares**

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.01	0.16	–0.12	–0.5	0.3	–0.3
Average σ	0.13	0.15	0.12	0.5	0.6	1.3
Average RMS	0.13	0.22	0.17	0.7	0.7	1.4
Maximum Error	–0.37	0.55	–0.49	–1.7	1.3	–3.7
n–observations	61	61	60	29	29	60

TABLE 16. **Helicopter, Least–Squares**

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.03	0.14	0.16	0.2	0.0	–0.5
Average σ	0.10	0.16	0.11	0.4	0.5	1.0
Average RMS	0.10	0.21	0.19	0.4	0.5	1.1
Maximum Error	0.31	0.63	0.48	–1.0	1.1	–2.6
n–observations	61	61	61	29	29	56

The least-squares adjustment also was applied to the anomalous gravity vector components of shorter missions. In this case, each of 17 missions was terminated/smoothed to approximately its center point, creating 34 missions of shorter length. Two missions, being forward/reverse over the same traverse, could not be broken for lack of enough known stations. They are included at their original full length. The three missions that were run in July 1980 to complete ground vehicle missions are not included in this presentation. The average duration of these missions was 1.13 hours with average distance 16.8 kilometers. The ground vehicle error statistics are shown in table 17.

TABLE 17. Ground Vehicle, Short Mission, Least Squares

	ξ(sec)	η(sec)	Δg(mgal)
Average Error	−0.2	0.3	−0.0
Average σ	0.5	0.6	1.7
Average RMS	0.5	0.7	1.7
Maximum Error	−1.3	1.2	4.1
n−observations	20	20	20

Data from the helicopter missions were analyzed in a similar manner (see table 18).

TABLE 18. Helicopter, Short Mission, Least-Squares

	ϕ(sec)	η(sec)	Δg(mgal)
Average Error	0.0	0.1	0.2
Average σ	0.4	0.5	0.9
Average RMS	0.4	0.5	0.9
Maximum Error	−1.1	1.2	2.6
n−observations	23	23	42

The average helicopter mission created in this manner had a duration of 0.38 hour and length of 15.0 kilometers.

An ideally smooth, straight, and level test course can be used to check the noise limitations of the system. The road beside the High Speed Sled Track (HSST) at Holloman AFB provides these test conditions and has a number of deflection stations along its 15.4 kilometers length. The RGSS was tested along the HSST on three occasions: in 1978 after it was accepted from the manufacturer, in January 1980 before the WSMR area–survey tests began, and in July 1980, when the system was returned to WSMR after repairs. Limited stations were available for gravity magnitude observations so no statistics were calculated for gravity anomaly.

The 1978 missions included 3 single passes, each on a 1–hour alinement from the north end of the track. For each of these missions, 1.5–minute travel periods between ZUPTS were used. ZUPT periods were 1 minute. The average duration of each survey was 1.50 hours.

In January 1980, the system was alined for an hour at the south end of the track, and a 0.72 hour northerly survey was run. After smoothing the height and positional data, a 0.75 hour reverse survey was performed. They are considered to be two independent single passes since the reverse pass was reinitialized and began only 0.92 hour after alinement was completed. Approximately 3–minute travel periods were used, along with 1–minute ZUPT periods.

The July 1980 test consisted of a 1–hour alinement at the south end of the track and a survey similar to that in January. A second July survey began at the south end of the track after a 25–minute alinement and was completed in the same manner. The vehicle engine was turned off at ZUPTS for this survey.

Deflection error statisties for HSST runs are shown in table 19. Both single traverses and the mean values for double (forward/reverse) traverses were analyzed.

TABLE 19. Ground Vehicle, HSST–Track

	Aug 78–Single		Jan 80–Single		Jan 80–Double	
	ξ(sec)	η(sec)	ξ(sec)	η(sec)	ξ(sec)	η(sec)
Average Error	0.1	–0.3	0.1	0.0	0.1	0.0
Average σ	0.4	0.3	0.3	0.2	0.2	0.2
Average RMS	0.4	0.5	0.3	0.2	0.3	0.2
Maximum Error	1.0	–0.7	0.7	0.5	0.5	0.3
n–observations	27	27	22	22	11	11

	Jul 80–Single		Jul 80–Double	
	ξ(sec)	η(sec)	ξ(sec)	η(sec)
Average Error	–0.1	0.2	–0.1	0.2
Average σ	0.4	0.3	0.2	0.1
Average RMS	0.4	0.3	0.3	0.3
Maximum Error	–0.9	0.7	–0.6	0.5
n–observations	22	22	11	11

	Jul 80–Single		Jul 80–Double	
	(25–minute alinement, vehicle engine off @ ZUPTS)			
	ξ(sec)	η(sec)	ξ(sec)	η(sec)
Average Error	–0.4	0.1	–0.4	0.1
Average σ	0.3	0.4	0.3	0.3
Average RMS	0.5	0.4	0.5	0.3
Maximum Error	–1.0	1.0	–0.9	–0.5
n–observations	22	22	11	11

Additional results will now be presented in conclusion of this section. These data pertain to ground vehicle and helicopter missions completed on various courses at WSMR to assess deterioration of deflection recovery owing to heading change of the system. Information is also given for height and the gravity anomaly and partially for positioning.

