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Accurate Navigation and Control of Continuous Mining Machines for Coal Mining

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m	meter
cm/hr	centimeter per hour	mm	millimeter
ft	foot	min	minute
ft/hr	foot per hour	ppm	part per million
ft/m	foot per metert	sec	second
hr	hour	%	percent
in	inch	°	degree
km	kilometer		

ACRONYMS USED IN THIS REPORT

CEP	circular error probable	MAPS	Modular Azimuth and Position System
CID	coal interface detection	NGS	National Geodetic Survey
CM	continuous miner	OP	open pit
CP	control point	PC	personal computer
EDMI	electronic distance measuring instrument	RCS	real-time control system
GA	grid azimuth	RPU	Remote Positioning Unit
GD	grid distance	RT	robotic transit
GPS	Global Positioning System	RMS	root mean square
HA	horizontal angle	SD	slope distance
HARN	High Accuracy Reference Network	SDLC	Synchronous Data Link Control
HD	horizontal distance	SEP	spherical error probable
HI	robotic transit height	SF	scale factor
HORTA	Honeywell Ore Recovery and Tunneling Aid	SGI	Silicon Graphics, Inc.
HR	signal height	SPCS	State Plane Coordinate System
IEEE	Institute of Electrical and Electronics Engineers	VA	vertical angle
INS	Inertial Navigation System	ZRP	zero-reference point
METF	Mining Equipment Test Facility	ZUPT	Zero-Velocity Update

ACCURATE NAVIGATION AND CONTROL OF CONTINUOUS MINING MACHINES FOR COAL MINING

By William H. Schiffbauer[1]

ABSTRACT

One of the safety and health research programs of the former U.S. Bureau of Mines Pittsburgh Research Center was the evaluation of technology that will provide remote-controlled operation of mechanized equipment in underground room-and-pillar mining. The purpose of this effort was to enable workers to be located away from the hazardous and unhealthful coal extraction area (the face). As part of this program, advanced machine navigation and control technologies were developed for underground room-and-pillar and highwall coal mining that can be applied to commercially available mining equipment. These technologies use off-the-shelf components and a flexible control software architecture to minimize the effort required to adapt them to mining equipment. An accurate, reliable navigation system that can provide the mining machine's heading and location is a critical requirement for a remote-controlled mining system. After investigating several different types of navigation sensors, researchers selected the Honeywell Ring Laser Gyro Inertial Navigation System (INS) as showing the most promise. It was installed on a continuous mining machine at our Mining Equipment Test Facility. Extensive testing at an open pit (OP) site was also performed. This report describes the INS as it was employed on the mining machine in the laboratory, in the field, and OP tests, and provides the accuracy and performance results of the OP and highwall tests.

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INTRODUCTION

The purpose of the research program on remote-controlled coal mining at the former U.S. Bureau of Mines[2] Pittsburgh Research Center was to develop enabling technology that will allow remote-controlled operation of all mobile mechanized equipment normally used for room-and-pillar and highwall coal mining while permitting workers to be located away from the hazardous coal extraction area (face). The advanced navigation and control technologies that were developed employ off-the-shelf hardware, thus minimizing the effort required to adapt the new technology to mining situations. Because the technology is modular, only those modules required for particular applications need to be applied. Although there are differences between underground and highwall mining systems, basic efforts to enhance health and safety are much the same for both: relocate the machine operators a safe distance away from areas where they are exposed to hazards, such as roof and highwall falls, respirable dust, and noise, and provide the operator with enough information and technology to ef-fectively operate the machines remotely. In highwall mining, operators are already provided with a protected control center. In room-and-pillar situations, a mobile skid, located in the vicinity of the section power center, which in most cases will be less than 150 m from the face, could be used for the control center. From this skid, the most hazardous machine activities can be controlled and directed by the machine operators.

NAVIGATION

The most important requirement for a remote-controlled mining system is an accurate, reliable navigation system that provides the heading and location of the continuous miner (CM) at all times. The navigation system provides information to the machine control computer so that the cutting by the CM can be controlled to a predetermined mine plan. For room-and-pillar mining, entries and crosscuts can be cut to required dimensions and location. In highwall mining, a constant rib width can be maintained between adjacent holes. Several different navigation devices were evaluated[3] in an effort to identify the best one for use on CM's. After investigating the alternatives, the Honeywell Inertial Navigation System (INS) was selected. This system, known commercially as the Honeywell Ore Recovery and Tunneling Aid (HORTA) (figure 1), will be referred to as "INS" for the remainder of this report. The system was previously known as the Modular Azimuth and Position System (MAPS) for military applications. It is the best navigation device for this application known at this time. The research team conducted several underground tests [Sammarco 1993] of the MAPS on a CM during coal cutting. This was an interactive and collaborative process with Honeywell, which made incremental changes to MAPS to improve accuracy. Satisfied with the MAPS performance at the conclusion of the underground test, the research team redesigned the CM control system and made additional recommendations to increase the INS accuracy, to improve the user interface for setup and data interpretation, and to provide for operation in a multiple computer environment.

Figure 1.—HORTA.

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[2] The safety and health research functions of the former U.S. Bureau of Mines were transferred to the National Institute for Occupational Safety and Health in October 1996.

[3] Different types of navigation sensors that were evaluated include laser ranging, ultrasonic, electronic compass, and linear potentiometers.

INS BASICS

The main sensing components of the INS are three gyroscopes (or gyros) and three single-degree-of-freedom linear accelerometers, all packaged in one box approximately 28 by 38 by 32 cm. The three gyro and accelerometer pairs are mounted orthogonally on collinear axes. The gyro (figure 2) is a rate-integrating gyro that does not use a spinning mass. Instead, it measures angular motion by measuring the frequency difference between two contrarotating laser beams. Mirrors are used to reflect each beam around an enclosed triangular path, which produces a "laser-in-ring" configuration.

The resonant frequency of oscillation is a function of optical path length. The two-laser beams have identical frequencies when the gyro is at rest. When the gyro is subjected to an angular turning rate (rotation) about an axis perpendicular to the plane of the two beams, one beam travels a longer path and the other beam travels a shorter one [Savage 1991]. Consequently, the two resonant frequencies change, and the frequency difference is directly proportional to the angular turning rate. The frequency difference is measured optically and converted to a digital output. The cumulative pulse count is proportional to the angular change.

Inertial navigation is the process of calculating position and velocity based solely on inputs from self-contained acceleration sensing instruments. Accelerometers provide the acceleration magnitude sensing function. Gyros provide the acceleration direction sensing functions (i.e., define the direction of the accelerometer sensing axes). The basic inertial navigation concept is to integrate the velocity data to determine vehicle position.

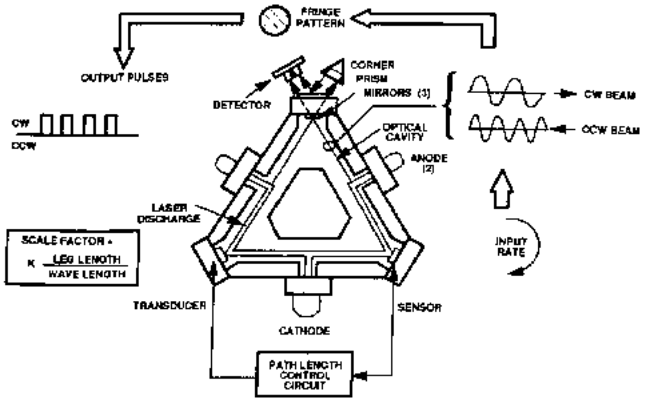

Figure 2.—Single laser ring gyro.

As the INS moves (i.e., as the CM moves), it accumulates velocity errors. Over time these errors can become large, rendering the CM position data invalid. A velocity error dampening mode, called Zero-Velocity Update (ZUPT), is employed, which mitigates the error buildup. By comparing the sensed velocities to the zero velocity condition, the INS can correct the velocity errors by setting them to zero. The INS automatically performs a ZUPT when it determines that the CM has stopped or will request a ZUPT if the predetermined ZUPT time interval has elapsed. The mining machine real-time control system (RCS) software developed by the research team responds to a ZUPT request by pausing the CM activities. Once the CM is stopped, a ZUPT will take approximately 10 sec to complete. Upon completion of the ZUPT, the INS tells the control system software to resume operation.

THE CONTROL SYSTEM

Continuous miner manufacturers offer radio or umbilical cord control for their mining equipment for off-board, line-of-sight operation from close proximity to the machine. Rather than using this radio link for computer control, we developed a fieldbus-style control network, based on BITBUS[4] standards, that allows non-line-of-sight control of all of the mining machine's moving parts. BITBUS employs the Synchronous Data Link Control (SDLC) protocol to ensure the integrity of the data passing over the link. Also, BITBUS employs the IEEE RS-485 electrical standard.

The control network (figure 3) consists of two microcontroller boards connected by a twisted-pair cable. One of the boards resides on the CM; the other resides in a 19-in rack at the remote control location and attaches to a personal computer (PC).

A second fieldbus network was added to provide data collection (data network) of the positions of all of the controllable moving parts of the machine, as well as the status of the machine's critical parameters, such as motor currents, hydraulic pressures, temperatures, and other relevant parameters. This BITBUS network consists of sensors, signal conditioning modules, and a microcontroller board on the CM, and a PC-AT card that plugs into a passive backplane in the 19-in rack. The two ends of the network are connected with a twisted-pair cable. The separation of the control network from the data collection network was the best way to integrate this system to obtain the greatest performance. The third connection between the CM and the 19-in rack is two twisted-pair cables that connect the machine-mounted INS to a PC-AT card that is plugged into the rack-mounted passive backplane. This data link is based on a Honeywell SDLC protocol standard, and it employs the IEEE RS-422 electrical standard.

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[4] BITBUS is a standard developed by INTEL Corp., Beaverton, OR.

The control network, the data collection network, and the INS are each hosted on their own 486 class single-board PC that is mounted in the passive backplane in the 19-in rack. All three single-board PC's share a common monitor and keyboard using a video/keyboard switcher. A key element of this application is the introduction of a shared-memory box and hardware that allows the single-board PC's to intercommunicate through extended-memory reads and writes.

The controller computer and the RCS software are the key elements for providing the coal mining operations. By using the data collected from all of the CM sensors and the INS and by executing commands on the CM, the controller is able to perform various coal-cutting scenarios. Scenarios now include premine test, room-and-pillar mining, and highwall mining. The premine tests perform a complete evaluation of all machine functions to ensure that the CM is capable of performing its mining activities. Room-and-pillar mining consists of cutting 40-ft (12-m) lifts in two passes with 70° or 90° crosscuts while using shuttle cars to load out the coal. A highwall scenario has also been created.

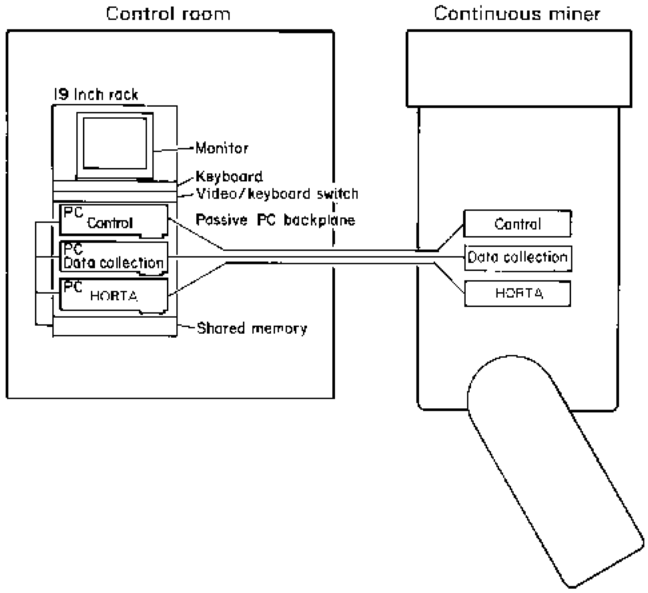

Figure 3.—Control network, basic.

AN EXPANDED CONTROL SYSTEM

Many applications can and have been added to the design of the basic control system. Each module adds another level of functionality to the system. Thus, we are capable of adapting their technology to the simplest or most sophisticated application simply by adding the modules required to suit the application. Figure 4 shows our control system's present capabilities.

The visualization system (VISUALIZATION) uses both collected and ongoing machine data to provide accurate three-dimensional (3-D) graphic representation of the mining machine, its past and present movements, and associated hardware relative to the mine surroundings. The visualization system user's interface permits the operator to zoom around the scene to view any part of the process that may be of interest. Additionally, top and side views of the CM for present and previous cuts can be displayed.

The simulator application (SIMULATOR) generates a steady stream of data that correspond to data that would normally be provided by the mining machine sensors, including the INS. This allows development and testing of the controller without engaging the massive hardware, such as the CM or haulage system. The haulage application (HAULAGE) provides control and monitoring of the haulage system that is used in the system. The coal interface detection application provides information about the thickness of the coal on the roof and the floor; it can also provide information about the thickness of a rib of coal (web coal) for highwall applications.

PRE-OP INS EXPERIMENTS

Tests on the INS performed with our mining system centered on determining the accuracy of the INS and the feasibility of the control system. Some of the underground tests done in 1992 were referenced previously in this report. Additional tests were performed at our Mining Equipment Test Facility (METF) during 1997. Each testing situation had been performed with some limiting factor that restrained our ability to fully validate the INS and the control system. It is important to note that to properly determine the accuracy of the INS, the INS must be subjected to the motion and vibration to which it would normally encounter in the act of mining coal.

UNDERGROUND INS TEST SHORTCOMINGS (1992)

1. The underground mine where the tests were performed was closed before system improvements could be made and tested.
2. The control system and software algorithms were not mature enough to perform all of the tasks that were mentioned in the section of this report entitled “The Control System."
3. ZUPT's were not handled by the software in the control system; therefore, inaccuracies due to velocity errors were present.
4. Geological restrictions (the basic nature of room-and-pillar mining) limited the tests that could be performed.
5. The transit (Leitz "Set 3") used as reference for accuracy measurements was manually operated and required a number of seconds to perform a position calculation. Because the accuracy of the INS is time-dependent, the time for transit measurements added to the accuracy uncertainty of the INS navigation data.

METF INS TEST SHORTCOMINGS (1997)

1. A valid test should be performed while cutting coal, because the vibration of the machine while cutting coal can have a great effect on the accuracy of the data provided by the INS. The material used for testing in the METF—coalcrete— is not a very good simulation for coal. It is much harder than coal and

very abrasive, which causes excessive wear to the CM. A good substitute to simulate real coal has yet to be found.

2. The amount of coalcrete available to perform tests is limited.

3. A manually operated transit was used to provide the reference for INS accuracy measurements. As mentioned before, it added to the accuracy uncertainty of the INS-derived navigation data.

The research team realized that an open pit (OP) mine experiment and the use of advanced surveying technologies could eliminate the limitations noted previously. First, the use of an OP site would remove the geological restrictions and facilitate the use of some verification method of the CM's position. Second, automation of the process of verifying the position of the CM in real time as it was moving would minimize the introduction of errors in determining the accuracy of the INS.

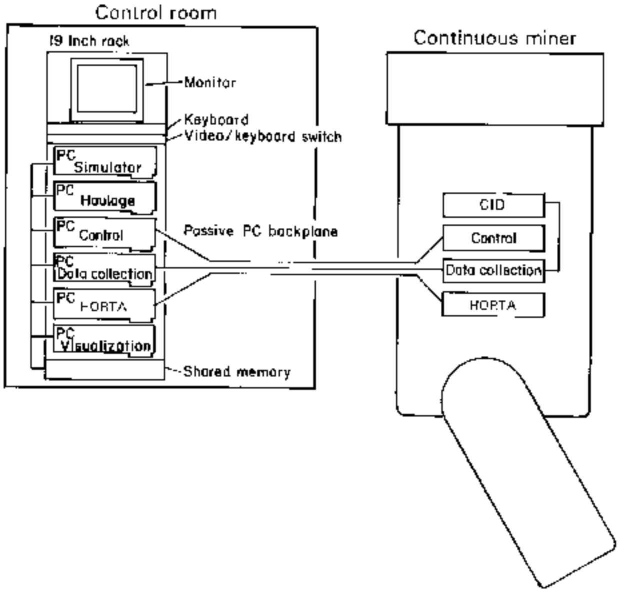

Figure 4.—Control network, expanded.

OP COOPERATOR

After a 2-year search for a cooperator with the necessary resources to perform the experiments, we executed a Cooperative Research and Development Agreement in January 1996 with Interwest Mining Co., Salt Lake City, UT. The site selected for the experiments was the company's Glenrock Mine in Wyoming. The test plan developed with Interwest included the full use of Pit 20, use of its Joy 12CM continuous mining machine (figure 5), and use of its haulage system (a Kloeckner Beckorit). Pit 20 was approximately 600 m long by 45 m wide by 50 m deep (figure 6). Our research team provided the navigation and control technology, which consisted of hardware installed on the CM and in our control trailer. The benefit to us was the ability to gather performance data on the INS to evaluate data accuracy. The benefit to the cooperator was to enable the company to evaluate remote control technology to include highwall mining methods to recover coal at the pit boundaries.

Figure 5.—JOY 12CM with stacking conveyor as used in OP experiments.

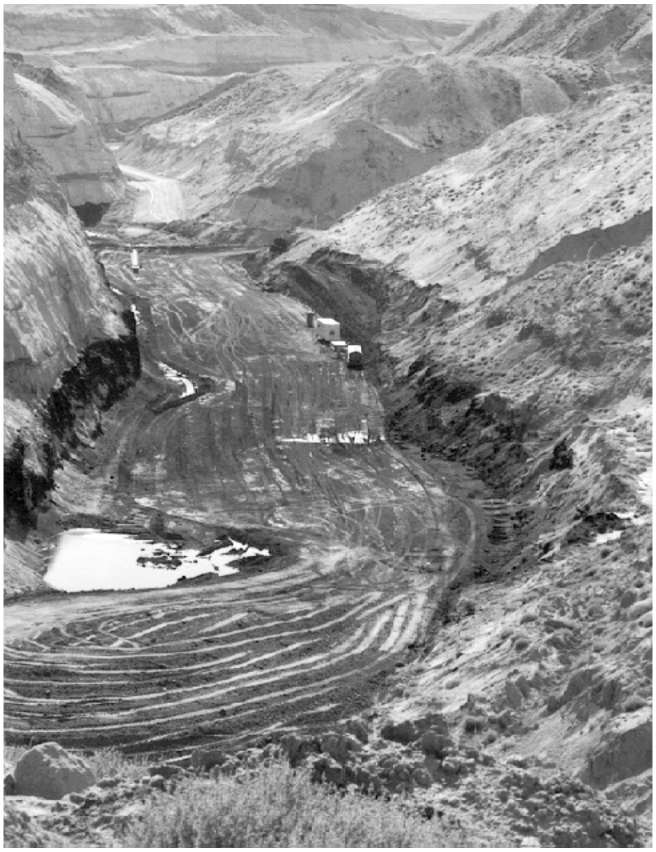

Figure 6.—Pit 20.

