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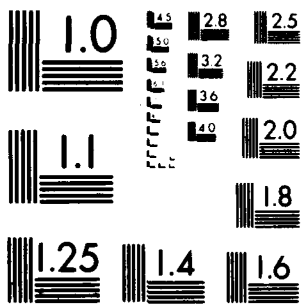

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Inertial Surveying is the process of ascertaining position and gravity field parameters from measured accelerations. Typically, the observer traverses the survey course in a vehicle such as a van or helicopter and operates instrumentation which records the vehicle's acceleration history as the survey proceeds. The instrumentation, similar to that used for inertial navigation, consists of very accurate and precise accelerometers, gyros, data (cont'd)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) recording equipment, a computer, and support electronics. The gyros provide a precise reference frame for the acceleration measurements. The computer integrates the acceleration measurements into velocity and position data to provide a real-time display during the traverse and stores information for later post-survey processing (smoothing).

The general theory, operations, system description and results will be presented.

INERTIAL SURVEYING TECHNOLOGY

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INERTIAL SURVEYING TECHNOLOGY

1. INTRODUCTION

Inertial Surveying is the process of ascertaining position and gravity field parameters from measured accelerations. Typically, the observer traverses the survey course in a vehicle such as a van or helicopter and operates instrumentation which records the vehicle's acceleration history as the survey proceeds. The instrumentation, similar to that used for inertial navigation, consists of very accurate and precise accelerometers, gyros to provide a precise reference frame for the acceleration measurements, data recording equipment, a computer and support electronics. The computer integrates the acceleration measurements into velocity and position data to provide a real-time display during the traverse and stores information for later post-survey processing (smoothing).

Post-mission smoothing removes systematic errors which accumulate during the survey and, when gravity field parameters are sought, separates anomalous gravity field acceleration from estimates of inertial system instrument (e.g., gyro and accelerometer) errors. State-of-the-art accuracies for such systems over 40 km distances are of the order of 40 cm for position (Ref. 1) 0.9 mgal for the gravity anomaly and 0.7 arcseconds for vertical deflection (Ref. 2)*.

*This level of anomaly and deflection recovery is not typical. It represents the best accuracy obtained using special survey procedures (discussed later). "Usual" gravity disturbance measurement accuracy is given in Section 3.

The key motivator for inertial surveying is productivity. One recent evaluation (Ref. 1) considered a project which involved 3,200 stations and 22,400 km of traverses. After the work was completed using an inertial survey system, (vs conventional position determination) it was estimated that 24 manyears had been saved.

2. GENERAL THEORY

A simplified description of an inertial survey system is presented in Fig. 2-1. Because the integration process continues over the entire time of the survey, error sources, if uncontrolled, will cause position error to increase rapidly to unacceptable levels.

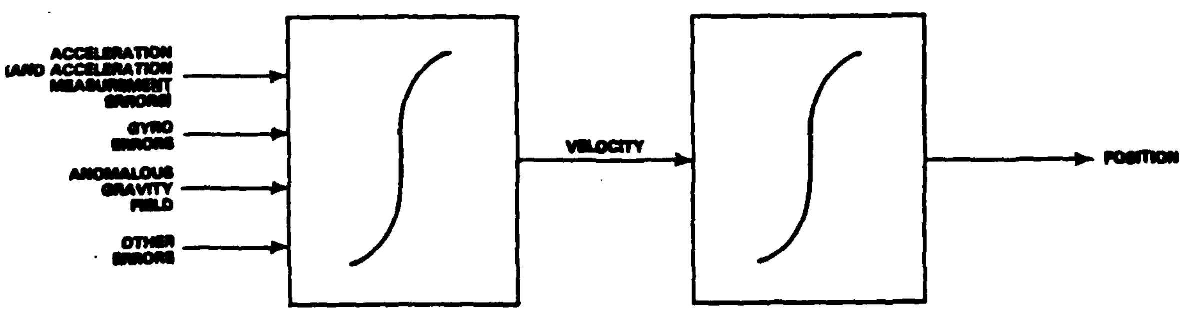

Figure 2-1

The method used to control these errors is to stop the vehicle frequently during the traverse. When the vehicle is stopped the inertial system should indicate zero velocity. Any departure from zero is a direct measure of errors driving the system. The sequence of velocity error measurements obtained in the course of the traverse provides the basis for accurate estimates of system error sources.

The process of halting the vehicle and recording the difference between indicated velocity and true (zero) velocity is referred to as a zero velocity update (ZUPT). The ZUPT concept is illustrated in Fig. 2-2. Frequent ZUPTs are an essential part of state-of-the-art inertial surveys. In their absence position errors would increase to hundreds of meters.