Table 20 shows error statistics for single passes over a V–shaped course running between stations Sands SW Base, Don and Tare. The NE–SW leg of this course is approximately 15 kilometers long, and the N–S leg is about 21 kilometers in length. The angle between the legs is about 35 degrees. While surveying along the NE–SW leg, three excursions, averaging 1.3 kilometers, were made to the left or right to access stations. Along the N–S leg, seven excursions, averaging 0.8 kilometers, were necessary to survey some stations. The time required to run this V–shaped course one–way was 2.36 hours. The course was run four times – two runs starting from one end of the traverse and two from the opposite end. The initial alinement at each end of the course was 1–hour long and the second alinement at the opposite end was 25 minutes long. The table 20 results are with the IMU hard–mounted in the ground vehicle in the usual operational mode.

TABLE 20. Ground Vehicle — IMU Hard–Mounted

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.25	–1.64	–0.08	0.5	–0.2	–0.3
Average σ	1.15	2.13	0.33	1.6	1.4	1.9
Average RMS	1.17	2.69	0.34	1.7	1.5	1.9
Maximum Error	–3.51	–6.86	–0.91	3.1	–3.5	–4.0
n–observations	60	60	64	48	48	46

Table 21 shows results for four similar missions over the V–shaped traverse. The direction of runs and alinements were the same as in the previous category. The major difference here is that the IMU was mounted on a turntable inside the ground vehicle and kept at a fairly constant heading for the whole mission. For example, if at the initial alinement station the porro–prism of the IMU was pointed north, then it was kept at that orientation for the entire mission by an assistant in the vehicle manipulating the turntable to keep the azimuth display nearly constant on the Control and Display Unit. Only approximate horizontal positioning is possible since the relationship between the IMU and the vehicle door reference mark varied with turntable rotation. Table 21 has the single pass statistics for the remaining geodetic values.

TABLE 21. Ground Vehicle — IMU Turned

	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.05	0.3	–0.4	0.3
Average σ	0.31	1.0	1.0	1.0
Average RMS	0.31	1.0	1.1	1.1
Maximum Error	1.35	2.4	–3.3	2.1
n–observations	56	47	47	43

An L–shaped traverse, also was surveyed with the IMU turned in the ground vehicle. This L–shaped course runs between stations Geri, Conn, and Oboe Prime–2 and consists of a 20 kilometers, N–S leg and a 19 kilometers, E–W leg, taking 1.90 hours to run, on the average. Only forward and reverse runs were made with each mission following a 1–hour alinement. The single pass statistics are given in table 22.

TABLE 22. Ground Vehicle — IMU Turned

	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.29	0.2	0.6	0.5
Average σ	0.44	0.8	0.6	0.8
Average RMS	0.53	0.9	0.9	0.9
Maximum Error	–1.53	–1.6	1.6	2.1
n–observations	28	26	26	26

The performance on this course for the anomalous gravity vector components is as good as achieved on the V–shaped course, giving credence to this operational technique's interpolation advantage.

Statistics from the mean of forward–reverse passes over the V–shaped course with the IMU hard–mounted in the ground vehicle are shown in table 23.

TABLE 23. Ground Vehicle, Double Passes — IMU Hard–Mounted

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.25	–1.69	–0.08	0.5	–0.2	–0.4
Average σ	0.86	1.69	0.28	0.8	0.7	1.1
Average RMS	0.90	2.39	0.29	1.0	0.7	1.1
Maximum Error	–1.79	–5.38	–0.56	2.2	–2.0	–3.1
n–observations	30	30	32	24	24	23

The results in table 23 are more than a factor of $1/\sqrt{2}$ better than statistics for single passes seen in table 20.

In table 24, the forward–reverse mean statistics are presented for the V–shaped course with the IMU turned. These results are seen to be about a factor of $1/\sqrt{2}$ better than table 21 values, which apply to single passes on the course with the IMU turned.