AUTOMATED CM POSITION DETERMINATION IN AN OP MINE

An investigation was conducted to find a system that could provide an accurate, continuous reference determination of the INS on the CM while it was mining coal, then provide those data to a PC for archiving. We determined that there were two possible solutions that could meet those needs.

The first system we considered was a Real-Time Kinematic Global Positioning System (GPS) (figure 7). The accuracies of such a system are in the centimeter range, and position data could be provided every few seconds. However, there was some question as to whether the system could track enough satellites over a wide enough area and over a long enough time from inside a 50-m-deep, 45-m-wide pit. After consulting several different companies providing GPS services, we concluded that it might be feasible. Purchase of the required hardware and software to do the job was considered, but the cost was prohibitive. The same GPS service providers who were previously consulted were given the opportunity of bidding to perform the navigation portion on the job, which was expected to last about 1 month. When the quotes to perform the required tasks came in, we decided to find another solution to the navigational needs of the experiment because of costs and uncertainty as to whether GPS could do the job.

The second system we considered was an automated transit with a capability of tracking a moving target (active prism) and transmitting the data to a receiver accessible by a PC. The automated transit, sometimes called a robotic transit, will be referred to as an "RT" for the remainder of this report. After a lengthy search, several RT's were found that could provide millimeter accuracies, with position updates every 0.5 sec while the CM was moving. We determined that purchasing an RT and performing the navigation tasks in-house were less expensive than hiring a firm to perform the required tasks. The final choice of which RT to purchase was primarily based on what was available on Government Services Administration contract. The RT procured was a Geodimeter System 4000 with Remote Positioning Unit (RPU 4002).

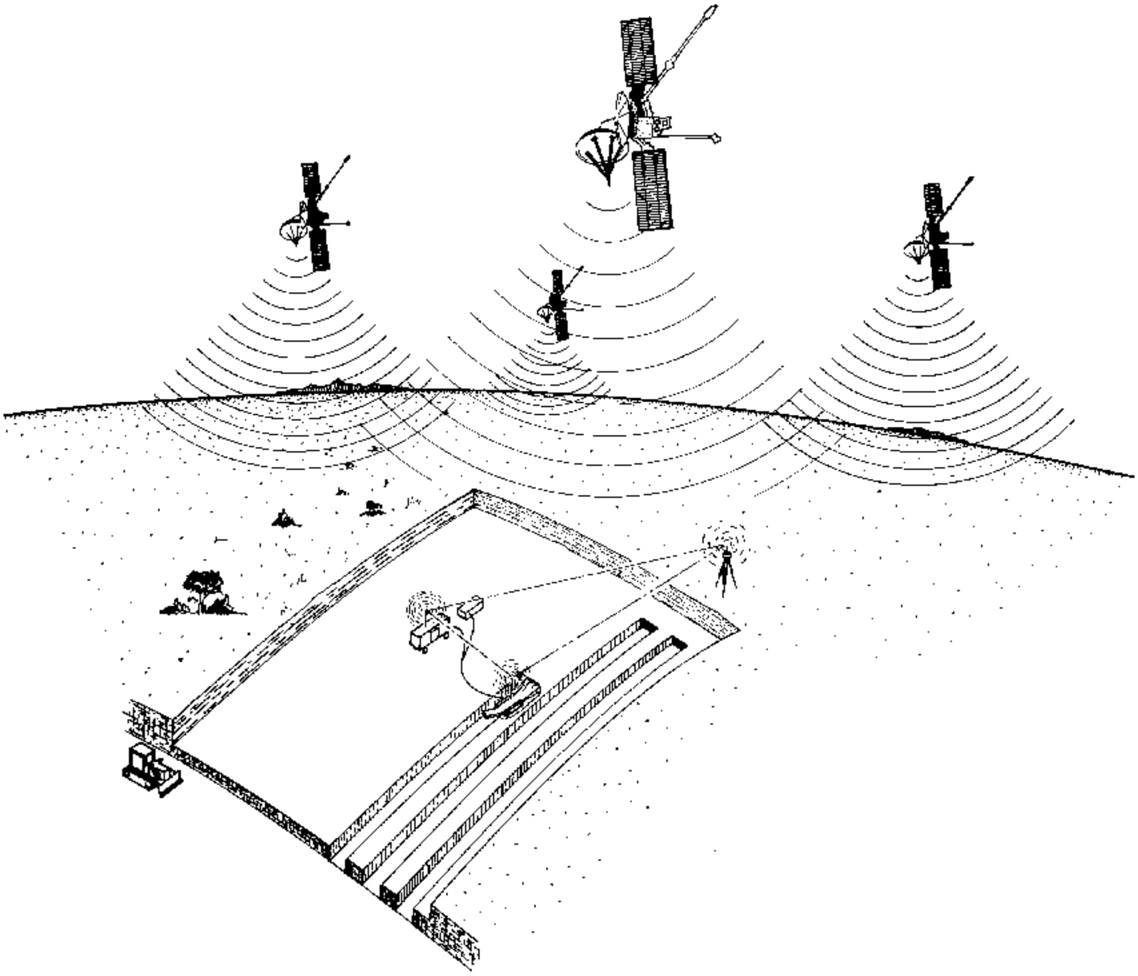

Figure 7.—GPS and the OP.

THE REFERENCE COORDINATE SYSTEM

Coordinate systems are the means of referencing geographic information to locations on the Earth's surface and are the reference to standard models of the Earth's surface represented by an oblate spheroid of revolution (a flattened sphere). There have been at least 14 different ellipsoids used to approximate the oblate spheroid best representing the size and shape of the geoid called Earth. The Clarke Spheroid of 1866 was chosen by Honeywell as the reference model used in the INS (see appendix A for more details on the Reference Coordinate System). The Clarke's 1886 spheroid datum (a set of quantities used as a basis to calculate other quantities) for the United States [Buckner 1993] is known as North American Datum of 1927 (NAD27), which is a State Plane Coordinate System (SPCS). With the advent of the satellite-based global positioning system (GPS) technology, the United States established a High Accuracy Reference Network (HARN) of reference points with positional accuracies of 0.1 m. These HARN points are referenced to the SPCS and can be used as reference locations for establishing secondary high-precision points using GPS techniques.

The site of the OP experiments resides in Wyoming SPCS East Zone 4901, and it is based on a Transverse Mercator projection. Two HARN points, BILL and Q32, are near the site.

NAD27 is specified in U.S. survey feet, not in meters. Therefore, the author was forced to keep most of the analysis data and results in feet rather than meters for uniformity. For comparison purposes, there are 3.280833333 ft/m for the U.S. survey foot. There is also an international survey foot; it is 3.280839895 ft/m.

NAVIGATIONAL REQUIREMENTS FOR THE OP TEST

A geodesist [Hamilton 1996] was hired to help define the navigational requirements of the test and to implement them. The plan developed consisted of three parts: placing three solid navigation control points (CP's) in Pit 20, establishing the points in the Wyoming SPCS East Zone 4901 using GPS, and then using the points as a reference for the RT.

The OP selected (Pit 20) for the experiments was approximately 600 m long in the east-west direction and about 45 m wide in the north-south direction. The three CP's were placed close to the southern edge of the OP and placed approximately 180 m apart in almost a straight line. The CP's consisted of 8-in (20.32-cm) diameter, 8-ft (2.44-m) long steel pipes buried to 4 ft (1.22 m) and set in a mass of concrete. Four feet (1.22 m) of the pipe protruded vertically. The top end of the pipe had a flat 10-in (25.4-cm) diameter, 0.5-in (1.27-cm) thick steel circular plate welded to it and a 5/8-in (1.58-cm) #11 all-thread rod welded to the center of it. The threaded rod protruded about 0.5 in (1.27 cm). These CP’s—designated WEST, MID, and EAST—provided us with a stable reference for the INS evaluation.

The plan was to connect these three CP's into higher order existing control stations in the Wyoming SPCS. The chosen control stations were Station BILL and Station Q32. BILL was located near the town of Bill, on the right of way of State Route 59. This is a distance of approximately 50 km from the project. Q32 was located about 10 km north of Casper along Interstate Highway 25, which was about 43 km from the project. These two stations are of the HARN type. A direct tie was made by the National Geodetic Survey (NGS) between BILL and Q32 in 1993 using GPS. Since NGS did this, all observations can be rigidly checked by loop closures. The method that was to be used to tie the OP CP's into HARN was the double occupancy method using two dual-frequency GPS receivers. Only two of the CP's (WEST and EAST) were to be tied in using the GPS receivers; the MID point would be tied in using the RT from the WEST and EAST. The method would consist of placing GPS receiver 1 (RCV1) and GPS receiver 2 (RCV2) at the following combination of sites: BILL-WEST, WEST-EAST, and WEST-Q32. When placed in the OP, however, the GPS receivers could only pick up three satellites, which were not sufficient for a position fix. Additionally, there was concern about multipath effects from the highwall, which would degrade the accuracy. The plan was modified in the field to provide two additional CP's on the top edge of the OP. One was placed on the western side (called A); the other, on the eastern side (called B) (figure 8). These points were used to tie the OP to HARN. The method consisted of placing RCV1 and RCV2 at the following

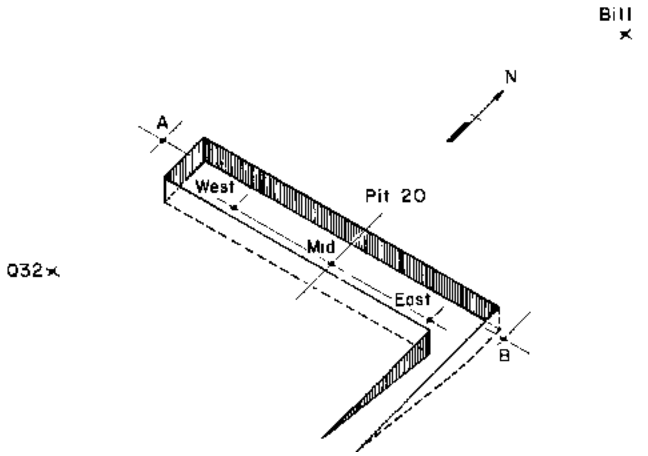

Figure 8.—OP CP’s.

combination of sites: BILL-A, A-B, and B-Q32. Each site was occupied for an amount of time related to the distance between the receivers for each occupation. The final results of the positions utilized the precise ephemeris, which was available approximately 7 days after the observations. The coordinates of the A and B were computed on three datums using the two HARN stations as a reference. The estimated accuracy of the new points, with respect to the existing datums, was 0.05 m on NAD83 93, 0.2 m on NAD83, and 1 m on NAD27. To associate the three CP's in the OP with A and B, the RT was used. A combination of measurements was made using the RT to minimize measurement errors. The RT two-face D bar method was used to minimize transit errors. The measurements consisted of placing the RT on CP's A and B and placing the target on the WEST, MID, and EAST CP's. The actual sequence was: A to B, A to WEST, A to MID, A to EAST, B to A, B to EAST, B to MID, and B to WEST. All of these readings were processed by the geodesist in a least squares adjustment, who derived the coordinates as listed in table 1. These coordinates were used throughout the experiments performed at the OP.

Table 1.—Coordinates for CP's in U.S. survey feet

	Northing	Easting	Altitude
A (NAD27)	861474.19	323804.92	—
A (NAD83)	922188.7	479827.37	5731.64 (NGVD29)
A (NAD93)	922190.35	479825.63	5734.53 (NAVD88)
B (NAD27)	860186.26	327109.09	—
B (NAD83)	920900.73	483131.57	5340.28 (NGVD29)
B (NAD93)	920902.38	483129.85	5348.17 (NAVD88)
EAST (NAD27)	860686.413	325520.155	5557.638 (NGVD29)
EAST (NAD83/93)	921402.576	481540.859	5560.532 (NAVD88)
MID (NAD27)	860867.346	324938.305	5567.319 (NGVD29)
MID (NAD83/93)	921583.513	480959.013	5570.213 (NAVD88)
WEST (NAD27)	861084.255	324445.770	5573.685 (NGVD29)
WEST (NAD83/93)	921800.425	480466.482	5576.579 (NAVD88)

FIELD TEST SYSTEM

The control and data acquisition system constructed for the field tests is shown in figure 9. The system consisted primarily of the parts described in the section of this report entitled "The Control System." A combination of video cameras and monitors provided a video reference of all of the experiments. TRACKER (described below) provided a data link to the RT, data acquisition, data archival, and plotting functions.

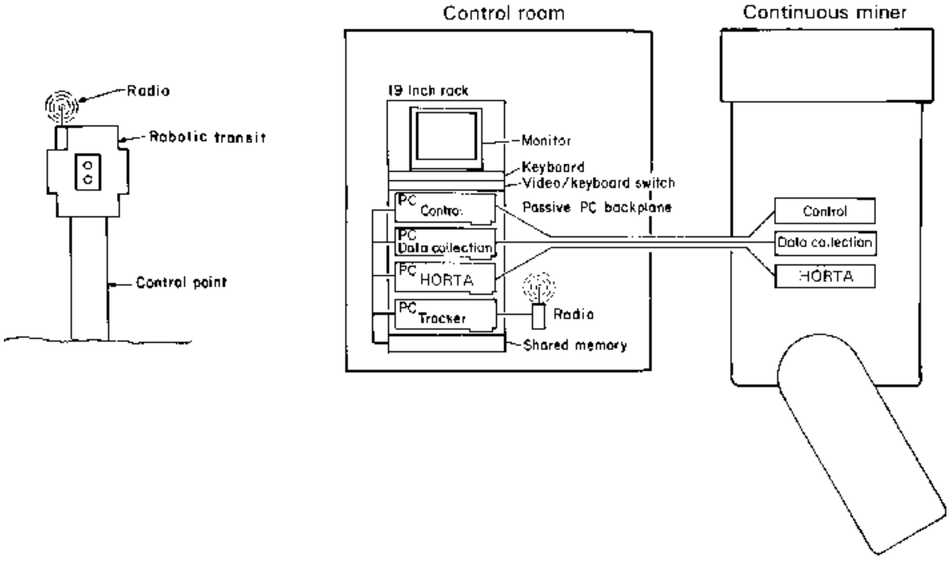

Figure 9.—Control system OP.

TRACKER

In the process of setting up all the hardware and software necessary to run the OP experiments, we identified a need to see the position output of the RT and the position output of the INS in real time to ensure that all systems were working correctly. Additionally, there was a need for software in a PC to collect and archive all pertinent data from the INS, RT, and RCS. This was addressed by adding a PC to the control system and creating a piece of software called TRACKER to perform the required functions. TRACKER was developed by a team member for the Windows 3.1 operating system using a standard C++ compiler.

THE MINE PLAN

The research plan was to cut into the coal seam (underfoot), which had its overburden removed. Later highwall cuts were to be made into the bottom edge of the OP. The actual experiments consisted mostly of two 90-m cuts into the floor of Pit 20 (figure 10) and two cuts into the highwall (12 m and 18 m, respectively). A stacking conveyor (figure 11) was used behind the CM on the 90-m cuts to prevent the back of the CM from getting buried. The coal being cut was dumped back into the trench. A Kloeckner Beckorit haulage system (figure 12) was used behind the CM while it was performing the highwall cuts (figure 13). The stacker conveyor was towed by the CM, and the Kloeckner Beckorit was manually operated by umbilical pendant independent of the CM control system.

Figure 10.—Two 90-m cuts.

Figure 11.—Stacking conveyor.

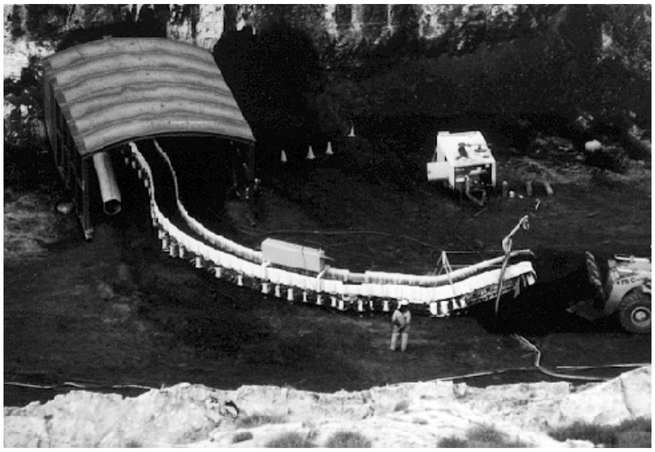

Figure 12.—Haulage system.

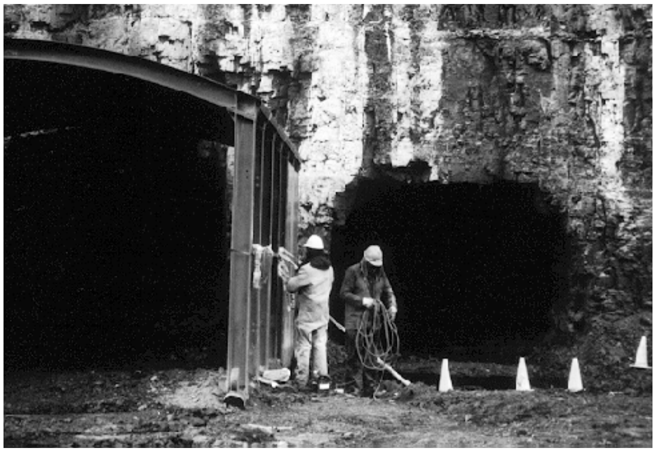

Figure 13.—Highwall.

INS INITIAL INSTALLATION AND ALIGNMENT TO THE CM

The INS was installed inside of a large steel box in what is normally the operator's compartment of the CM. The placement of the INS in reference to the target was accounted for to eliminate offsets in the position calculations. The INS was then initialized using the CM installation data. Software that acts as the "user interface" and communicates with the CM-mounted INS, facilitated this operation. This software is called AHITS (provided by Honeywell), and it executes in the HORTA PC. The steps taken to initialize the INS with the CM installation data were:

1. Select a "Coordinate Frame Code." This code associates the orientation of the INS as it is installed on the CM in X, Y, and Z orientation. For this installation, +X pointed toward the CM cutters (machine forward), +Y pointed toward the right side of the CM (the operator side), and +Z pointed upward. The code entered was 34.

2. The CM zero-reference point (ZRP) is inputted. The ZRP for this installation was the center of the target. The parameters entered into AHITS were ΔX, ΔY, and ΔZ, which represented offset measurements from the ZRP to center mark on the top of the INS. These measurements were −15 in for the ΔX, −7.5 in for the ΔY, and +64.5 in for the ΔZ.

3. Enter the INS/CM Boresight Angles. These parameters compensate for the alignment differences between the INS and CM in azimuth, pitch, and roll (altitude). For example:

INS... azimuth = 95.0°, pitch = 5.0°, roll = −3.2°
CM... azimuth = 97.0°, pitch = 3.2°, roll = −1.2°

The parameters for this installation were all zero.

4. Command an INS shutdown. This causes the installation parameters to be stored in the INS's electrical erasable programmable read only memory.