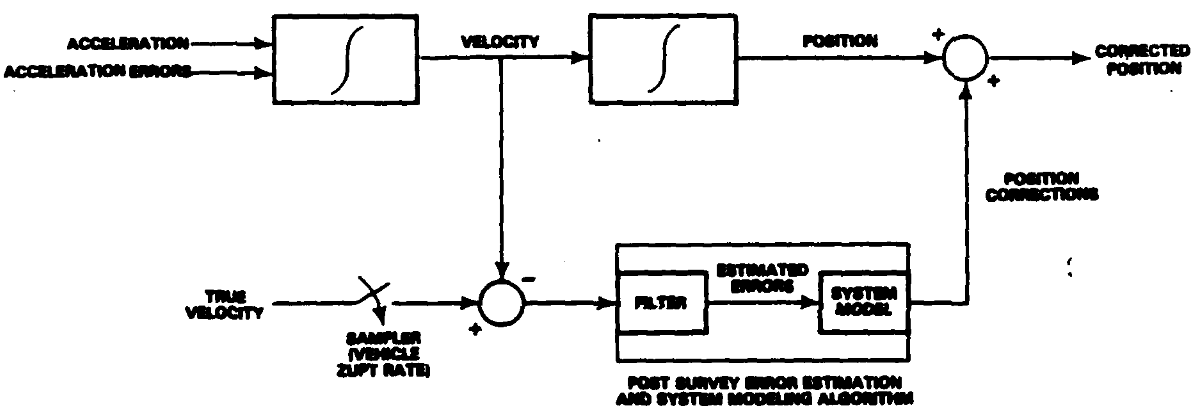

Figure 2-2

3. HISTORICAL DEVELOPMENT

While inertial technology is comparatively new, the adaptation of this technology to geodetic problems is newer still. The concept of a geodetic inertial system materialized with the experimental development at the U.S. Army Engineer Topographic Laboratories (USAETL) of the Position and Azimuth Determining System* (PADS) for use in artillery surveys. During that developmental program, open traverses of 200 km were being measured routinely with three-dimensional accuracies of ±10m to ±15m.

Since these sensors respond to the combined acceleration vector produced by the vehicle and the gravitational field, the surveying results suggested that the Kalman filter was separating these forces to the degree that gravity and deflection information (to some modest accuracy) could be extracted from that system. This idea was quickly field-tested, and the results were consistent with the performance expectations of that system. In a field with gravity excursions of 80-mgal and 14 arcsecond deflections, the gravity determinations compared within ±3 mgals of the actual values, and the deflections showed an agreement of 3 arcseconds. Following these tests, various simulations were conducted based on more sensitive, but available sensors with the outcome that in 1973 a total geodetic system development was started at USAETL.

Following this, hardware and software modifications were mde to PADS to upgrade it for geodetic determinations. Recent capabilities for a three-hour mission (a traverse of

*This development saw the first successful implementation of the ZUPT concept by James Huddle and Hal Banbrook of Litton as part of the Kalman Filter based software.

about 75 km) are approximately 50 cm in latitude and longitude and 30-40 cm in height. Gravity and deflection determinations are accurate to 2 mgals and 1.5 arcseconds, respectively.

Users of the system in a helicopter mode like the Geodetic Survey of Canada are achieving comparable horizontal position accuracies and slightly less accuracy vertically (because of rapid vertical excursions of the helicopter). The mission distances by helicopter are appreciably greater. Typically, they range from 150 to 200 km.

In addition to the Litton-developed system described above, marketed commercially under the trade name Autosurveyor, the late seventies also saw development of inertial survey systems by Ferranti, Honeywell and Singer. The Ferranti system (known as the Ferranti Inertial Land Surveyor or FILS) and Honeywell System (called the Inertial Positioning System Number Two or IPS-2) involve the use of an inertially stabilized platform with accelerometers. Strictly speaking, the Singer Land Navigation (ANS 2000) System is not inertial since, instead of using accelerometers, it measures velocity via a pickoff from the vehicle's odometer. However it uses gyros to establish an inertial coordinate reference and provides "dead reckoning" position information of sufficient accuracy to merit attention.

Several Ferranti units are currently in operation. So far Honeywell has manufactured a single prototype but has others under construction. The Singer equipment is intended as a low cost alternative where less accuracy (20m over 10km) is satisfactory.