TABLE 24. Ground Vehicle, Double Passes — IMU Turned

	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.05	0.3	–0.4	0.3
Average σ	0.22	0.5	0.7	0.9
Average RMS	0.22	0.6	0.8	1.0
Maximum Error	0.63	1.1	–1.9	–1.6
n–observations	27	23	23	21

Table 25 gives forward–reverse statistics for the L–shaped course. Again, the results are about a factor $1/\sqrt{2}$ better than table 22 values for single passes over the course with the IMU turned.

TABLE 25. Ground Vehicle, Double Passes — IMU Turned

	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.30	0.2	0.6	0.5
Average σ	0.25	0.5	0.4	0.6
Average RMS	0.39	0.5	0.8	0.8
Maximum Error	–0.94	0.8	1.3	1.5
n–observations	14	13	13	13

In table 26, statistics are presented for segments of the V–shaped traverse (i.e. the missions are terminated/smoothed to the corner station). This creates essentially two straight segments, one NE–SW and the other N–S. Statistics for single passes with the IMU hard–mounted in the ground vehicle are given in table 26 in the first three columns, and for the mean of forward–reverse passes, in the last three columns. The average created mission duration and length were 1.18 hours and 18 kilometers, respectively.

TABLE 26. Ground Vehicle, Short Single/Double Passes — IMU Hard-Mounted

	SINGLE			DOUBLE		
	ξ(sec)	η(sec)	Δg(mgal)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	−0.1	−0.1	−0.5	−0.1	−0.1	−0.5
Average σ	0.5	0.7	1.4	0.4	0.6	1.0
Average RMS	0.5	0.7	1.5	0.4	0.6	1.1
Maximum Error	−1.3	−1.7	3.7	−0.8	−1.6	2.0
n–observations	44	44	44	22	22	22

Table 27 provides statistics for the same scheme as given above, except that for these values the IMU was turned in the ground vehicle.

TABLE 27. Ground Vehicle, Short Single/Double Passes — IMU Turned

	SINGLE			DOUBLE		
	ξ(sec)	η(sec)	Δg(mgal)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	0.1	−0.1	0.4	0.1	−0.1	0.4
Average σ	0.5	0.7	0.7	0.5	0.5	0.6
Average RMS	0.6	0.7	0.8	0.5	0.5	0.7
Maximum Error	1.2	−1.3	2.0	1.1	1.0	1.7
n–observations	43	43	39	21	21	19

In table 28, information is provided on segments of the L–shaped course. Termination and smoothing to the corner station on this traverse creates E–W and N–S segments, again with some lateral excursions from the segments necessary during the survey. Table 28 statistics represent single pass values in the first three columns, and mean (forward–reverse) values in the last three columns for the IMU turned in the ground vehicle. The average created mission duration and length were 0.95 hour and 20 kilometers, respectively.

TABLE 28. Ground Vehicle, Short Single/Double Passes — IMU Turned

	SINGLE			DOUBLE		
	ξ(sec)	η(sec)	Δg(mgal)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–0.2	0.1	0.2	–0.2	0.1	0.2
Average σ	0.6	0.5	0.9	0.5	0.4	0.7
Average RMS	0.6	0.5	0.9	0.6	0.4	0.8
Maximum Error	–1.6	–1.1	1.8	–0.8	–0.8	1.3
n–observations	24	24	24	12	12	12

These results are similar to those seen in table 27 from the V–shaped course.

The statistics in table 29, which concludes this section, pertain to a single pass over the L–shaped course with the system in the helicopter. The operational mode involved removing the IMU from the helicopter to the survey marker for every ZUPT. The 35 kilometers mission lasted 1 hour.

TABLE 29. Helicopter, Single Pass — IMU Hard Mounted

	ϕ(m)	λ(m)	H(m)	ξ(sec)	η(sec)	Δg(mgal)
Average Error	–2.04	2.74	0.23	–0.9	–0.6	–1.1
Average σ	0.81	1.07	0.14	0.3	0.3	1.9
Average RMS	2.19	2.94	0.27	0.9	0.7	2.2
Maximum Error	–3.36	4.49	0.41	–1.5	–0.9	–4.2
n–observations	14	14	14	9	9	8

DISCUSSION

ANALYSIS OF TEST RESULTS • Reducing the duration of RGSS missions generally improved the determination of all six geodetic parameters. For example, a comparison of average RMS values in tables 1 and 3 indicates that reducing the ground vehicle mission duration from 2.18 to 1.7 hours provided a 37 percent improvement in position, 21 percent improvement in elevation, 50 percent improvement in deflection, and 24 percent improvement in gravity anomaly. A comparison of average RMS values in tables 2 and 6 indicates a 25 percent improvement in deflection and 30 percent improvement in gravity anomaly when the duration of helicopter missions is reduced from 0.77 to 0.38 hour.