INS OPERATION

After each INS power-up operation, the INS must be initialized in the following steps:

1. Perform a ZRP position update. This position update provides the INS with its starting position coordinates for alignment. The data required include the SPCS NAD27 grid code (for Wyoming it was 4901) and a measured northing, easting, and altitude for the target on the CM.
2. Wait for alignment to complete. The INS has a built-in alignment mode that minimizes system errors. This alignment mode takes about 25 min to complete. Upon completion, AHITS provides an alignment completion message.
3. Enter survey mode. This mode begins as soon as alignment is completed. Newer or updated position data can be entered at any time during the survey mode.
4. When the INS is to be powered down (for any reason), it should be commanded to shut down via the AHITS software. The reason for this procedure is that while the INS is operational it continuously refines its internal calibrations and accuracies. The INS was designed to learn the characteristics of the machine on which it is installed and, in so doing, helps to improve INS performance. Executing a commanded shutdown stores all of the learned information in the INS EEPROM; an uncommanded shutdown does not.

EQUIPMENT SETUP PROCEDURES

The RT was mounted on top of a CP, and a target was affixed to the top of a second CP. The RT was initialized according to the manufacturer's requirements. The RT height (HI) above its CP's top plate, as well as the signal height (HR) above its CP, was measured and recorded. The raw data (horizontal angle (HA), vertical angle (VA), slope distance (SD), and horizontal distance (HD)) to the second CP were recorded. Next, the RT was put into the remote mode (called RPU), and it was set to search for the target that was placed on the CM. The HA, VA, and SD obtained from the target on the CM were entered into the spreadsheet to generate the corrected SPCS for the CM. These coordinates (northing, easting, and altitude) were entered into the INS, RCS, and the Silicon Graphics, Inc., (SGI) computer for the initial starting reference for the experiment. As the coal was cut, data from the RT, INS, and RCS were recorded in triplicate by TRACKER, RCS, and SGI for redundancy.

SYSTEMS ACCURACY

Honeywell cites an estimated two-dimensional (2-D) position accuracy of 25 cm/hr circular error probable (CEP) and an azimuth accuracy of 0.028° with an azimuth oscillation of 0.0055° from the initial gyro-compass azimuth. The altitude accuracy of the INS was not specified. In the OP tests, only the 2-D position and altitude accuracy were measured. We combined the altitude and the position data into a factor called spherical error probable (SEP) in order to present 3-D data.

CEP is the radius of a circle, centered about true, such that any measured position, selected from the total sample population, has a 50% probability of lying inside the circle. A 2-D normal distribution is assumed. CEP is computed as follows:

$$\mathrm{CEP} = 1.1774 \left[\frac{\mathrm{RMS}_n + \mathrm{RMS}_e}{2} \right] ,$$

where RMS_n is the RMS error of northing,

RMS_e is the RMS error of easting,

and 1.1774 is the radii of 50% probability circles (CEP).

RMS error is the square root of the mean of the sum of the squared errors, relative to the reference value(s), for all measurements in the sample population. RMS error is computed as follows:

$$\mathrm{RMS}_x = \left[\frac{\sum_{i-1}^{N} X_i^2}{N} \right]^{1/2} ,$$

where N = total number of measurements in the sample,

and X_i = error in the i’th measurement with respect to the reference value.

RMS can also be thought of as the sample standard deviation.

SEP takes into account the altitude data and effectively provides a 3-D accuracy factor. SEP is the radius of a sphere, centered about true, such that any measured position, selected from the total sample population, has a 50% probability of lying inside the sphere. A 3-D normal distribution is assumed. Honeywell does not provide an SEP for the INS, but we derived SEP's for the OP test data. The SEP is computed as follows:

$$\mathrm{SEP} = 1.538 \left[\frac{\mathrm{RMS}_n + \mathrm{RMS}_e + \mathrm{RMS}_a}{3} \right] ,$$

where RMS_n is the RMS error of northing,

RMS_e is the RMS error of easting,

RMS_a is the RMS error of altitude,

and 1.538 is the radii of 50% probability spheres (SEP).

The RT, which provided the base line for accuracy measurements at the OP, has an accuracy factor (when operated in the tracking mode) that is expressed as ±(10 mm + 5 ppm).[5] The RT also has built-in software that provides for correction of collimation, tracker collimation, and horizontal axis tilt errors.

In preparation for the OP tests, the RT’s electronic distance measuring instrument (EDMI) was checked for accuracy at an NGS base line site. An NGS program provides surveyors with a means to detect and correct errors in EDMI’s at any of 300 EDMI calibration base lines throughout the United States. These highly accurate base lines provide a locally accessible standard for length measurement. We tested the RT against the CASPER calibration base line near Casper, WY. This base line was established in conjunction with the Professional Land Surveyors of Wyoming. The RT was tested at a distance of 150 m and 430 m. At the 150-m marker, the RT measured 149.9878 m; at the 430-m marker the RT measured 429.91999 m. (The RT results include compensation for temperature, pressure, and transit induced errors.)

DATA ARCHIVING METHODOLOGY

Originally, data were to be collected by three different systems (PC, SGI, and TRACKER). For a variety of reasons, data were mainly taken by the PC, sometimes by the SGI, and never by the TRACKER. For the data files taken, a file naming convention was adopted. The first two characters of the file name were the month (e.g., 09 = September), the next two were the day (e.g., 13 = 13th day of the month), the next two were the hour in 24-hr format (e.g., 15 = 3:00 p.m.), and the final two were the minutes (e.g., 22 = 22 min after the hour). There was no particular convention used for the file extensions until the data files were prepared for final analysis. The PC files were given .pcu extensions and the SGI files were given .sgu extensions.

The data collected were copied from shared memory. Each block of data saved was composed of 39 elements. The elements

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[5] Geodimeter System 4000 user manual.

were delimited with a comma, and the block was ended with a carriage return. The elements were:

INS easting
INS northing
INS altitude
INS azimuth
INS pitch
INS roll
INS time in service
INS status 0
INS status 1
INS status 2
INS status
INS alert 0
INS alert 1
INS alert 2
INS alert 3
CM state 0
CM state 1
CM state 2
CM state 3
CM center of rotation easting
CM center of rotation northing
INS cross track
INS along rack
INS delta azimuth
TRACKER easting
TRACKER northing
TRACKER altitude
TRACKER HA
TRACKER VA
TRACKER SD
TRACKER time of day
TRACKER temperature
TRACKER barometric pressure
CM current
CM conveyor swing angle
CM pan angle
CM shear angle
CM conveyor elevation angle
CM hydraulic pressure

Data were collected on about a 2-sec interval; this interval varied somewhat.

DATA ANALYSIS

The objective of the OP test was to compare the primary output of the INS (northings, eastings, and altitude) to the values derived from the output of the RT. Used at sea level, one can generally take the position output of the RT and directly compare it to that of the INS depending, of course, on the level of accuracy required for the analysis. The worksite altitude, however, was over 1,500 m. Thus, temperature, pressure, reduction of the HD to the ellipsoidal surface, and the reduction of the HD from the ellipsoid to the grid had to be factored into the data reduction to calculate the resultant northings, eastings, and altitude. Data required from the RT to perform these calculations are the HA, VA, and SD. Additionally, known coordinates (CP's), must be used as reference. The temperature and pressure also must be included. The corrections are only applied to the SD, but the other parameters (HA and VA) are needed to calculate the coordinates and altitude. The corrections to SD are described below:

1. The observed distance should be corrected for any target or RT offsets.
2. The distance is corrected for atmospheric delays (varies with temperature and pressure). In order to maintain an accuracy of 5 ppm (i.e., 1.5 mm over 305 m), it is necessary to measure the temperature to an accuracy of 4 °F and a pressure to 0.25 in Hg (305 m is used in many of the examples because this was the distance between two of the CP's).
3. Reduce the SD to an HD.
4. Reduce the HD to the ellipsoidal surface.
5. Reduce the ellipsoidal surface to the grid. (The reduction of HD to the ellipsoidal surface and then to the grid can be combined into one "scale factor," depending on the level of accuracy required of the survey).

The following procedures described here generate the coordinates and altitude:

1. The grid azimuth (GA) to the target is determined by adding the HA to the known GA from the RT to the CP.
2. Knowing the GA and the grid distance (GD) to the target on the CM, the coordinates of the target on the CM can be computed.
3. Knowing the HD and the VA to the target on the CM, the altitude of the target can be computed.

Although the above listed procedures can always be used to generate coordinates and altitude from the raw values (HA, VA, and SD) supplied by the RT, the method can be simplified as described below, which are the procedures we employed to generate coordinates and altitude. A sample set of calculations is provided later.

Measure the known distance between two CP points, such as WEST to EAST, whose separation is accurately known. By comparing the HD against the known distance, a correction factor can be computed that combines the atmospheric effects on the EDMI, which varies with temperature and pressure and the reduction from HD to the ellipsoid and to the grid (the latter two of these corrections are constant).

By comparing the VA against the known difference in altitude, the coefficient of refraction can be computed. However, we decided to ignore the coefficient of refraction because of a negligible impact on accuracy. If the temperature and pressure were not compensated for, an error of 1.8 cm per 305 m of distance would result. If the reduction to the ellipsoid (sea level on NAD27) and the reduction to the grid were not performed on HD, an error of 10 cm per 305 m of distance would result. The coefficient of refraction is less crucial and was not factored into the result. Ignoring it results in an error of about 0.3 mm per 305 m of distance.

A sample set of calculations that was performed is as follows:

A. Calculate the Scale Factor (SF)

1. Put the RT on the MID CP and the target on the WEST CP, and take a reading. The CP coordinates are MID (northing 860867.346 ft, easting 324938.305 ft, altitude 5567.319 ft) and WEST(northing 861084.255 ft, easting 324445.770 ft, altitude 5573.685 ft). The RT values obtained were HA = 0°00′03″, VA = 89°23′04″, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft.
2. Convert VA to radians ($VA_r = 1.55942744597$).
3. Calculate the scale factor (SF): SF = GD/HD, where GD is the true grid distance between CP's and HD is the measured distance.

$$GD = \sqrt{\Delta N^2 + \Delta E^2}$$

(See equation at bottom of this page.)

$$HD = SD \bullet \sin(VA_r) = (538.325\ \text{ft}) \bullet \sin(1.55942744597)$$

$$= 538.293932933\ \text{ft}$$

$$SF = 538.177772842\ \text{ft} / 538.293932933\ \text{ft}$$

$$= 0.99978420607$$

B. Determine the CM position

1. Using the RT on MID, sight in the target on the CM, and record results. The RT values obtained were HA = 292°11′40″, VA = 89°20′55″, SD = 298.133 ft, HI = 0.935 ft, and HR = 0.0 ft.
2. Convert HA and VA to radians ($HA_r = 5.09975511158$ and $VA_r = 1.55942744597$).
3. Calculate HD:

$$HD = SD \bullet \sin(VA_r) = 298.133\ \text{ft} \bullet \sin(1.55942744597)$$

$$= 298.113733146\ \text{ft}$$

4. Correct HD to HD_c using SF:

$$HD_c = HD \bullet SF = 298.113733146\ \text{ft} \bullet 0.99978420607$$

$$= 298.049402012\ \text{ft}$$

5. Determine the horizontal azimuth and convert it to radians:

$$HAZIR = MODULO(HA_r, \pi) = MODULO\ (5.09975511158, 2\pi)$$

$$= 5.09975511158$$

6. Calculate the northing:

$$\text{Northing} = 860867.346\ \text{ft} + HD_c \bullet \cos(HAZIR)$$
$$\text{Northing} = 860867.346\ \text{ft} + 298.049402012\ \text{ft} \bullet \cos(5.09975511158)$$
$$\text{Northing} = 860979.934463\ \text{ft}$$

7. Calculate the Easting

$$\text{Easting} = 324938.305\ \text{ft} + HD_c \bullet \sin(HAZIR)$$
$$\text{Easting} = 324938.305\ \text{ft} + 298.049402012\ \text{ft} \bullet \sin(5.09975511158)$$
$$\text{Easting} = 324662.338908\ \text{ft}$$

C. Calculate the Altitude

$$\text{Altitude} = 5567.319\ \text{ft} + HD_c \bullet \cos(VA_r) + HI - HR$$
$$\text{Altitude} = 5567.319\ \text{ft} + 298.04940201\ \text{ft} \bullet \cos(1.5594274459) + (0.935\ \text{ft} - 0)$$
$$\text{Altitude} = 5571.642\ \text{ft}$$

$$GD = \sqrt{((861084.255\ \text{ft} - 860867.346\ \text{ft})^2 + (324445.770\ \text{ft} - 324938.305\ \text{ft})^2)}$$
$$= 538.177772842\ \text{ft}$$

OP RESULTS

The data from the OP were primarily taken over 2 days (September 13 and 14) and consisted of nine data files. The PC collected data over both days; the SGI, only on September 13. The PC generated three files on September 13 and one file on September 14; the SGI generated five data files on September 13. The first 90-m cut was performed on September 13; the second

90-m cut, on September 14. The data file collected and the details of each are described below.

File 09130927.pcu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0°, VA = 89.2306°, SD = 538.33 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.99978825238. With the RT on MID and the target on the CM, the RT data were HA = 291.1544°, VA = 88.1948°, and SD = 403.588 ft. The calculated coordinates of the starting point of the CM were northing = 861013.611 ft, easting = 324562.4326 ft, and altitude = 5580.008 ft. The file consisted of 603 blocks of data. The RT and the INS position data plot is shown in figure 14. The RT and the INS altitude data plot is shown in figure 15. Ascatter plot of the RT and the INS northing and easting differences is shown in figure 16.

File 09131309.pcu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0003°,

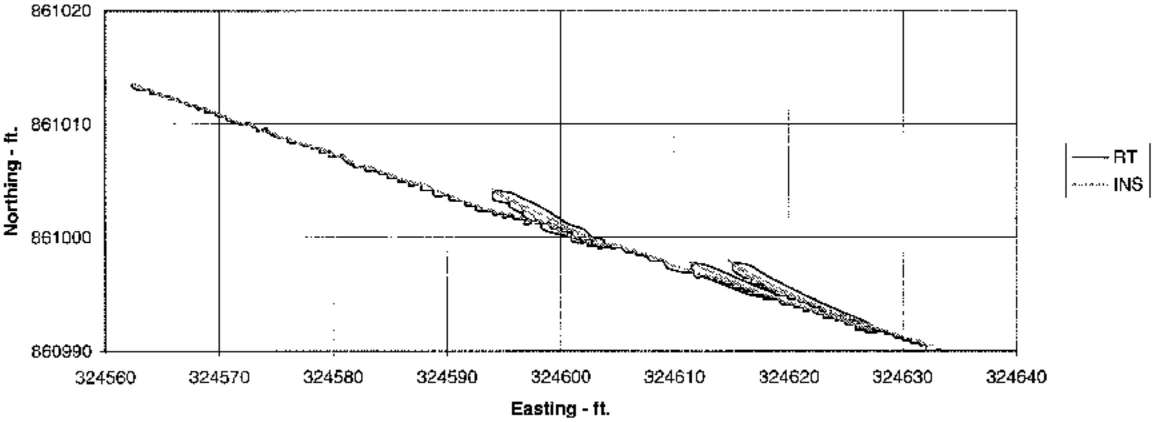

Figure 14.—RT and INS position file 09130927.pcu.

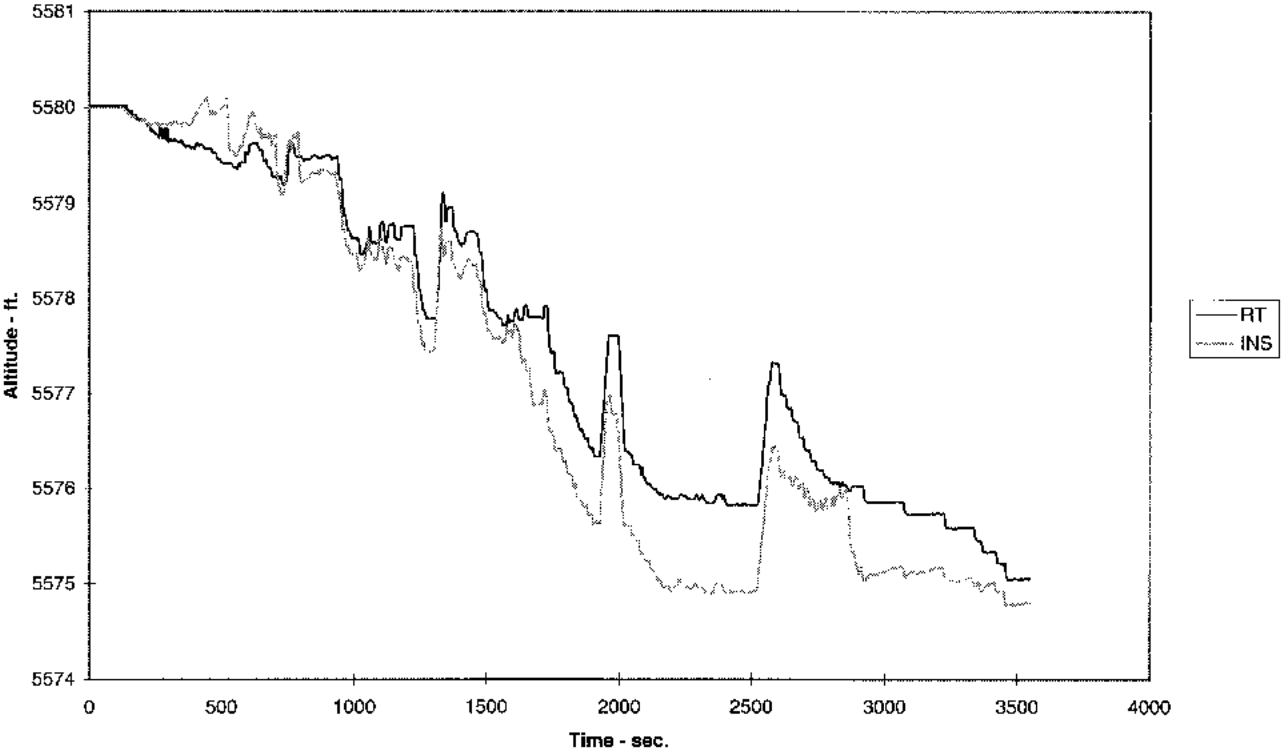

Figure 15.—RT and INS altitude file 09130927.pcu.

The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 977 blocks of data. The RT and the INS position data plot is shown in figure 17. The RT and the INS altitudedata plot is shown in figure 18. A scatter plot of RT and the INS northing and easting differences is shown in figure 19.

File 09131522.pcu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0003°, VA = 89.2304°, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 735 blocks of data. The RT and the INS position data plot is shown in fig-ure 20. The RT and the INS altitude data plot is shown in figure 21. A scatter plot of the RT and the INS northing and easting differences is shown in figure 22.

File 09130928.sgu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0°, VA = 89.2306°, SD = 538.33 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.99978825238. With the RT on MID and the target on the CM, the RT data were HA = 291.1544°, VA = 88.1948°, and SD = 403.588 ft. The calculated coordinates of the starting point of the CM were northing = 861013.611 ft, easting = 324562.4326 ft, and altitude = 5580.008 ft. The file consisted of 666 blocks of data. The RT and the INS position data plot is shown in figure 23. The RT and the INS altitude data plot is shown in figure 24. A scatter plot of the RT and the INS northing and easting differences is shown in figure 25.