4. INERTIAL SURVEY METHODS/OPERATIONS

An Inertial Survey Traverse is illustrated Schematically in Fig. 4-1. Helicopter survey operation is similar, except that the velocities and traverse distances are greater.

A typical traverse is begun with system calibration and initialization performed at the starting point. Frequent practice is to establish temperature stabilization by running the system for an hour or more prior to calibration. Following initialization by inserting the starting point coordinates and

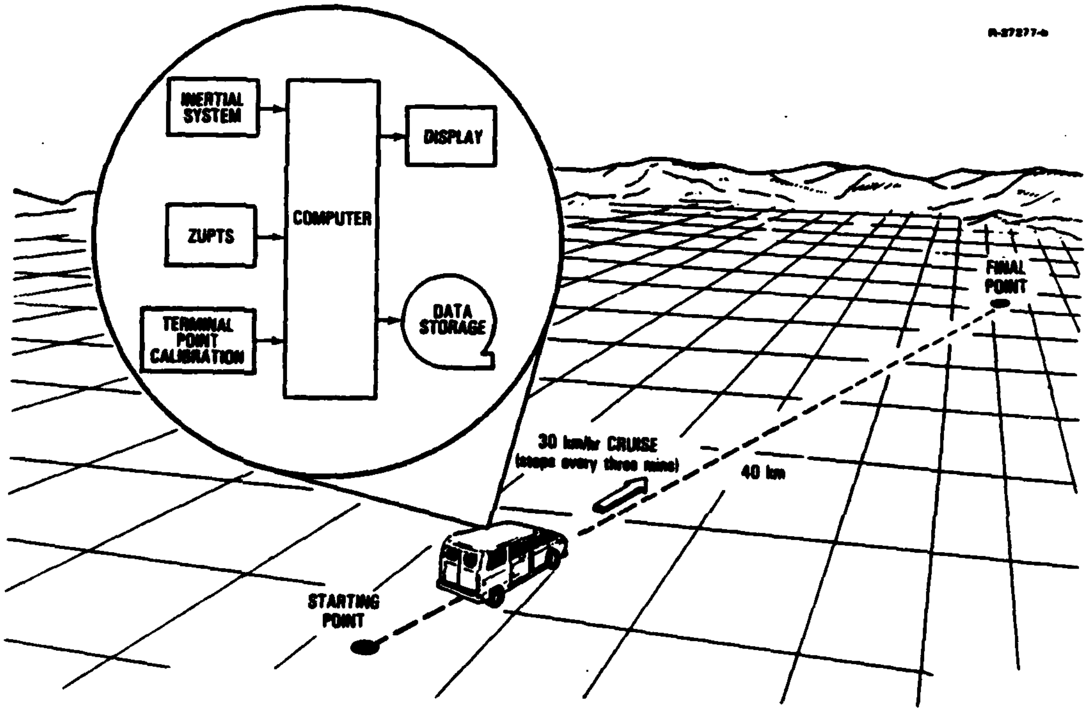

Figure 4-1

elevation, the traverse is run. After completing the traverse, the recorded data (position, velocities, ZUPTs, calibration parameters, initial and final traverse point coordinates) are processed to recover the survey quantities. In many applications where the traverse segment is part of an overall survey net, additional post-processing which takes advantage of net ties is used to reduce errors further and to strengthen the results. Inertial survey data processing is similar to conventional survey network procedures in this regard.

Over the last few years, a number of additions and refinements to inertial survey procedures have been incorporated both experimentally on a production basis. Examples include repeating each traverse in the opposite direction, performing multiple traverses, establishing position "Mark" points for multiple repeat traverse adjustments (Ref. 5) and controlling azimuth sensitivity. Azimuth sensitivity, which results from environmental factors (e.g., temperature, vibration, magnetic fields) affecting the inertial components differently as the host vehicle's heading changes, becomes a problem on traverses which depart markedly from straight lines. Survey geometries which involve "L" or "V" shapes are particularly severe. Operating procedures designed to reduce azimuth effects include recalibrating at corners and physically rotating the inertial system "box" to maintain near-constant spatial relationships among internal gimbal structures.

An approach used successfully to control vibration-induced errors in helicopter surveys involves reducing the noise experienced by the inertial system during ZUPTS. This is accomplished by physically removing the inertial system instrument assembly (while still operating via a long cable) from the aircraft and placing it on the ground (Ref. 2). In this quiescent environment the ZUPT is performed. The inertial assembly is then replaced in the helicopter and the traverse proceeds.