Operating the RGSS in the helicopter generally provided better results than operating in the ground vehicle. Comparing the average RMS values in tables 1 and 2 shows that the helicopter provided a 32 percent improvement in position, 43 percent improvement in deflection, and 5 percent improvement in gravity anomaly. However, elevation accuracy decreased 12 percent in the helicopter. The distances covered in each mode of transportation was about the same and the method of data compilation was the same. The major difference was average time required to complete a traverse: 2.18 hours for the ground vehicle and 0.77 hour for the helicopter. As indicated above, the shorter duration should improve all parameters. The decrease in elevation accuracy obtained in helicopter operations was probably due to a possible increase in vertical axis quantization error owing to vibration of the IMU by the helicopter during traverses. Also, the vertical channel scale factor was not calibrated dynamically and greater vertical excursions in the helicopter could increase scale asymmetry errors. Also important for improved deflection accuracy was the removal of the IMU from the helicopter for all ZUPTS. It is expected that inferior deflection accuracy would have been obtained without this unique operational technique.

One—half of the helicopter missions were conducted following 25–minute alinements, versus 1–hour alinements for all vehicle missions. This should have been a disadvantage for positioning in the helicopter mode since large platform azimuth errors can result only from completing the short alinement. Since platform azimuth drift bias was well compensated and flying missions were speedy, no positioning deterioration from forward (1–hour alinement) passes was seen. Over the 11 reverse missions surveyed, this accounts for a time savings of 5.5 hours with respect to performing the 1–hour alinements for these missions.

It became apparent early in the helicopter missions that significant height and gravity anomaly errors resulted when any initial travel periods were too long (4 minutes). The helicopter pilots were instructed to fly 50 to 100 feet (15 to 30 meters) above terrain and at 100 knots maximum speed during travel periods. Overall average speed enabled covering a distance of about 8 kilometers in 3.5 minutes, which is too much during initial travel because the Kalman filter is not efficient at these times. Also, in an area like WSMR, it is possible to pass through too large of a gravity anomaly at this distance, causing the 16–mgal–change warning signal to switch on. After these problems occurred on an initial mission, the initial travel distances (approximately 8 kilometers) were broken down with intermediate ZUPTS on all subsequent missions.

The speed of the helicopter mode is extremely advantageous in inertial surveying; however, judgement should be used concerning travel period lengths at various mission stages. This precaution also applies to rapid height changes possible during short travel periods.

As expected, averaging the results of forward and reverse passes over a traverse reduced the error in determining all geodetic parameters. This is shown by a comparison of average RMS values in tables 1 and 7 for ground vehicle operations and in tables 2 and 8 for helicopter operations. The increase in accuracy in the ground vehicle was 30 percent for position, 38 percent for elevation, 29 percent for deflection, and 10 percent for gravity anomaly. Improvements for these parameters in the helicopter were 30 percent, 18 percent, 25 percent, and 20 percent, respectively. In general, double passes provided a factor of $1/\sqrt{2}$ improvement over single passes for both the ground vehicle and helicopter.

A comparison of tables 5 and 9 shows no significant improvement in average RMS values for deflections when double passes are made on short lines (approximately 1 hour duration). The gravity anomaly was improved by 12 percent. A comparison of tables 6 and 10 also shows no improvement in average RMS for deflections and gravity anomaly was improved by 21 percent. Although double passes do not seem to improve the accuracy of deflection determination on short lines, it is still desireable to make double passes not only because of increased accuracy in gravity anomaly but because positions and elevations will probably be more accurate.

Compiling the test data as grid traverses is another way of providing redundant observations. A comparison of tables 7 and 11 for ground vehicle missions and tables 8 and 12 for helicopter missions indicates that grid traverses provide approximately the same reduction in error as double run traverses. A comparison of tables 11 and 13 for ground vehicle missions and tables 12 and 14 for helicopter missions indicates that the standard deviations of the errors from grid double passes are approximately half those for grid single passes.

Compiling the test data by simple least–squares adjustments, as described in the comments in table 15, provides further reduction in errors. Comparing tables 1 and 15 for full–length ground vehicle missions showns the standard deviations were 2 or 3 times lower after least–squares adjustment when compared to single pass results for ground vehicle missions. Comparing tables 7 and 15 shows a 40 percent improvement in position, a 13 percent decrease in accuracy for elevations, a 30 percent increase for deflections, and 26 percent increase for gravity anomaly. Comparing tables 2 and 16 shows the standard deviations were almost 2 times lower after least–squares adjustment of helicopter single pass data. Comparing tables 8 and 16 indicates an improvement of 21 percent for position, 14 percent for elevation, 17 percent for deflection, and 31 percent for gravity anomaly after least–squares adjustment of helicopter double pass data. Similar improvement was not seen for short missions created by terminating each mission at approximately its center point (see tables 17 and 18). This perhaps indicates that trending type errors are less significant for shorter distances.