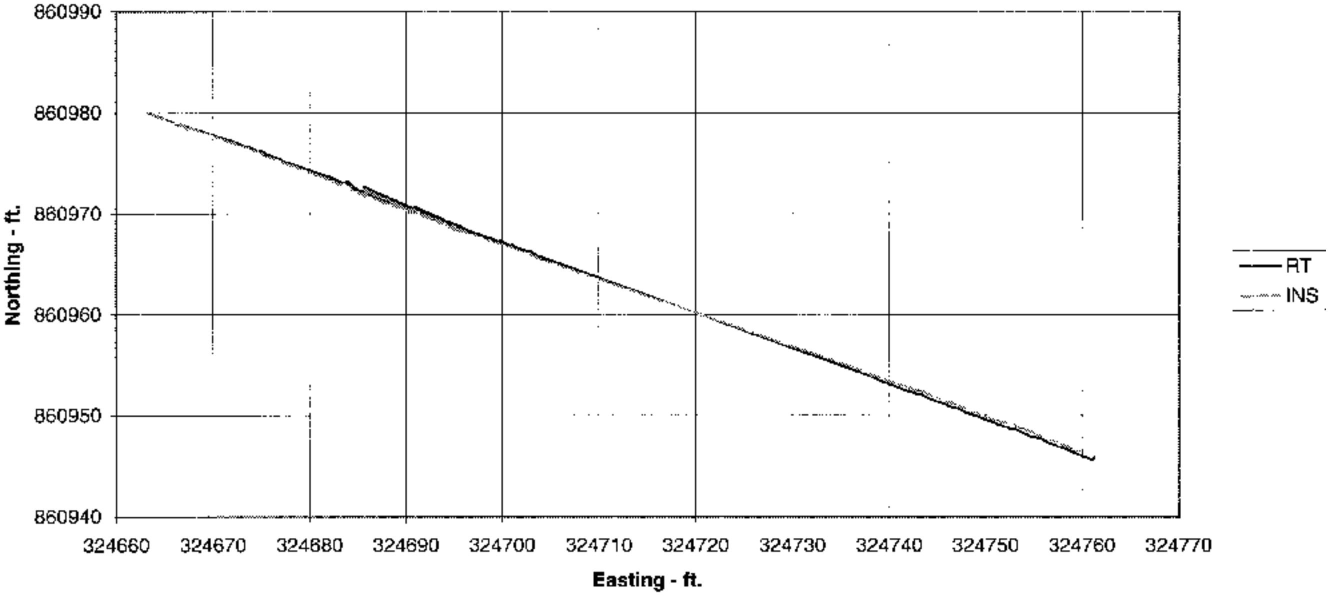

Fig osition file 09131309.pcu.

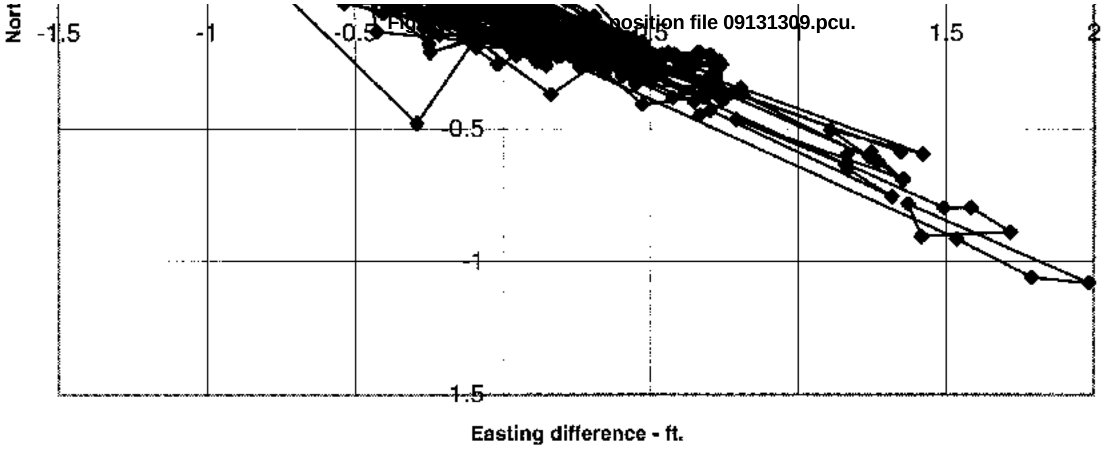

Figure 16.—RT and INS northing and easting difference file 09130927.pcu.

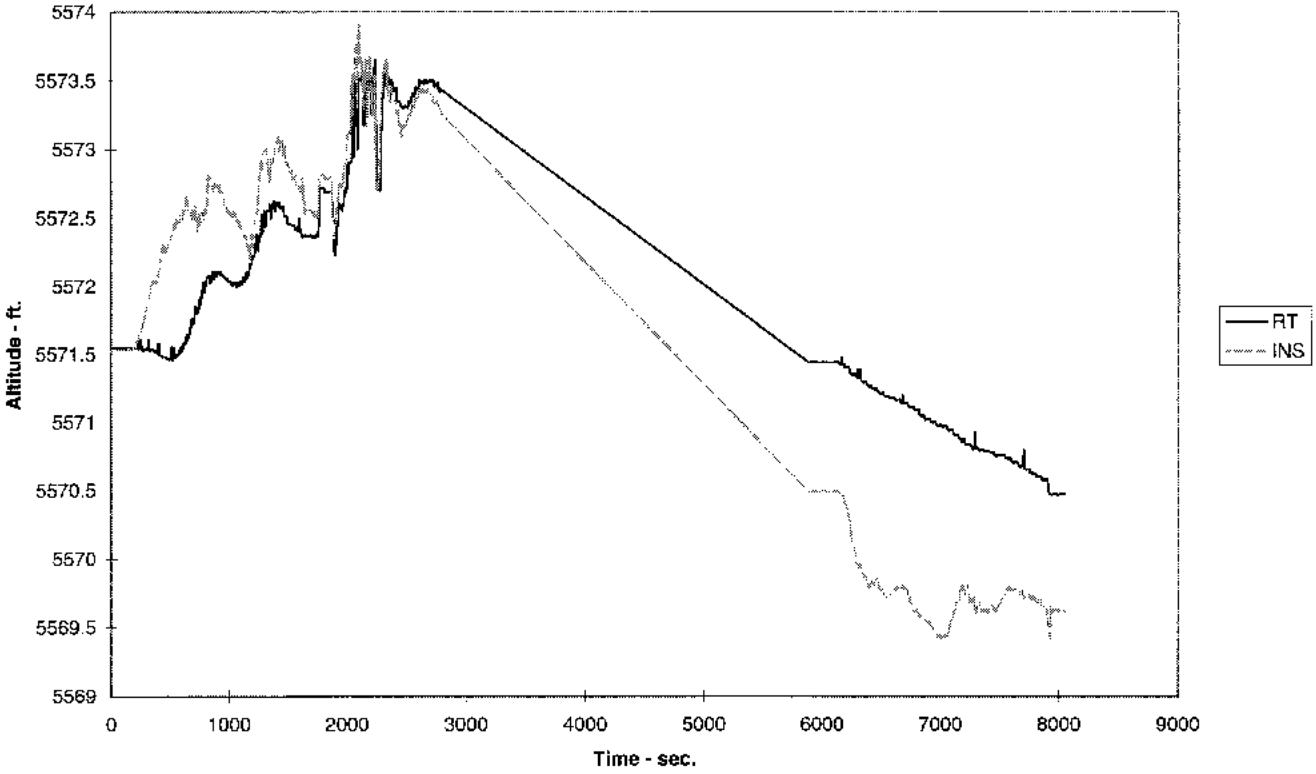

Figure 18.—RT and INS altitude file 09131309.pcu.

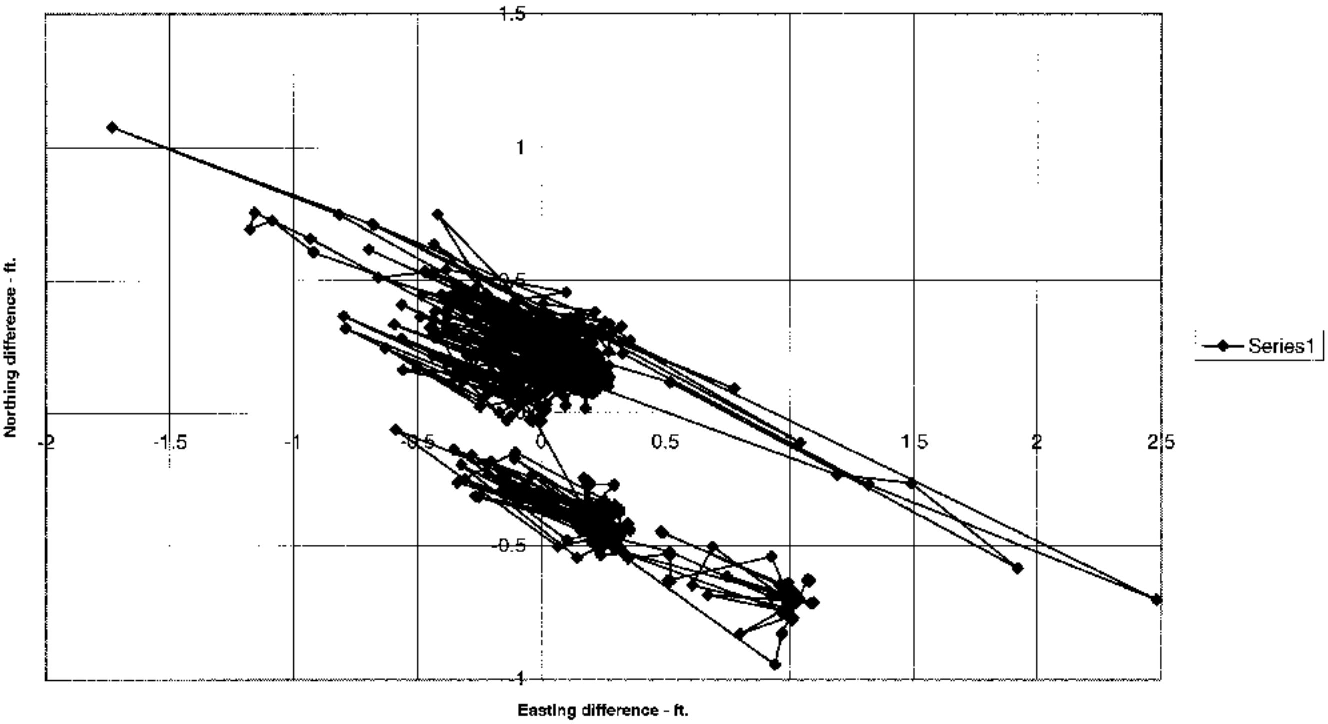

Figure 19.—RT and INS northing and easting difference file 09131309.pcu.

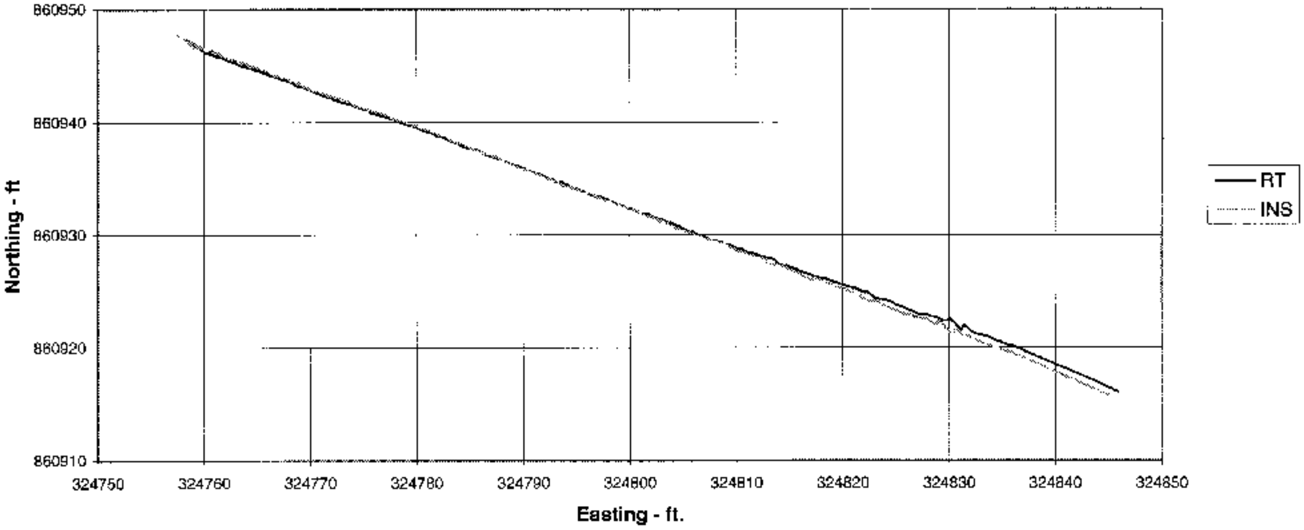

Figure 20.—RT and INS position file 09131522.pcu.

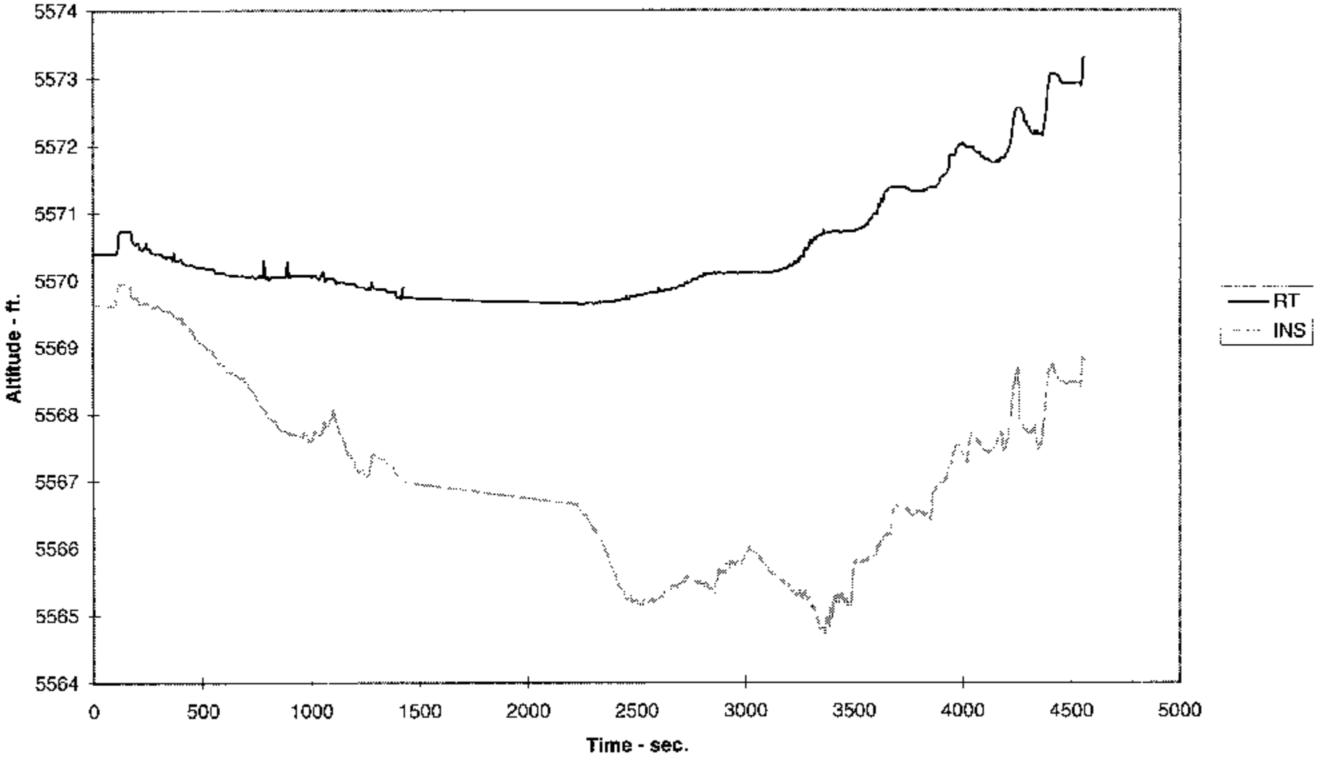

Figure 21.—RT and INS altitude file 09131522.pcu.

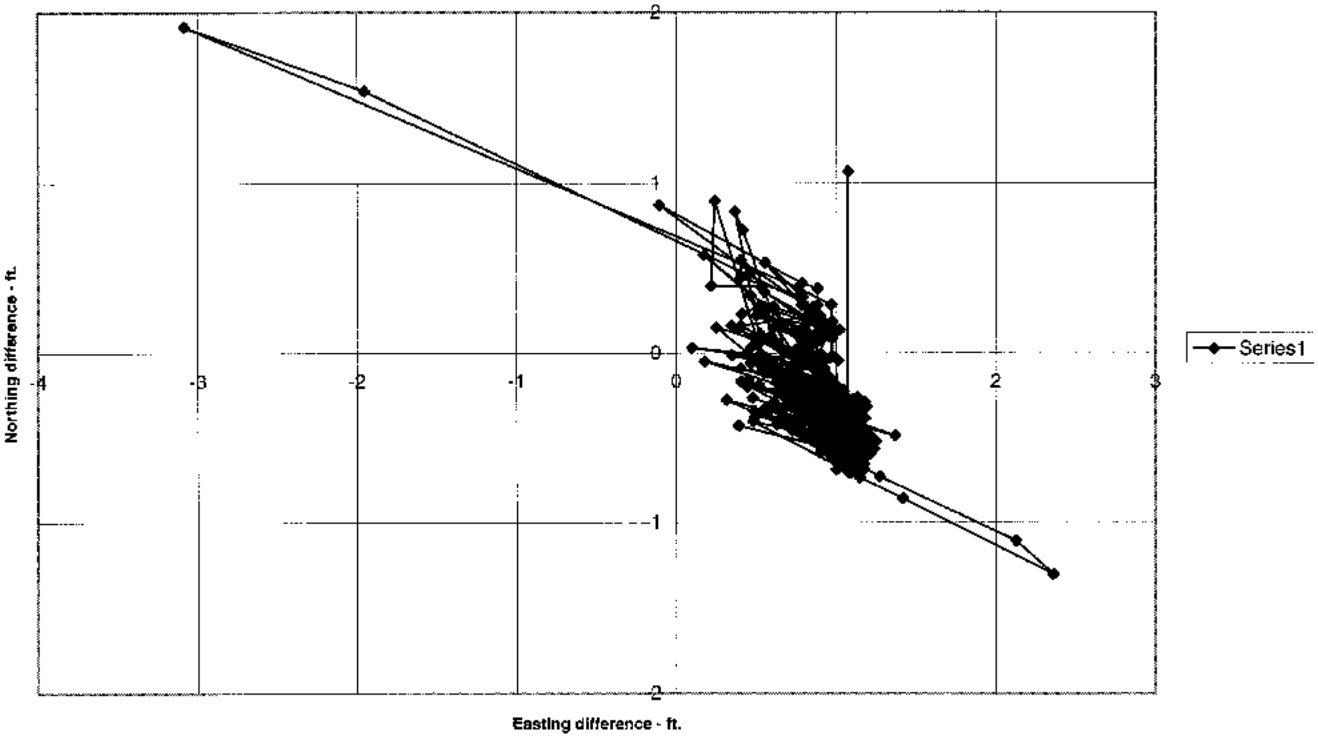

Figure 22.—RT and INS northing and easting difference file 09131522.pcu.