In addition to the special operational procedures described above, experienced field operators make appropriate allowances for the sensitive nature of the inertial equipment. Driving (or flying) is done as gently as possible; jolts are avoided; special attention is given to data entries and work shifts are adjusted to complete each scheduled traverse before powering down the equipment. The latter can involve work days of eleven hours or more (Ref. 6).

5. INERTIAL SURVEY SYSTEMS

A summary of currently available inertial survey systems, their size, weight and costs based on manufacturer-supplied data, is presented in Table 5-1. The accuracies given in the table correspond to single, irregularly-shaped traverses, post-mission data smoothing and no special efforts to control azimuth sensitivity. For this reason the performance levels indicated in the table are not the same as the "state-of-the-art" figures provided in the introduction.

6. DATA ADJUSTMENT TECHNIQUES

Choice of inertial survey data smoothing algorithms and survey adjustment procedures is an area of very active current research. Although some work is still done with simple removal of bias, trend, quadratic etc. (to force consistency on the measured data), most practitioners employ considerably more mathematically sophisticated error estimation tools. The algorithms often take into account the dynamical

TABLE 5-1
CURRENTLY AVAILABLE INERTIAL SURVEY SYSTEMS

MANUFACTURER AND MODEL(S)	APPROXIMATE COST	SIZE* (m^3)	WEIGHT* (kg)	POSITION ACCURACY (m)	VERTICAL DEFLECTION ACCURACY ($\widehat{sec}$)	GRAVITY ANOMALY ACCURACY (mgal)
LITTON AUTOSURVEYER	$485K	0.071	150	0.4† (Ref.7)	2† (Ref.7)	1.5† (Ref.7)
HONEYWELL GEO-SPIN (IPS-2)	$625K - 800K‡‡	0.191‡‡	141‡‡	0.6# (Ref.8)	4# (Ref.8)	10# (Ref.8)
FERRANTI INERTIAL LAND SURVEYOR (FILS)	$700K‡	0.075**	80**	~1.0† (Ref.9)	----	----
SINGER LAND NAVIGATION SYSTEM (ANS 2000)	$30K - 40K##	0.024	14	~1.0†† (Ref.10)	----	----

*TOTAL OF ALL COMPONENTS

†40km TRAVERSE, 3-5 min ZUPTS

#65 km TRAVERSE, 4 min ZUPTS

‡EXCLUDING REQUIRED POST PROCESSOR ($100K)

**EXCLUSIVE OF PANEL

††32km TRAVERSE, NO ZUPTS

##FOR PLANNED PRODUCTION VERSION

‡‡EXCLUDING OPTICAL MEASUREMENT UNIT

--NO GRAVITY OR DEFLECTION RECOVERY CAPABILITY behavior of inertial system errors, the statistical nature of the anomalous gravity field, the uncertainty in gyro and accelerometer outputs and the heterogeneous nature of the measured quantities. Data reduction and adjustment methodologies which have been examined or are undergoing current consideration include: Kalman Filtering/Smoothing, Finite Element Analytic Analysis, Spline Function Interpolation, Space Domain Collocation, Wiener Smoothing, Karhunen-Loeve Expansion and Maximum Likelihood Estimation. To date the most popular algorithms have been Kalman Filter based. For example, software provided with the Litton Autosurveyor is based on a reduced-order Kalman Smoother. A Kalman-type program has also been developed for the Ferranti System (Ref. 11). However the increasing need to handle many traverses and arbitrary geometries may supplement or supplant the Kalman filter algorithms which require theoretical extensions to adequately treat area problems. Optimal network adjustments will require mathematical procedures which are designed to account for initial prefiltering and individual traverse data reduction operations.

7. IMPROVEMENTS IN CURRENT SYSTEMS

The software and operational advances discussed earlier are resulting in ongoing accuracy improvements and increased inertial survey productivity. Much progress has been made in the last four years as chronicled in Refs. 12 and 13. The future will continue to see advances in the data processing and procedural areas.

Hardware developments, as in the past, continue to be directed toward upgrading the inertial system sensors. Litton has proposed further improvements to the Autosurveyor by additional special gyro selection procedures intended to further reduce noise and calibration parameter uncertainty.

The Honeywell GEO-SPIN* System, a new application of highly accurate military inertial navigation technology, possesses gyros very close to the modern state of the art. Early testing has demonstrated certain hardware problems (Ref. 8) which, after correction, should allow the GEO-SPIN System to take full advantage of its technology. Inertial sensor improvements in the Ferranti system are also being examined.

The interest in gyro improvements is motivated by two considerations. One is to increase productivity by lengthening the interval between ZUPTS. By reducing the errors (especially gyro errors) that the ZUPTS are meant to control, the ZUPT data spacing can be relaxed.