The noise limitations of the system for determining deflection of the vertical are indicated in table 19 from data taken at various times on the HSST. The average RMS did not change significantly between the single pass results and double pass results. Turning the vehicle engine off during ZUPTS did not cause a significant change. The system noise limitation appeared to be 0.4 arc second RMS for deflection components.

System performance on the V–shaped course, as indicated in table 20, was better than expected for height, deflection, and gravity anomaly. The results for those values were almost as good as the statistics for the straighter, single pass traverses shown in table 1. The position results are typically poor for non–straight courses. Prior to this work at WSMR, the system received a spare lower gyro and new heading compensation tables and a spare A–1000 accelerometer and new associated heading compensation tables. The up–to–date compensation tables appear to be functionally more successful than former tables. Tables 20, 21, and 22 indicate that the turntable provides a technique for significantly improving the accuracy of interpolating the deflections and the gravity anomaly on courses with major heading changes and up to 2.36 hours in duration. In terms of RMS, a 31 percent improvement in deflections is seen when the IMU case is maintained at a fairly constant heading (turned with respect to the vehicle). For the anomaly, a 42 percent improvement is seen. A 9 percent improvement is noted for height. At least in these limited experiments, a real advantage was realized with the turntable for anomalous gravity vector component interpolation. These missions indicate significant sensitivity remaining in the IMU owing to heading change.

Comparing tables 20 and 23 shows that the same improvement is obtained between single passes and double passes as noted in comparing tables 1 and 7; the double passes are more than a factor of $1/\sqrt{2}$ better than the single passes. The same improvement was noted in comparing tables 21, 24, and 25 (IMU turned). When the V–shaped traverse is shortened by terminating at the corner station (thus creating two short traverses), there was a significant improvement in the determination of deflection and gravity anomaly (compare table 20 with the single pass results in table 26). Note that the main effect of using double passes rather than single was the decrease the maximum errors (see table 26). In comparing tables 26, 27, and 28, no difference is seen in deflection statistics for the IMU hard–mounted or turned in the ground vehicle. This is the case despite the fact that short excursions left and right from each segment were necessary to survey some stations. With respect to the vertical channel, the anomaly accuracy is significantly improved when turning the IMU. These results seem to indicate that short excursions from a traverse do not significantly bother gyro drift, and little error is integrated on these short side trips (less than 6 minutes duration). Level accelerometer bias change is apparently only mildly influenced by such side trips. The vertical accelerometer bias is apparently adversely influenced by the lateral excursions in view of the different results in each mode.

The limited data obtained in the helicopters on the L–shaped traverse (table 29) indicates that the RMS errors for position, defelction, and gravity anomaly are similar to those obtained from single passes on the straighter traverse missions.

SYSTEM IMPROVEMENTS • Certain operational, hardware, and software modifications can provide the means for more accurate recovery of the components of the deflection of the vertical. Specifically, traverses should be kept short, straight, and smooth. The improved performance of the RGSS under these conditions was discussed in more detail in the preceding section on test data analysis, particularly with respect to HSST runs in the ground vehicle and on helicopter missions. Shorter, straighter, and smoother missions in each case led to better performance.

In Todd,[8] it was predicted that a shorter mission time of 42 minutes would achieve an average RMS deflection accuracy of 0.4 arc second on a single pass. Data obtained on the HSST support this conclusion, i.e. missions that averaged 40 minutes achieved an average RMS of 0.35 arc second with a gyro pair displaying a 1σ drift instability of approximately 0.0014 degrees per hour with a 2–hour correlation time.[9,10] These same parameters, characterizing the exponentially correlated gyro drift, also indicate that the expected accuracy on 2.18–hour courses (average ground vehicle test traverse) would have an average RMS of 1.4 arc seconds. Here an insignificantly different average RMS of 1.35 arc seconds was obtained from actual ground vehicle missions (table 1).

Unexpected results were achieved in the helicopter mode regarding the gyro drift characterization parameters (calculated from ground vehicle mission results before and after lower gyro replacement). Using an average helicopter mission time of 0.77 hour (46 minutes), the predicted average RMS deflection values were 0.4 arc second. Instead, an average RMS value of 0.8 arc second was obtained on single passes in the helicopter traverses. Additionally, improved performance was expected because helicopter missions were straighter and smoother than their corresponding ground vehicle missions.