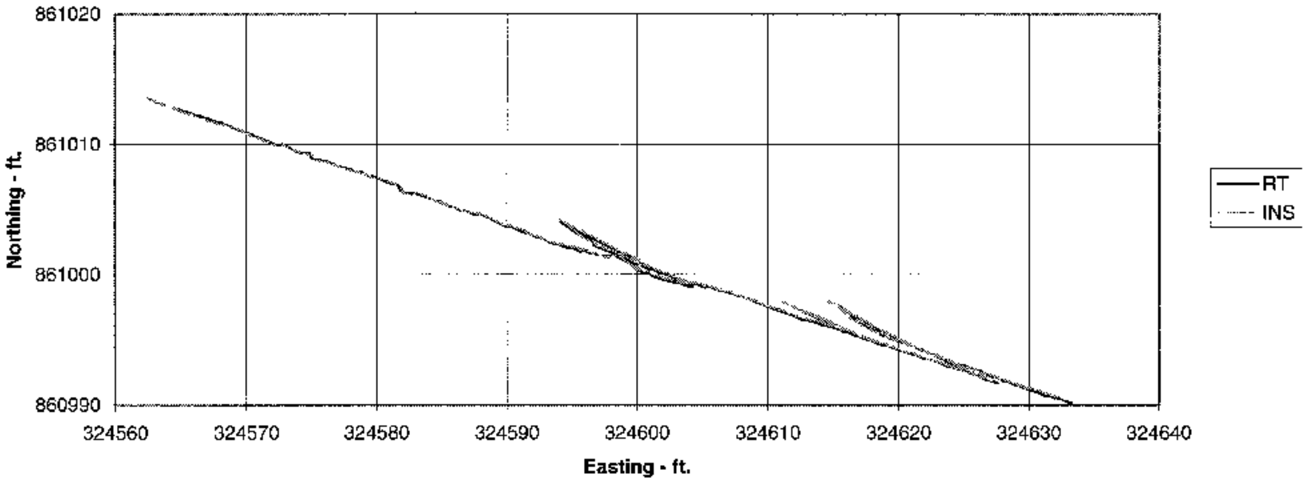

Figure 23.—RT and INS position file 09130928.sgu.

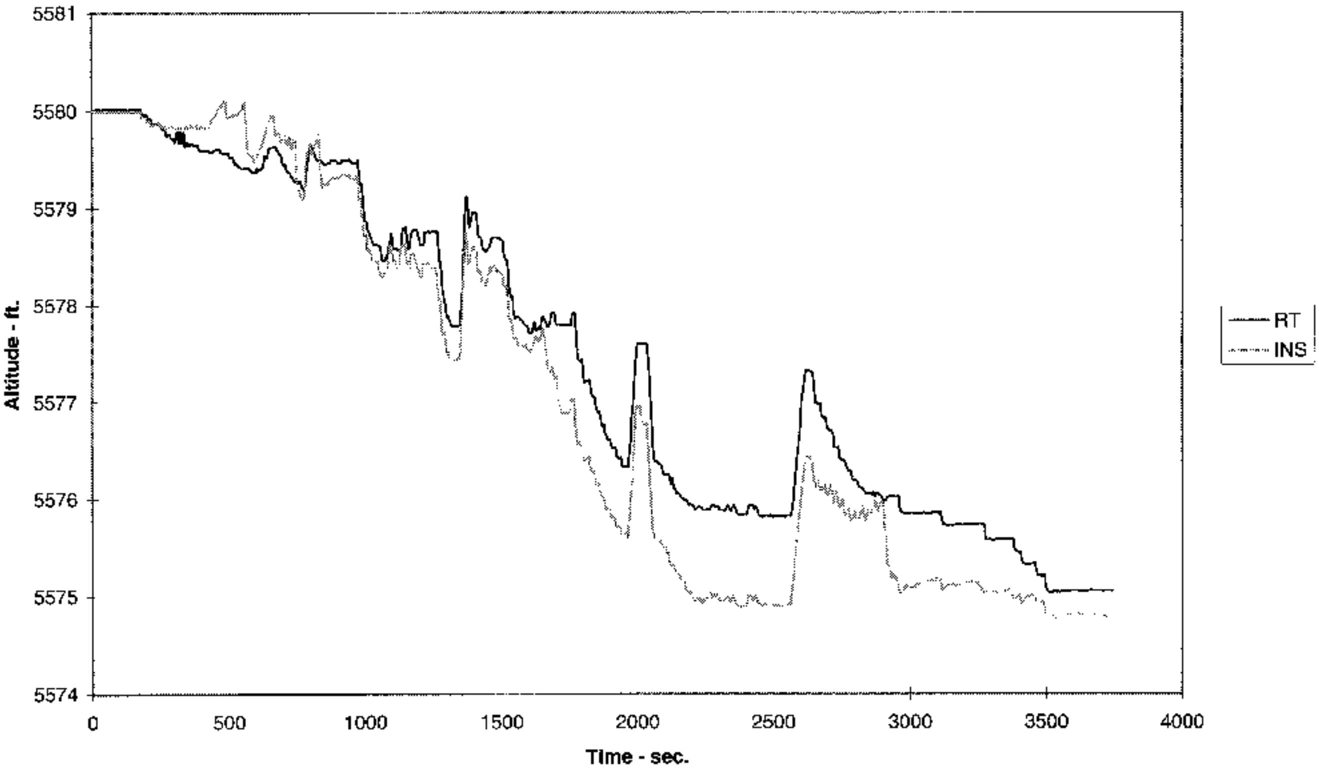

Figure 24.—RT and INS altitude file 09130928.sgu.

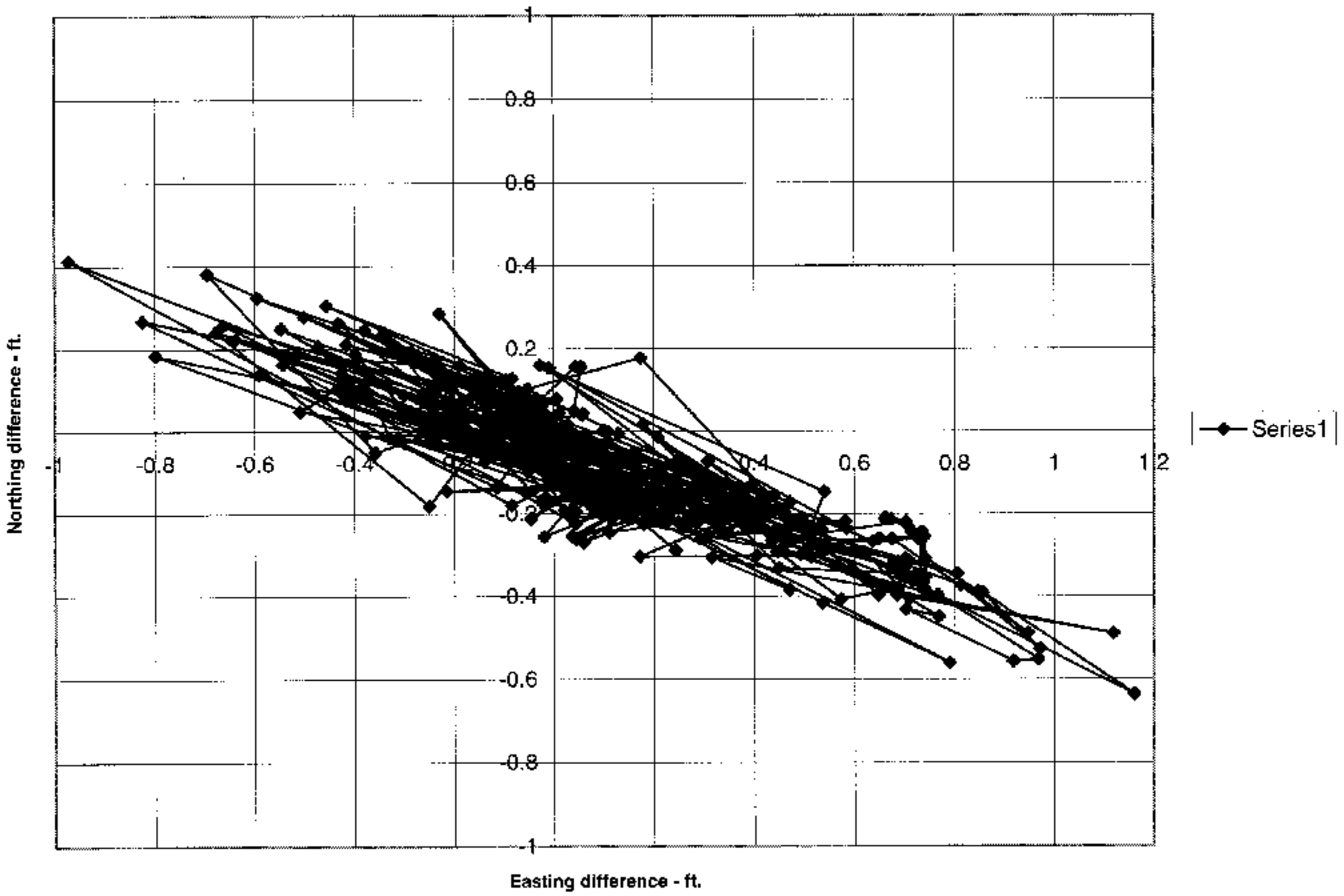

Figure 25.—RT and INS northing and easting difference file 09130928.sgu.

File 09131307.sgu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0003°, VA = 89.2304°, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 539 blocks of data. The RT and the INS position data plot is shown in figure 26. The RT and the INS altitude data plot is shown in figure 27. A scatter plot of the RT and the INS northing and easting differences is shown in figure 28.

File 09131450.sgu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0003°, VA = 89.2304°, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 413 blocks of data. The RT and the INS position data plot is shown in fig-ure 29. The RT and the INS altitude data plot is shown in figure 30. A scatter plot of the INS northing and easting differences is shown in figure 31.

File 09131525.sgu

The RT data were HA = 0.0003°, VA = 89.2304°, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 817 blocks of data. The RT and the INS position data plot is shown in figure 32. The RT and the INS altitude data plot is shown in figure 33. A scatter plot of the RT and the INS northing and easting differences is shown in figure 34.

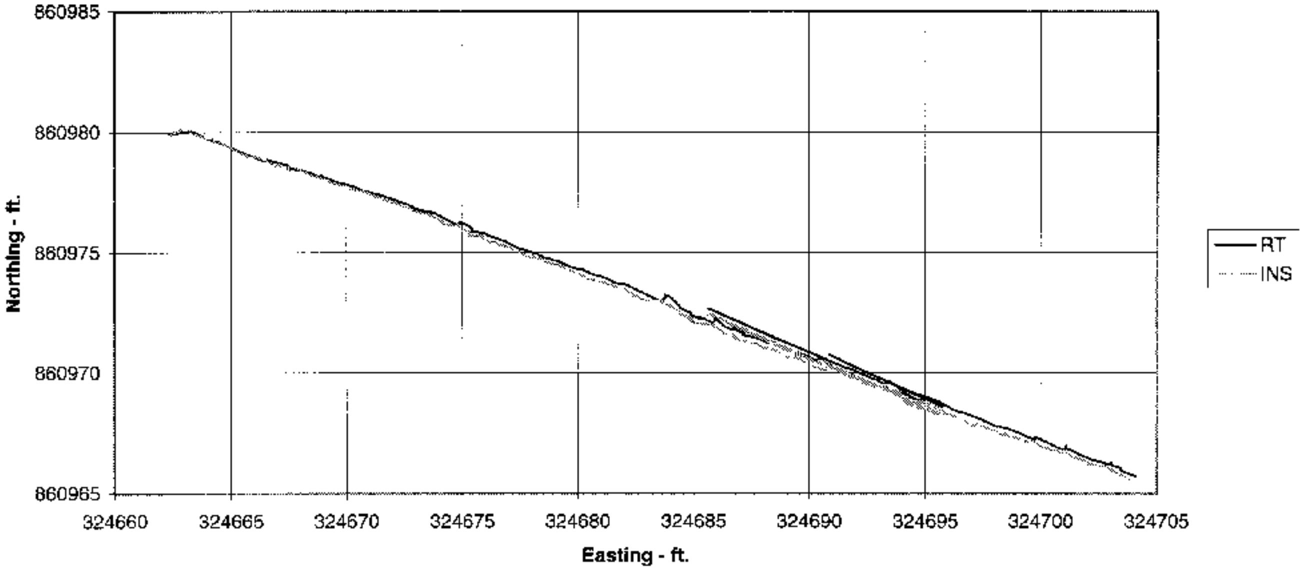

Figure 26.—RT and INS position file 09131307.sgu.

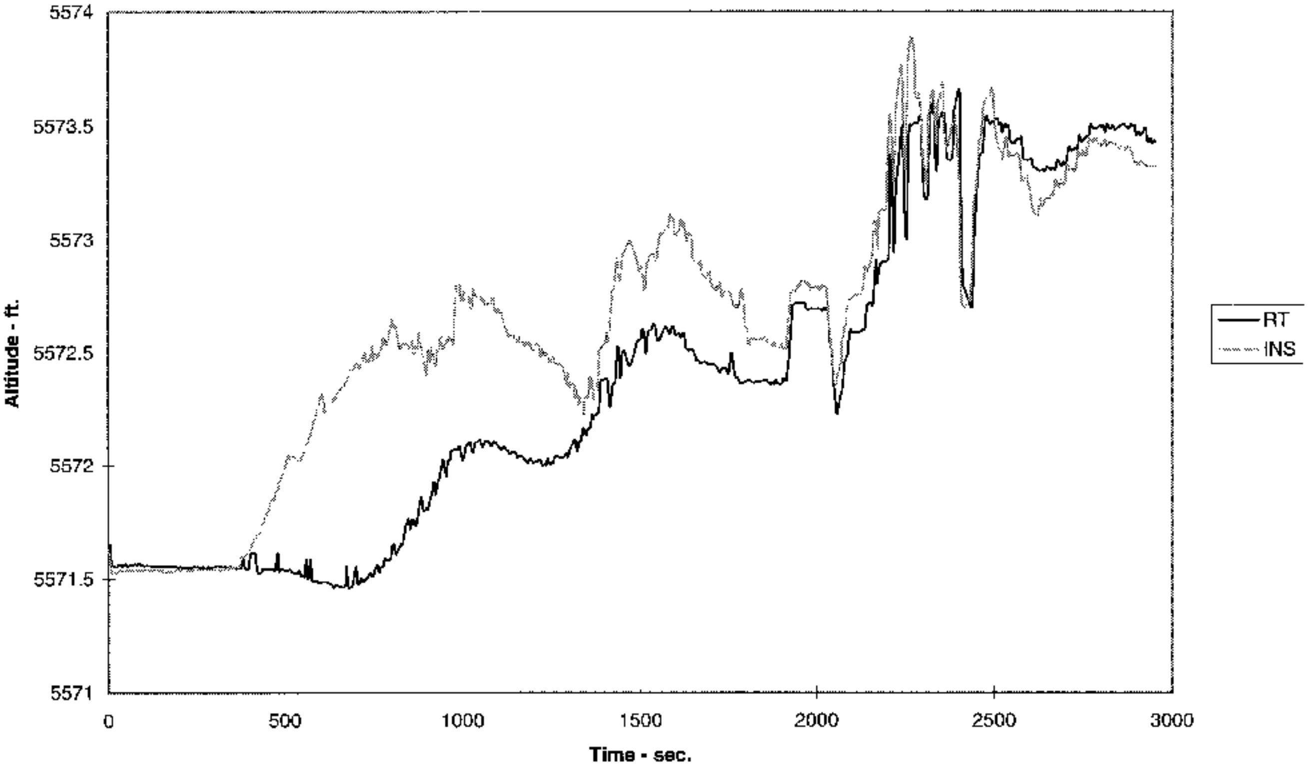

Figure 27.—RT and INS altitude file 09131307.sgu.

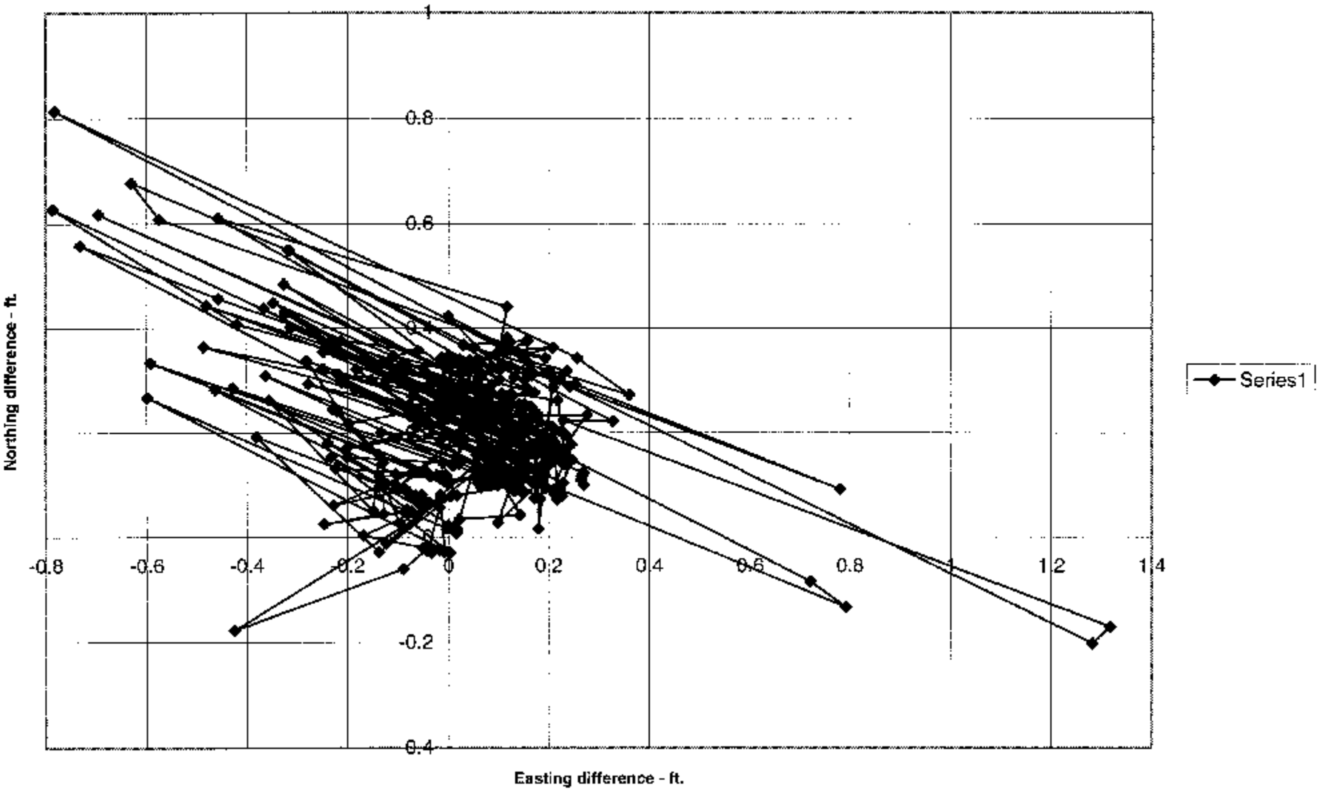

Figure 28.—RT and INS northing and easting difference file 09131307.sgu.