Based on the achieved performance over these 46–minute helicopter missions, a 1σ value of correlated drift was calculated for a 2–hour correlation time to be 0.0033 degrees per hour. Helicopter missions terminated/smoothed near mission midpoint attained an average RMS deflection value of 0.6 arc second. These missions averaged 0.38 hour (23 minutes) in length. Again, assuming exponentially correlated noise with

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[8] M. Todd, "Interim Report: Rapid Geodetic Survey System (RGSS) Deflection of the Vertical and Gravity Anomaly Tests at White Sands Missile Range, 1980." Topographic Development Laboratory, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia.

[9] James R. Huddle, "The Measurement of the Change in the Deflection of the Vertical with a Schuler–Tuned North–Slaved Inertial System." Litton Guidance and Control Systems, Woodland Hills, California, November 1977.

[10] James R. Huddle and R.H. Lentz, "Post–Mission Smoothing and Analysis of the Measurements of the Change in the Deflection of the Vertical Obtained by the Rapid Geodetic Survey System (RGSS) at the White Sands Test Range. Litton Guidance and Control Systems, Woodland Hills, California, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, ETL–0065, September 1976, AD–A032 525.

correlation time of 2 hours, the 1σ value of drift instability calculated from these short mission results is 0.0069 degrees per hour. This discrepency is not possible and indicates that the parameter of 2 hours for the correlation time is in error. Iteratively adjusting the correlation time and calculating 1σ drift values based on field results from the 46– and 23–minute missions yields relative agreement at a 1σ value of drift instability equal to 0.0035 degrees per hour with a correlation time of 1.5 minutes.

The helicopter mode provided a different environment for the system owing to higher levels of high frequency vibration during travel periods. Also, lower IMU ambient temperatures were noted during travel periods because of windy conditions on board the helicopter with the side doors open. Frequent checks on internal platform instrument temperatures showed minimal change from normal operating values, although the top of the outer case for the IMU was removed (during helicopter tests only). However, this was also the case when the IMU ambient temperature was very high during the pre–mission alinement process when the IMU was on the ground in the sunlight, set adjacent to the initial survey point. Another factor is the more dynamic character of the survey operation in which speeds between stops exceeded 100 knots. Why the above radical change in gyro pair drift characteristics occurred under these conditions is not certain. Possibly, the assumptions that gyros are the source of the greater percentage of deflection error contribution or that an exponential autocorrelation function characterizes unstable gyro drift are not valid for operation in the helicopter environment. In any event, the operational advantage of shorter (time–wise) missions did not conform to predictions,[11] with respect to the helicopter surveys. The changes occurring in the system environment in going to the shorter, straighter, and smoother (at low frequency) helicopter mode surveys require investigation.

Some relatively simple alterations might be tried in dealing with these environmental type problems. To give the IMU a smoother ride, with respect to high frequency vibrations occurring during travel periods, one could use better shock insulating between the IMU case and the helicopter floorboard. For these tests, the IMU case feet were extended with 3/4–inch thick circular plywood blocks. The feet were set into a plywood board that was strapped tightly to the floor of the helicopter. Inserting a piece of form rubber between the plywood board and the floor does reduce some vibration into the IMU. However, better approaches should be investigated.

With respect to stabilizing IMU ambient temperature, insulation is again the simplest approach. The IMU gimbal and electronics case and canopy should be better insulated with the canopy top cover in place. Keeping the IMU cool would be a problem resulting from this arrangement. Peltier cooling, as employed in the PADS, would effectively solve this problem. The packaged IMU should not be too large; otherwise, removal at ZUPT's would be cumbersome.

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[11] M.Todd, "Interim Report: Rapid Geodetic Survey System (RGSS) Deflection of the Vertical and Gravity Anomaly Tests at White Sands Missile Range, 1980." Topographic Development Laboratory, U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia.

Reduced mission time is an advantage in the helicopter mode with respect to more linear error growth and smaller closure errors at mission termination. However, the system should be calibrated at travel speed to accommodate possible deficiences in instruments, electronics, and calculations. System scale factor calibration is given as an example of this aspect. With north and east scale factors calibrated in the ground vehicle, the following values were calculated on subsequent calibration missions in the ground vehicle and helicopter:

Ground vehicle north–south calibration average error	–6 ppm
Ground vehicle north–south calibration repeatability (1σ)	13 ppm
Ground vehicle east–west calibration average error	8 ppm
Ground vehicle east–west calibration repeatability (1σ)	12 ppm
Helicopter north–south calibration average error	+67 ppm
Helicopter north–south calibration repeatability (1σ)	14 ppm
Helicopter east–west calibration average error	+41 ppm
Helicopter east–west calibration repeatability (1σ)	13 ppm