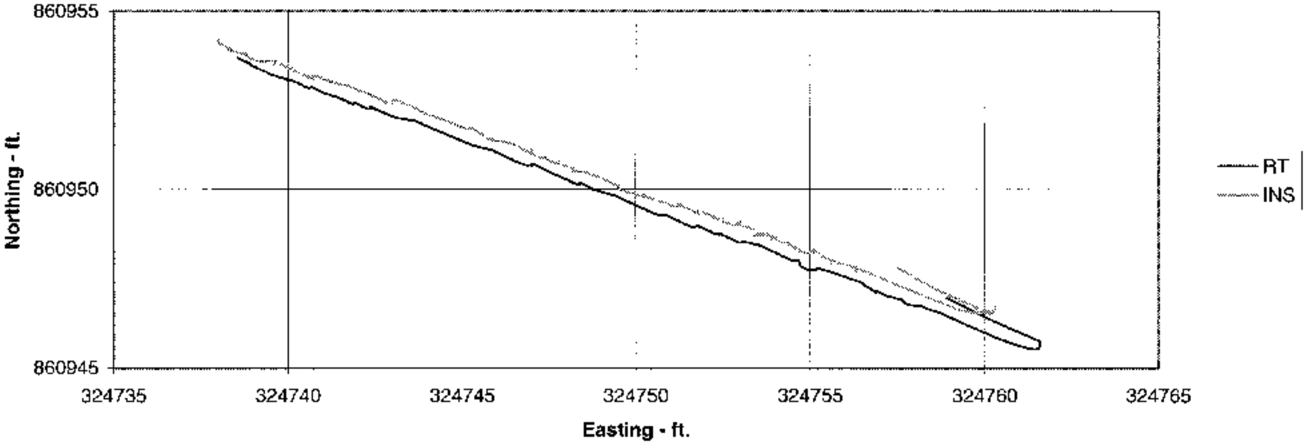

Figure 29.—RT and INS position file 09131450.sgu.

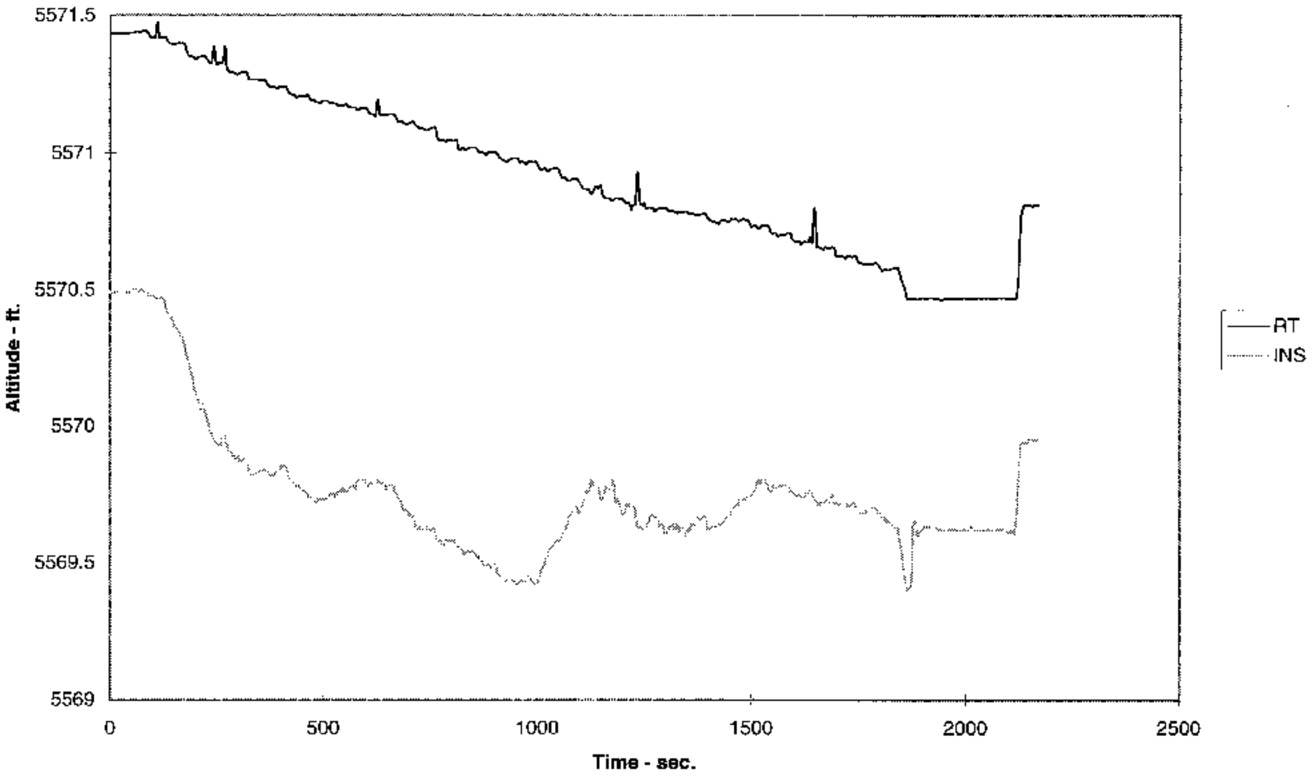

Figure 30.—RT and INS altitude file 09131450.sgu.

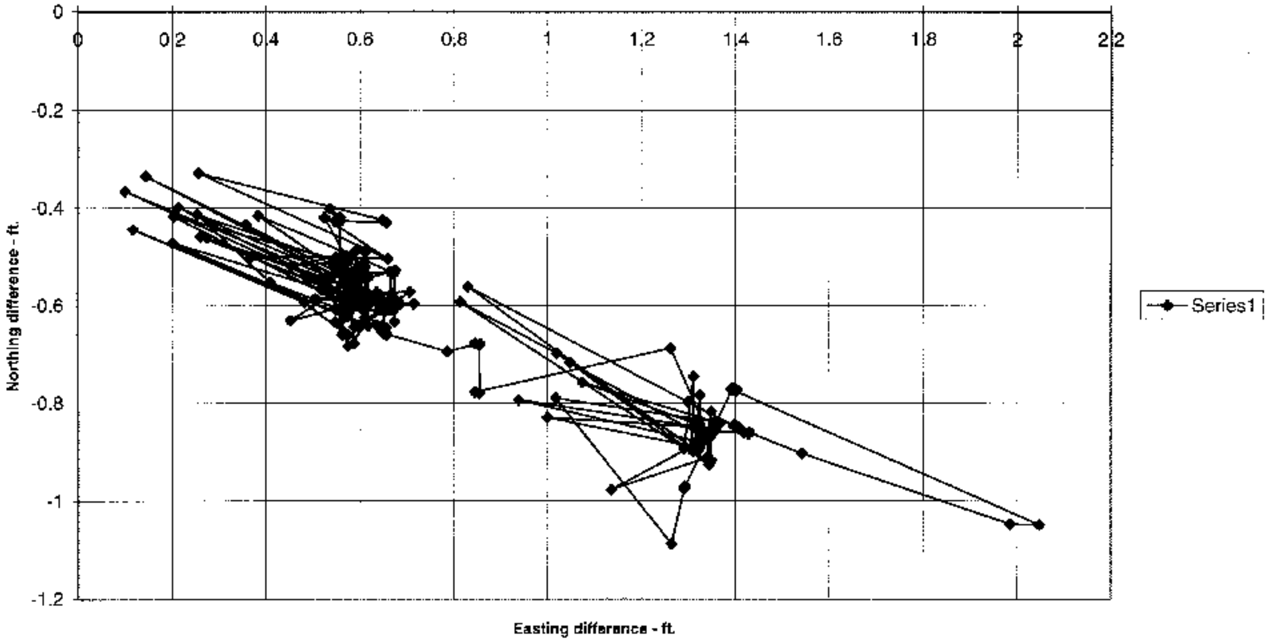

Figure 31.—RT and INS northing and easting difference file 09131450.sgu.

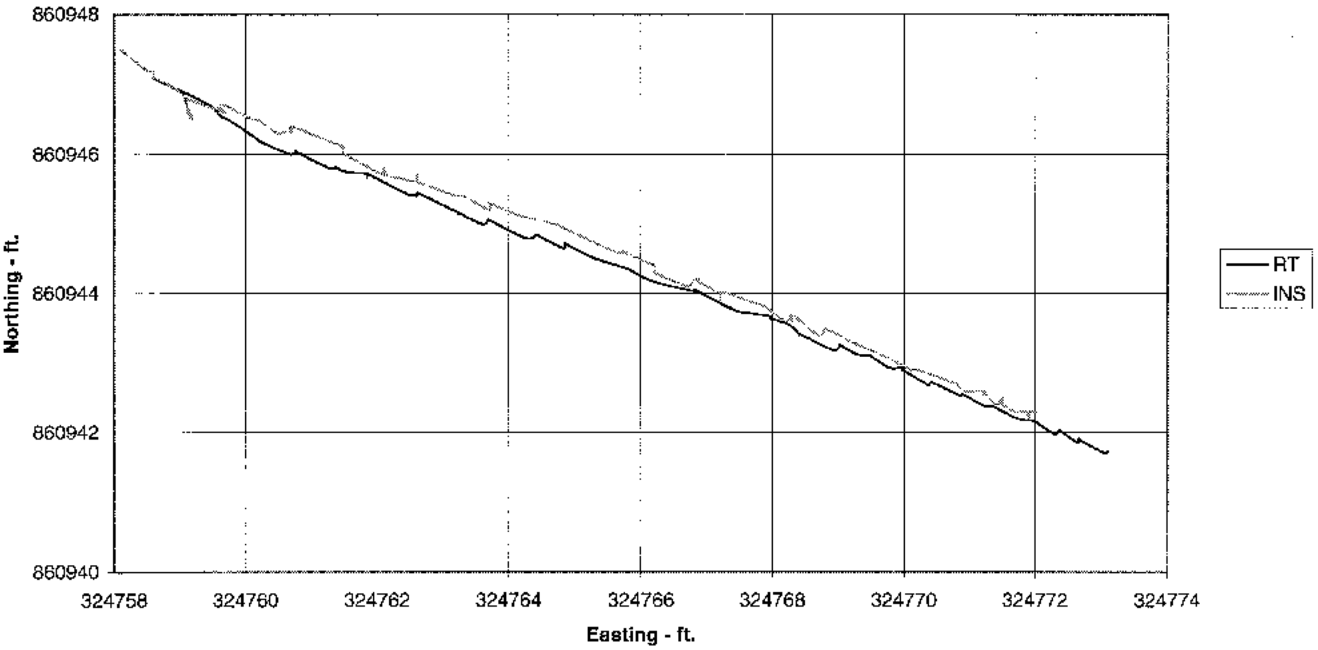

Figure 32.—RT and INS position file 09131525.sgu.

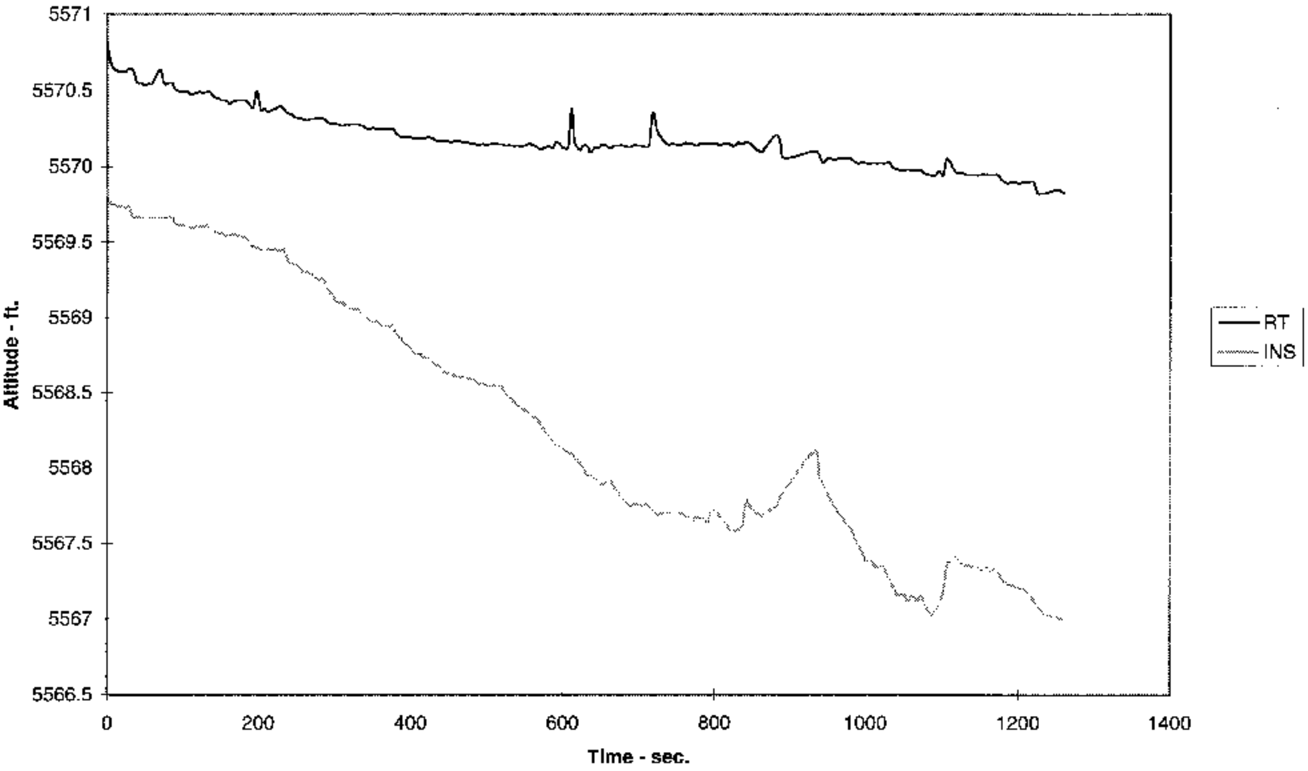

Figure 33.—RT and INS altitude file 09131525.sgu.

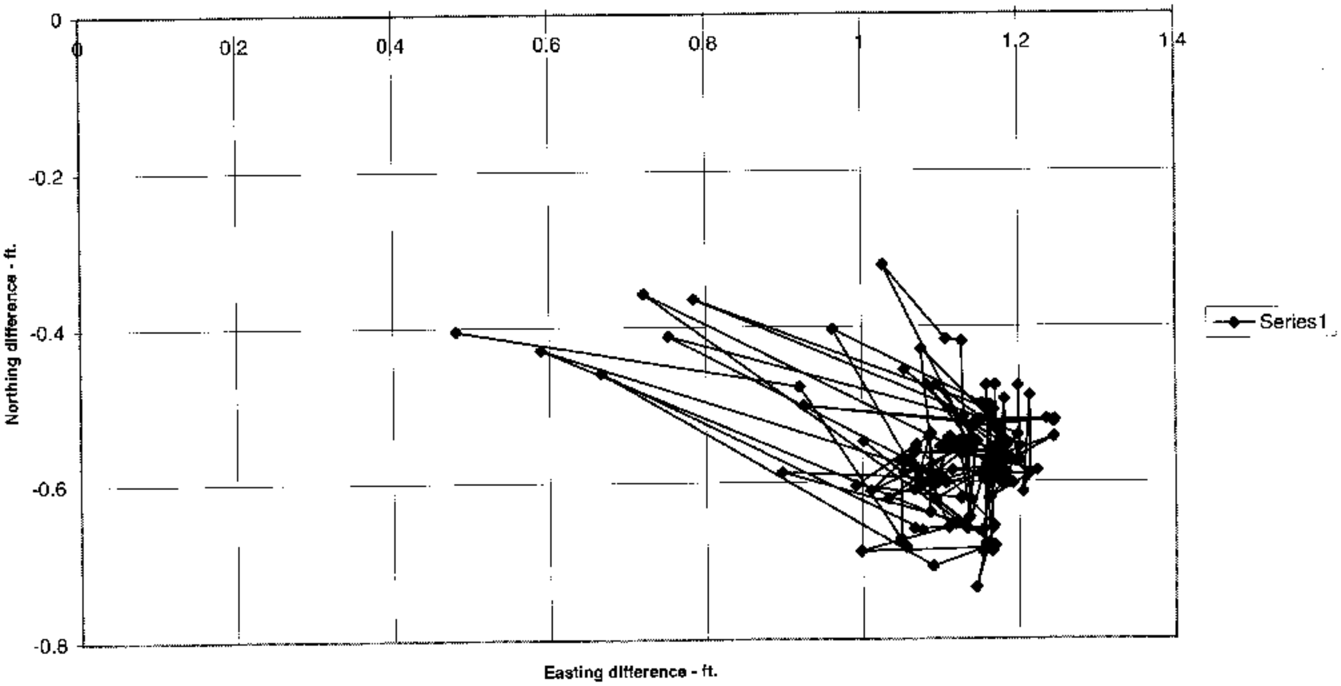

Figure 34.—RT amd INS northing and easting difference file 09131525.sgu.

File 09131600.sgu

The RT was placed on the MID CP, and the target was placed on the WEST CP. The RT data were HA = 0.0003°, VA = 89.2304°, SD = 538.325 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.9997982135. With the RT on MID and the target on the CM, the RT data were HA = 292.114°, VA = 89.2055°, and SD = 298.133 ft. The calculated coordinates of the starting point of the CM were northing = 860979.936 ft, easting = 324662.342 ft, and altitude = 5571.642 ft. The file consisted of 816 blocks of data. The RT and the INS position data plot is shown in fig-ure 35. The RT and the INS altitude data plot is shown in figure 36. A scatter plot of the RT and the INS northing and easting difference is shown in figure 37.

File 09140933.pcu

The RT was placed on the MID CP, and the target was placed on the EAST CP. The RT data were HA = 0.0006°, VA = 90.5814°, SD = 609.585 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.999729317206. With the RT on MID and the target on the CM, the RT data were HA = 294.3028°, VA = 88.3522°, and SD = 403.667 ft. The calculated coordinates of the starting point of the CM were northing = 861034.698 ft, easting = 324571.217 ft, and altitude = 5578.185 ft. The file consisted of 3,170 blocks of data. The RT and the INS position data plot is shown in fig-ure 38. The RT and the INS altitude data plot is shown in figure 39. A scatter plot of the RT and the INS northing and easting differences is shown in figure 40.