No changes in scale factor values were made between calibrations in the two vehicles, and observations were made traveling north, south, east, and west. Quantization was significantly affected in going to the helicopter mode. However, repeatability was similar to ground vehicle mode precision, indicating that the scale factors can be calibrated in the helicopter (the correct values were installed in the computer for helicopter missions). A bias alone does not cause problems, since it is removable at mission closure. Combinations are a more serious problem since non–linear error growth can occur. Although level axes scale factors can be easily checked and calibrated at the system level in the helicopter mode, other error sources are not as easily monitored. These sources include platform drift rate noise in azimuth and about the level axes, platform axes gyro torquer scale factor errors, and vertical axis quantizer error. Other error sources, such as sensitive axes misalinements, should remain the same from ground vehicle to helicopter. The influence of the helicopter environment on these components and functions should be investigated. Software compensation of calibration parameters and other variables as a function of the velocity vector may be required for ultimate deflection interpolation accuracy with utilization of the system in different vehicles.

To summarize, the foregoing discussion has emphasized the result of operational change on system performance. In going to the faster, smoother and straighter helicopter mode, environmental changes were significant enough to affect basic system characteristics. Reconciliation of these problems might be accomplished with system level calibration, substitution of improved configurations and instruments, and software modifications implementing more comprehensive compensations for determined errors.

Software modifications that would be advantageous include better compensation tables and routines for minimizing the effects of heading and environmental changes (increased velocity, vibration) on instruments and their calibrated values. The results of the grid and least–squares data reduction techniques indicate that an optimal area adjustment technique could be developed for enhanced determination of anomalous gravity vector components.

CONCLUSIONS

1. The Rapid Geodetic Survey System (RGSS) provides a fast and versatile means of interpolating geodetic positions, elevations, deflections of the vertical, and gravity anomalies between geodetic control points having known values for these parameters.

2. When operated in a Chevrolet "Suburban" 4–wheel–drive vehicle on single pass traverses with an average duration of 2.18 hours, the RGSS provided the following accuracies (stated as average RMS):

Position	—	0.43	meter
Elevation	—	0.24	meter
Deflection of the Vertical	—	1.4	arc second
Gravity Anomaly	—	2.1	milligal

3. Operating the RGSS in an Army UH – 1 helicopter over the same traverses used for ground vehicle operations provided on average traverse duration of 0.77 hour and the following accuracies (average RMS) for single pass traverses:

Position	—	0.27	meter
Elevation	—	0.27	meter
Deflection of the Vertical	—	0.8	arc second
Gravity Anomaly	—	2.0	milligals

4. Double pass traverses generally provided accuracies that were better than single pass traverses by a factor of $1/\sqrt{2}$ in both the ground vehicle (2.18 hours average traverse duration) and the helicopter (0.77 hour average traverse duration).

5. In general, reducing the duration of RGSS traverses in the ground vehicle and the helicopter provided better accuracies for all the geodetic parameters determined by RGSS.

6. Compiling the test data as a grid of single pass traverses (to increase redundancy) provided approximately the same accuracy as obtained with double pass traverses in both the ground vehicle and the helicopter. Compiling the test data as a grid of double pass traverses (for even greater redundancy) provided approximately twice the accuracy as obtained by compiling the test data as a grid of single pass traverses in both the ground vehicle and the helicopter.

7. Compiling the test data obtained in the ground vehicle or the helicopter by a simple least–squares adjustment provided somewhat better accuracy than compilation as a grid of traverses.

8. Operating the RGSS in the ground vehicle on a V–shaped traverse decreased the accuracy of all geodetic parameters except the gravity anomaly when compared to relatively straight traverses of approximately the same duration (2.18 to 2.36 hours).

9. The accuracies obtained on the V–shaped traverse were increased by 31 percent for deflections of the vertical and 42 percent for gravity anomalies by mounting the IMU on a turntable and turning the outer case of the IMU to minimize changes in heading due to vehicle motion.

10. Optimum determinations of the deflection of the vertical and gravity anomaly were obtained on relatively straight, smooth and short (less than 1.7 hour duration) traverses run in both directions in a grid pattern. Compiling the resulting data with a simple least–squares adjustment provided an accuracy of approximately 0.5 arc second

(average RMS) for deflections of the vertical when operating the RGSS in either the ground vehicle or the helicopter. An accuracy of 1.7 milligal (average RMS) for gravity anomalies was obtained in the ground vehicle and 0.9 milligal was obtained in the helicopter.

11. The RGSS system noise level was 0.4 arc second (average RMS) for deflections of the vertical, as indicated by operation in the ground vehicle on an ideal test course – the extremely straight, smooth and level 15.4–kilometer course along the High Speed Sled Track at Holloman AFB, New Mexico.

12. The results of this test program indicate that the following changes should improve the accuracy of the RGSS in determining deflections of the vertical and gravity anomalies:

a. Perform system calibrations in the velocity range encountered in helicopter operations in addition to the usual calibrations in the velocity range of the ground vehicle.

b. Modify the RGSS IMU to provide better isolation from helicopter vibrations and from changes in ambient temperature.

c. Modify the RGSS onboard software to provide better compensation for the effects of changes in azimuth, velocity and vibrations while traversing.

13. The increased accuracy obtained by compiling the test data as grid traverses and by simple least–squares adjustments indicates that an off–line program could be developed to provide optimum area–wide adjustment of deflections of the vertical and gravity anomalies.

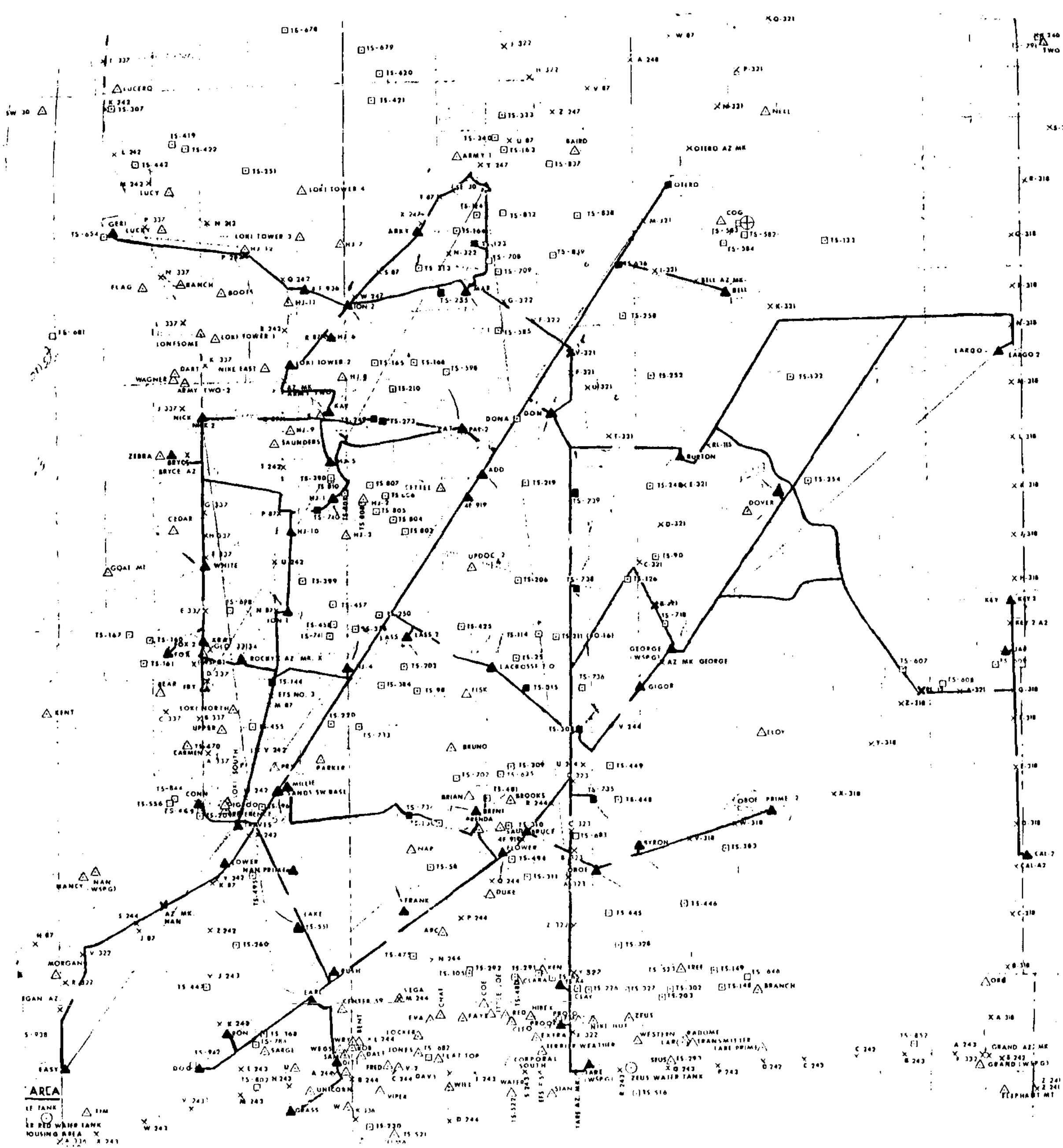

FIGURE 1. White Sands Test Area.