HIGHWALL RESULTS

The highwall tests required a new CP that was in line with the hole, because the RT and target are a line-of-sight system. Any obstructions stop the data flow. We only expected to obtain a small amount of data from the test. The new CP was named "SEC". With the RT on MID and the target on EAST, the RT measured HA = 359.5954°, VA = 90.5813°, SD = 609.59 ft, HI = 0.935 ft, and HR = 0.3 ft. The calculated SF was 0.999721. A tripod was placed at the intended SEC point, and a target was mounted on it. With the RT on MID and the target on SEC, the RT measured HA = 106.3055°, VA = 90.5353°, and SD = 188.53 ft. The SEC coordinates calculated from these values were northing = 860813.7739 ft, easting = 325118.9844 ft, and altitude = 5565.3 ft. The details of the data file generated for the highwall test are described below.

File 09261449.pcu

The RT was placed on the SEC CP, and the target was placed on the MID CP. The RT data were HA = 0.0004°, VA = 89.2336°, SD = 188.565 ft, HI = 0.854 ft, and HR = 0.3 ft. The calculated SF was 0.999458489729. With the RT on SEC and the target on the CM, the RT data were HA = 18.4215°, VA = 90.0256°, and SD = 77.487 ft. The calculated coordinates of the starting point of the CM were northing = 860887.1288 ft, easting = 325143.8196 ft, and altitude = 5566.0870 ft. The file consisted of 1,502 blocks of data. The RT and the INS position data plot is shown in figure 41. The RT and the INS altitude data plot is shown in figure 42.

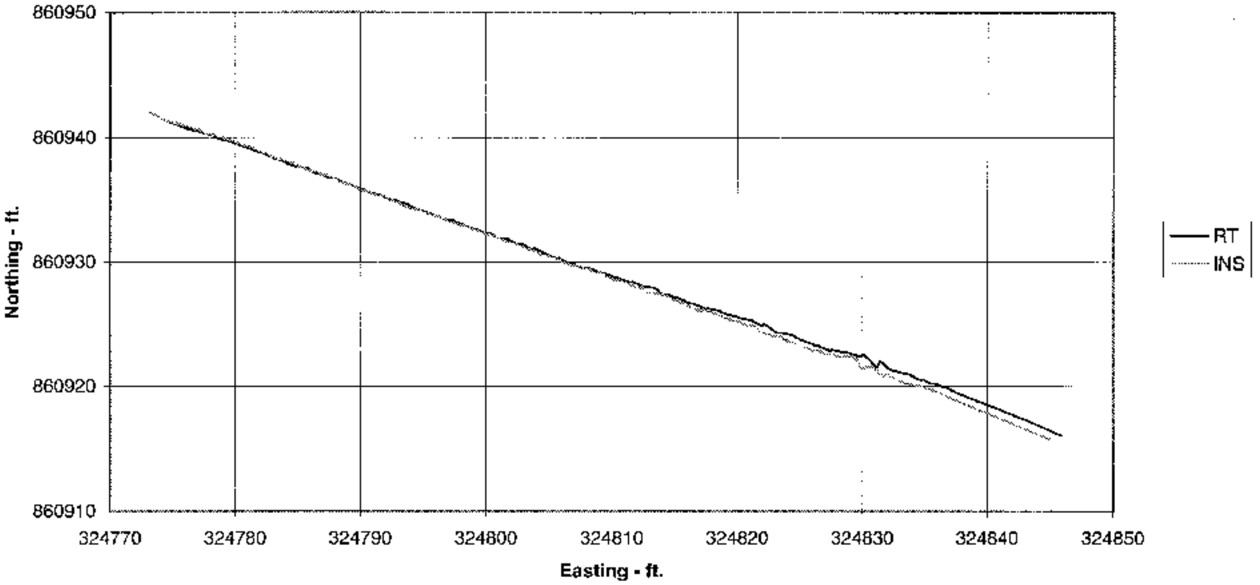

Figure 35.—RT and INS position file 09131600.sgu.

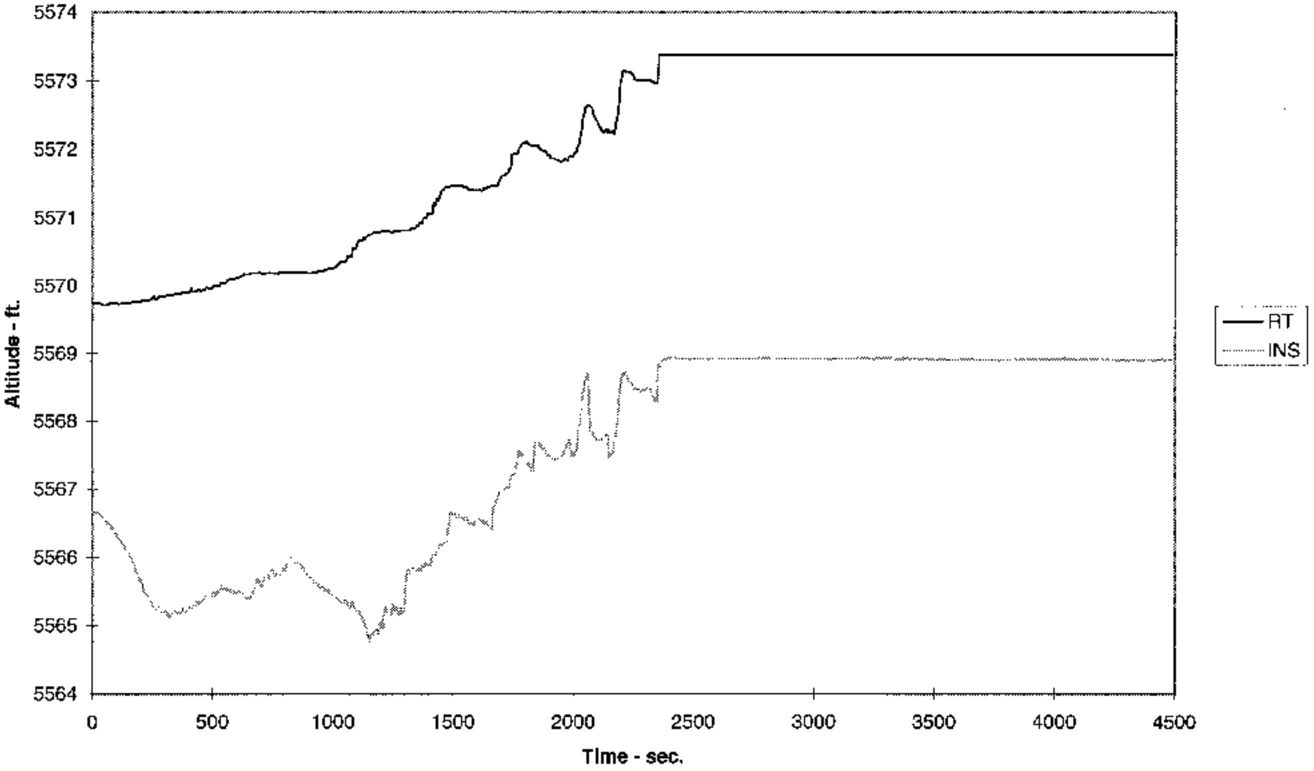

Figure 36.—RT amd INS altitude for 09131600.sgu.

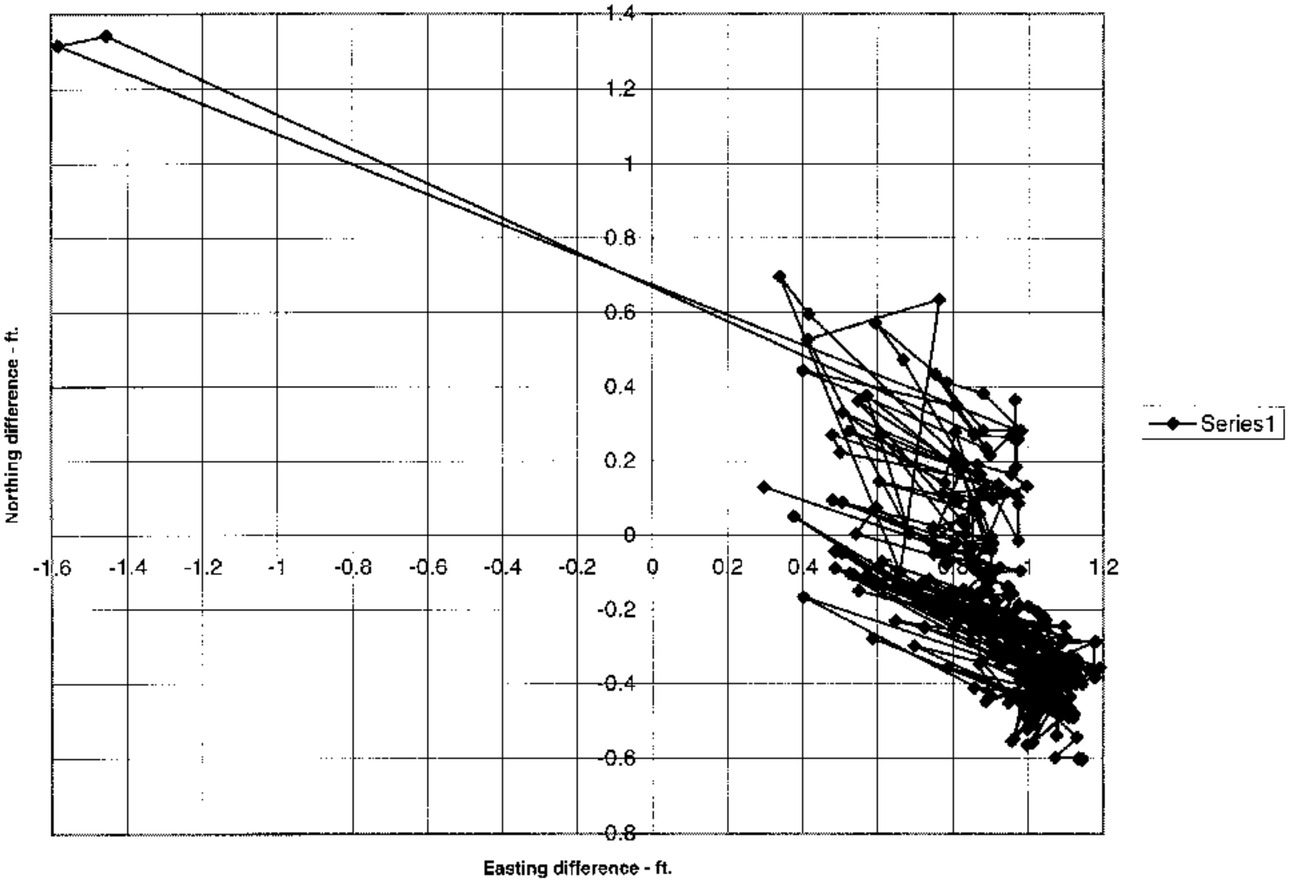

Figure 37.—RT and INS northing and easting difference file 09131600.sgu.

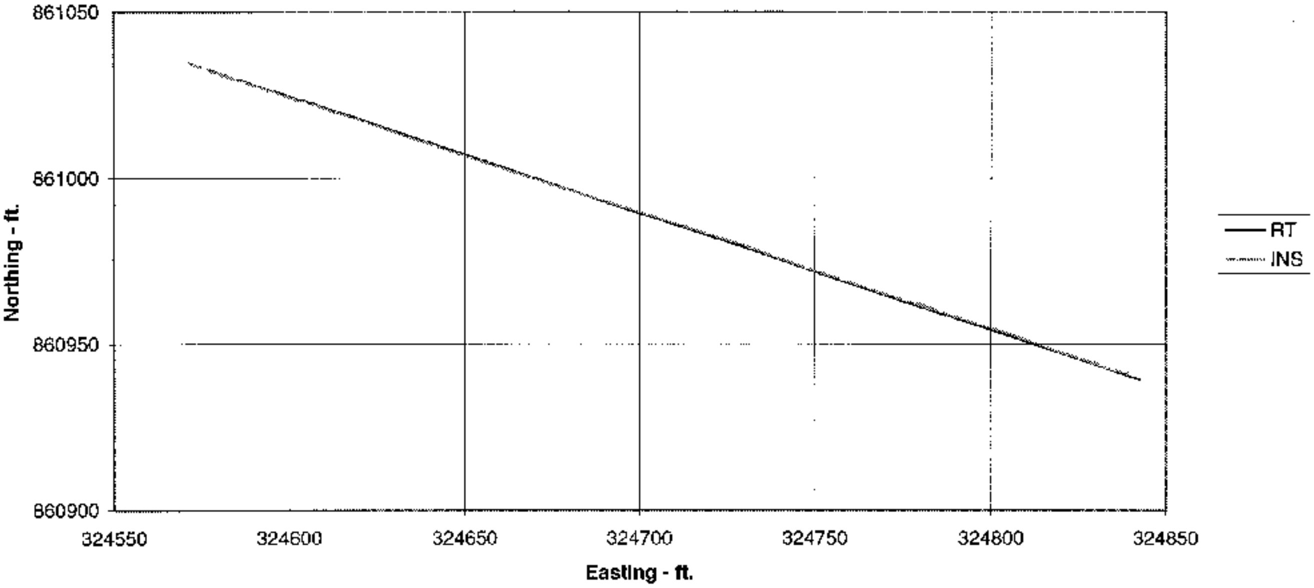

Figure 38.—RT and INS position file 09140933.pcu.

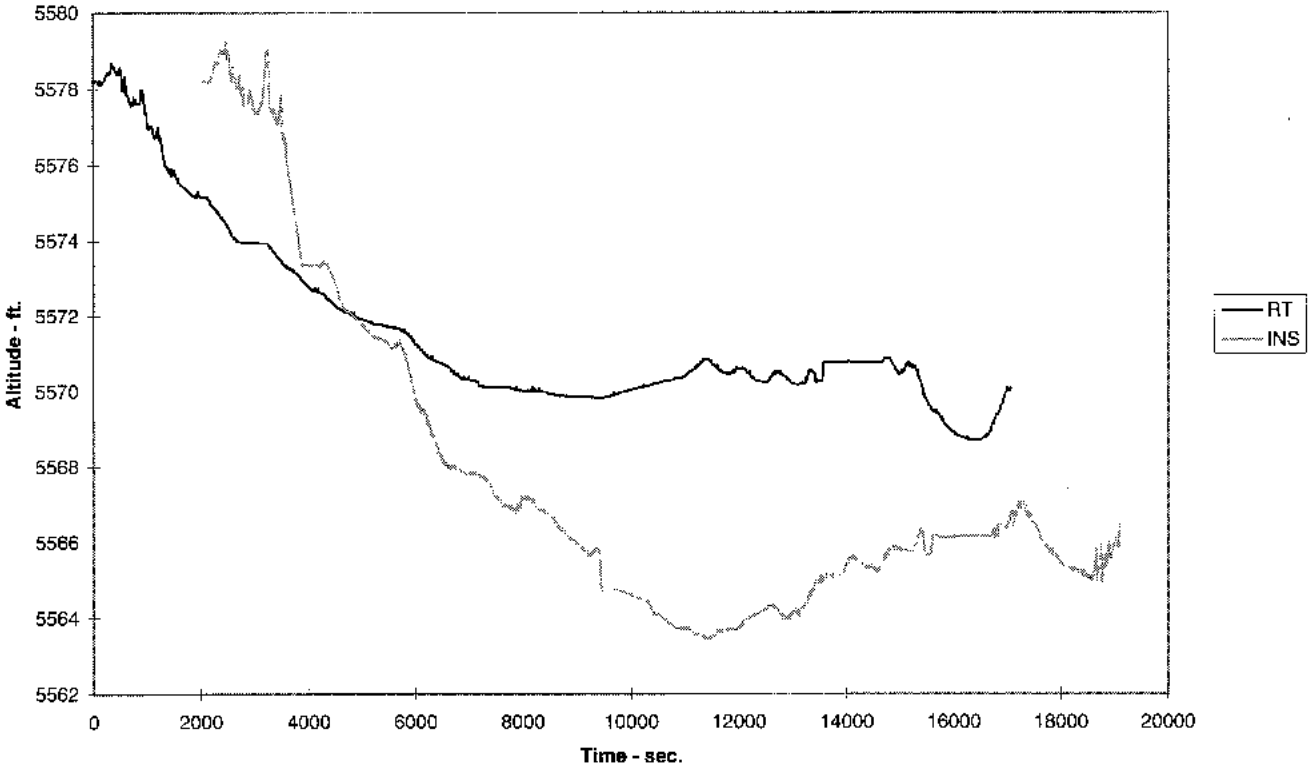

Figure 39.—RT and INS altitude file 09140933.pcu.

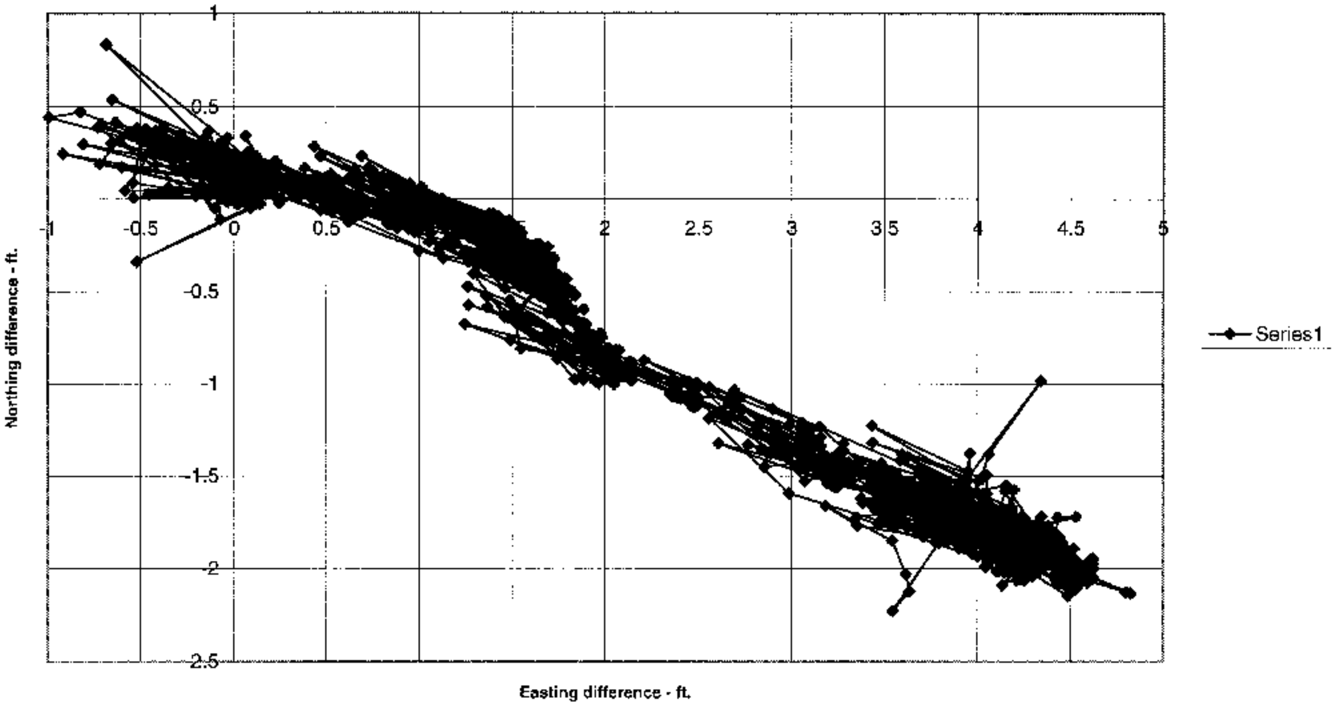

Figure 40.—RT and INS northing and easting difference file 09140933.pcu.

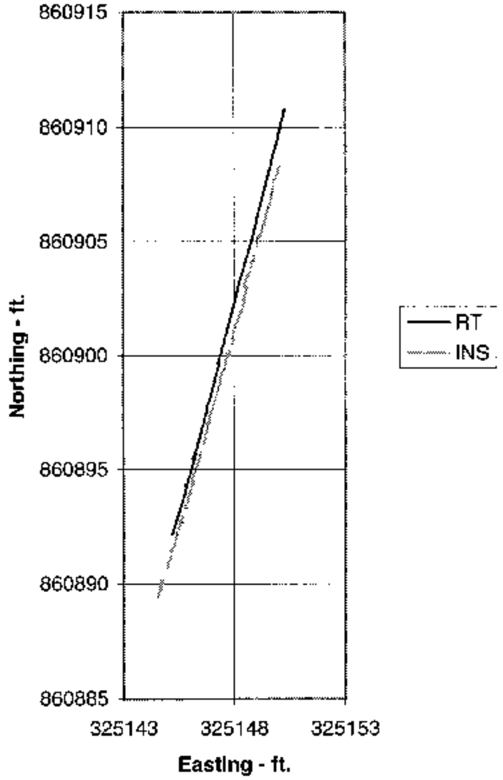

Figure 41.—RT and INS position file 09261449.pcu.

A scatter plot of the RT and the INS northing and easting differences is shown in figure 43.

The CEP's and SEP's for all of the OP files are shown in table 2. The CEP's and SEP's were calculated based on the data contained in the table. The minutes shown are cumulative from file to file. The last position update is shown in the first file that it was performed. The CEP's and SEP's carry over from file to file depending on the last position update performed. Essentially, the data used to calculate the CEP's and SEP's were extracted from all of the files associated with one position update and were divided by the total amount of time that data were recorded in order to calculate the CEP's and SEP's. The CEP's ranged from 3.62 cm/hr to 28.16 cm/hr; the SEP's ranged from 10.18 cm/hr to 49.07 cm/hr over the entire series of tests. The mean of the CEP's was 13.1 cm/hr; the mean of the SEP's was 22.44 cm/hr. More data should be obtained in order to improve the confidence level of the results presented. The data in table 2 are shown in U.S. survey feet, but the results are presented in metric in order to be consistent with other users of the INS who do not use the NAD27 datum.

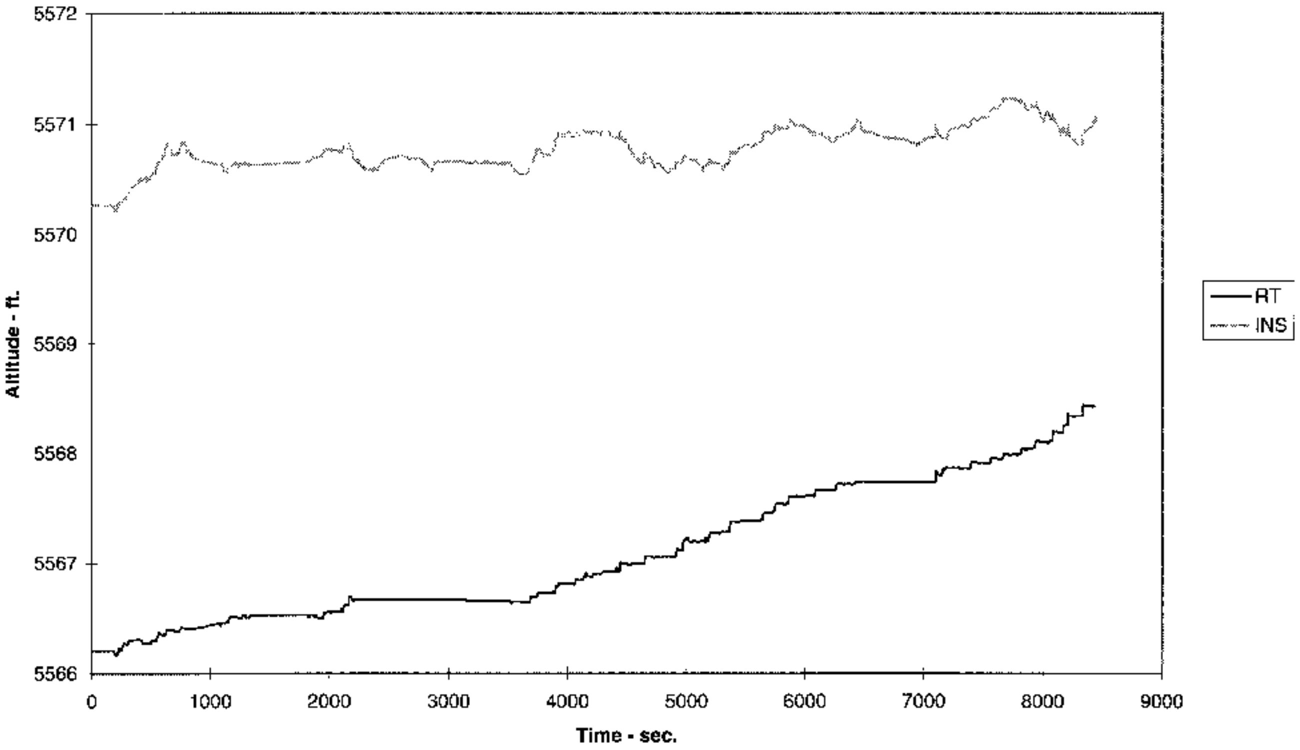

Figure 42.—RT and INS altitude file 09261449.pcu.

Table 2.—Data file summaries

File name	Time	Delta east sq	Delta north sq	Delta alt sq	Results
09120927.pcu Last position update 9:27	9:27 start 10:26 end (59 min)	162.9925 sum 692 blocks	42.6932 sum 692 blocks	218.696 sum 692 blocks	CEP = 0.432 ft/hr SEP = 0.665
09131309.pcu Last position update 13:09	13:09 start 15:22 end (133 min)	172.5297 sum 976 blocks	139.732 sum 976 blocks	715.761 sum 976 blocks	
09131522.pcu	15:22 start 16:37 end (208 min)	758.6947 sum 734 blocks	153.9687 sum 734 blocks	10600.6 sum 734 blocks	CEP = 0.119 ft/hr SEP = 0.334
09140933.pcu Last position update 9:33	9:33 start 14:14 end (281 min)	33830.48 sum 3169 blocks	6414.007 sum 3169 blocks	62467.1 sum 3169 blocks	CEP = 0.59 ft/hr SEP = 0.999
09261449.pcu Last position update 14:49	14:49 start 17:08 end (139 min)	519.4153 sum 1501 blocks	13973.84 sum 1501 blocks	20264.5 sum 1501 blocks	CEP = 0.924 ft/hr SEP = 1.61
09130928.sgu Last position update 9:27	9:26 start 10:28 end (62 min)	119.0189 sum 665 blocks	31.26214 sum 665 blocks	11.1372 sum 665 blocks	CEP = 0.376 ft/hr SEP = 0.394
09131307.sgu Last position update 13:09	13:06 start 13:55 end (49 min)	119.568 sum 538 blocks	25.99194 sum 538 blocks	89.39 sum 538 blocks	
09131450.sgu	14:49 start 15:25 end (85 min)	357.0373 sum 412 blocks	186.7908 sum 412 blocks	577.26 sum 412 blocks	
09131525.sgu	15:25 start 15:46 end (106 min)	279.9923 sum 220 blocks	73.30422 sum 220 blocks	868.867 sum 220 blocks	
09131600.sgu	15:58 start 17:12 end (180 min)	759.8401 sum 816 blocks	80.34661 sum 816 blocks	16894.0 sum 816 blocks	CEP = 0.139 ft/hr SEP = 0.416

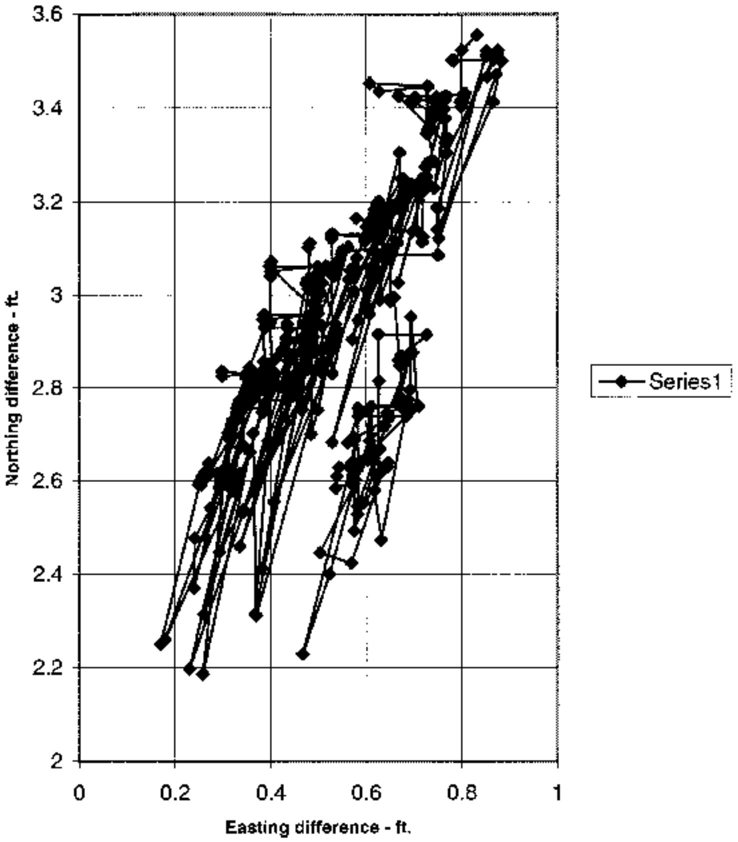

Figure 43.—RT and INS northing and easting difference file 09261449.pcu.

SUMMARY

The Pittsburgh Research Center under the former U.S. Bureau of Mines developed technology that provides remote control and navigation of continuous mining machines to enhance the safety of U.S. underground coal mine workers. The control system was built in modular form so that it can be adapted to most coal mining machine applications using only the modules required for a particular mining scenario. The technology developed permits the operator to effectively work at distances up to 150 m from the hazardous coal production area (the face). The INS employed by the research team was tested in a variety of coal mining conditions; results indicate that it may provide adequate navigation of the CM while mining coal. However, additional testing using the same methods presented here is required to minimize the anomalies and improve the confidence level of the CEP presented (13.1 cm/hr) and the SEP presented (22.44 cm/hr). Final accuracies for CEP and SEP in the same range as the presented accuracies would indicate that the HORTA is a viable candidate for reasonably accurate CM navigation. This report has detailed the entire system, as well as all of the performance results.

ACKNOWLEDGMENTS

The team members and the responsibility of each are included here to acknowledge their contributions to the success of this project: Donna L. Anderson - data acquisition and display; John Elkin - Glenrock mine manager; Edward F. Fries - TRACKER software; Christopher C. Jobes, Ph.D. - RCS; Jon A. Hummer (Spacemark, Inc. (SMI)) - CM systems and operation; William H. Lewis - video systems and control trailer; Timothy J. Lutz - stacking conveyor and CM operation; Timothy J. Matty - CM systems and operation; Kenneth Perry - mine development administrator, Interwest Mining Co.; William H. Schiffbauer - INS, RT, control system, data acquisition, data analysis; Michael J. Schmid - Honeywell INS system representative; George H. Schnakenberg, Jr., Ph.D. - project manager, data analysis, spread sheets; Raymond W. Vereneck (SMI) - CM systems and operation; and Jeffrey H. Welsh - group supervisor.

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APPENDIX A.—IN-DEPTH DESCRIPTION OF THE REFERENCE COORDINATE SYSTEM

Coordinate systems are the means of referencing geographic information to locations on the Earth's surface and are the reference to standard models of the Earth's surface represented by an oblate spheroid of revolution (a flattened sphere). The equatorial diameter (the major axis) of the Earth is approximately 27 miles greater than the polar diameter (minor axis). Generally, the Earth is interchangeably referred to as a "spheroid" or an "ellipsoid."

The shape of any Earth datum, such as "sea level," is not a perfect spheroid due to variations in the strength and direction of gravity. This imperfect shape is called the geoid. The geoid is an equipotential surface, perpendicular to the direction of gravity at all points. The plumb line, or the vertical (defined by gravity), is affected by land masses and the density of crustal rock near the surface. This causes the surface of the geoid to undulate, with the physical effect of "bumps" or waviness. The geoid is therefore not a mathematical surface like a spheroid.

The geoid shape has been determined by astrogeodetic and gravimetric methods. The equipotential surface is determined by a least squares fit of the observed data. Its position is unknown exactly because the data are not continuous. There can be local anomalies between observation stations causing deviations from what the best fit indicates.

For all except geodetic-related work, the geoid and the spheroid have been considered to coincide and are simply called "sea level" by most surveyors. The differences are not important for local surveys where high accuracy may be of little concern, but in high-accuracy surveys, the differences cannot be ignored.

The position of a point on any spheroid used to describe the Earth is represented by latitude and longitude, which are angular coordinates. Latitude is the angle from the equatorial plane to the point measured along a meridian line. Latitudes can be either north or south of the equator. Longitude of a point is the angle measured east or west of a 0° reference meridian plane to a meridian plane through the point. The reference meridian is called the "prime meridian" and passes through Greenwich, U.K. In surveying, geodetic positions vary according to which spheroid is being used at a particular place and point in time, and this must be considered when comparing values of spherical coordinates.

There have been at least 14 different ellipsoids used to approximate the oblate spheroid best representing the size and shape of the geoid called Earth. The Clarke Spheroid of 1866 endured in the United States from 1866 to 1986. Honeywell chose to use that model for the INS system discussed in this report. There are, however, more recent ellipsoids. The Clarke's 1866 spheroid datum for the United States is known as the North American Datum of 1927 (NAD27). The dimensions of the Clarke's 1866 spheroid for the United States is well defined, but that is not the case for the entire Earth.

The INS used by us employs the State Plane Coordinate System (SPCS) called NAD27 [Buckner 1993]. This was chosen because most U.S. underground coal mine maps conform to NAD27. More accurate systems (e.g., WGS84), however, were referenced to determine the basic accuracy of the INS. The NAD27 system was established in the late 1920's for use in the United States and was based on the astronomic location of an origin station called Meades Ranch located in Kansas. Meades Ranch, along with an azimuth to a nearby station called Waldo, became the origin for geodetic coordinates in the United States. The datum was chosen to "best fit" the figure of the Earth in the continental United States (as best as could be done at the time). This position was propagated throughout the network primarily by triangulation and later by trilateration. Triangulation consisted of a series of triangles or quadrilaterals in which all angles were measured, and base lines (a surveyed line established with more than usual care to which surveys are referred for coordination and correlation) were measured at given intervals to provide scale control. In addition, astronomic observations were made at certain stations (Laplace stations, which compensate for the difference between astronomic and geodetic azimuth) to control the tendency of the network to swing. Trilateration, which became feasible with the advent of EDMI's, consists of measurements of both angles and distances in a polygon, or often a chain of lines that formed a traverse (a method of surveying in which lengths and directions of lines between points on the Earth are obtained by or from field measurements and used in determining the positions of the points). The inclusion of space-based methods of measurements (first using stellar cameras, then Doppler, and later GPS), along with the possibility of directly measuring lines tens to hundreds of kilometers long with EDMI's, led to the discovery of distortions in the existing network, which had been built up piecemeal over decades. This led NGS to undertake a total readjustment of the interconnected network that covered North America and Central America as far south as Panama. The result was the development of a reference system that best fit the world as a whole and that has its origin at the center of the Earth. This is the Geodetic Reference System of 1980 (GRS80), which is nearly identical to the satellite system, World Geodetic System of 1984 (WGS84). The readjustment was completed in 1988. This new datum is known as the North American Datum of 1983, 1986 adjustment (NAD83), and has an absolute accuracy of about 1 m across the country, with relative accuracies of about 3 ppm. Since then, high-precision GPS methods have been used to establish a network of accurate (0.1 to 1 ppm) stations known as HARN. These HARN stations result in a homogenous network with absolute accuracies of about 0.1 m. The difference between NAD27 and NAD83 varies all over the country. In the area in Wyoming, where our test was run, the difference is about 44 m. NAD27, NAD83, GRS80, WGS84, and HARN have been discussed here because these systems were used to set up the local CP's used at the Wyoming site.

Simply put, the SPCS NAD27 provides a means to use plane surveying methods on a spherical Earth. NAD27 provided means, through mathematical projections, for precise conversion of latitudes and longitudes into X and Y (cartesian) coordinates, referred to assigned origins in each State. Each State also has enacted legal statutes adopting a mathematical definition and zone. Some States have multiple zones. The zones for all States are given four-digit codes for unique identification. The zones are called projections, of which there are three types: Lambert, Transverse Mercator, and Oblique Mercator. The Lambert system is usually used for states whose long dimension is east-west direction; the Transverse Mercator system is used for States that lie north-south. The only state using Oblique Mercator is Alaska. The site of the OP experiments resides in Wyoming SPCS East Zone 4901; it is based on a Transverse Mercator projection.

NAD27 is specified in U.S. survey feet, not in meters. Therefore, the author was forced to keep most of the analysis data and results in feet rather than meters for uniformity. For comparison purposes, there are 3.280833333 ft/m for the U.S. survey foot. There is also an International survey foot; it is 3.280839895 ft/m.

Until very recently, elevations were referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) which, prior to 1973, was known as the Sea Level Datum of 1929. Its origin is the observed heights of mean sea level at 26 tide gauges, 21 in the United States and 5 in Canada. Because mean sea level is not constant over time, the name for the datum was not correct. The datum is not mean sea level, the geoid, or any other equipotential surface. As with the Horizontal Network, the Vertical Network developed distortions over time and crustal motion occurrences affected much of the networks. This led to the decision to tune the network, and the North American Vertical Datum of 1988 (NAVD88) came into being. For this datum, the height of the primary tidal benchmark at Father Point/Rimouski, Quebec, Canada, was held as the fixed constraint. The mark is located at the mouth of the St. Lawrence River. The research team used NGVD29 as its reference for the INS.

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