The second reason for better gyros results from increasing needs for high accuracy gravity quantity surveys. If a traverse regime involving frequent ZUPTS (e.g, 3-5 minutes) is employed, improvement in both position and vertical deflection accuracy is gained. This is illustrated in Fig. 7-1 for a 64 km survey with four minute ZUPTS. Figure 7-2 presents the corresponding improvements in vertical deflection recovery. Note the significant effect of a more accurate gyro. Improvements are most pronounced in the center of the traverse where the system is farthest (in both space and time) from its calibration points.

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*DMA operates a GEO-SPIN system. It is known as IPS-2.

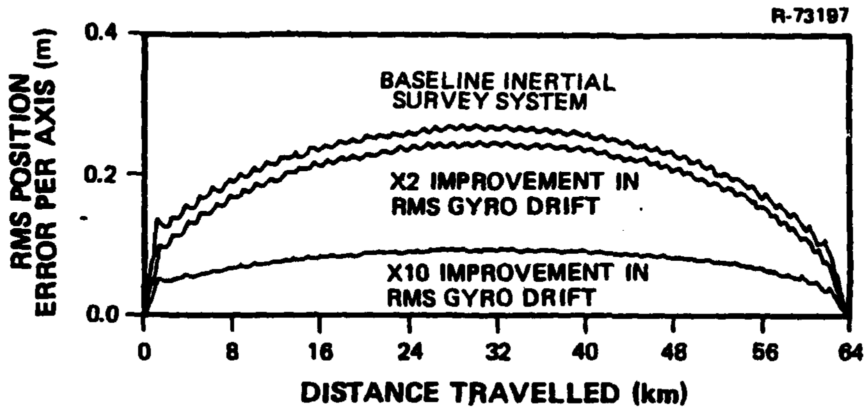

Figure 7-1

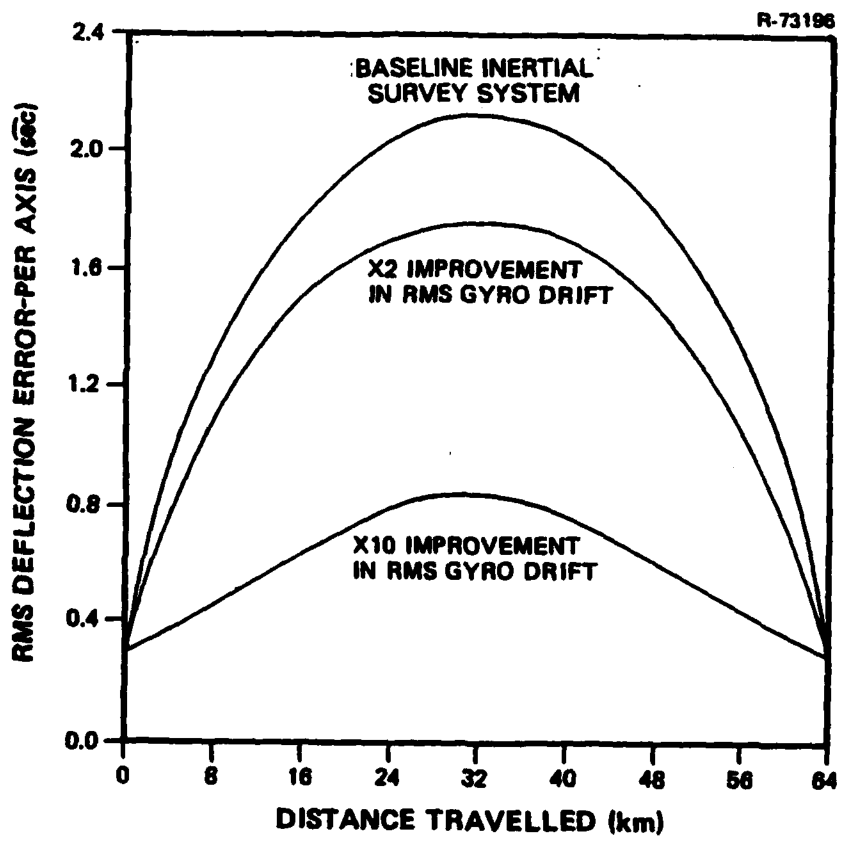

Figure 7-2

8. GRAVITY GRADIOMETER

The same motivations which encourage improvement of inertial survey system sensors also invite consideration of other sources of information which can be used to enhance the quality of measured variables or provide additional knowledge about error sources. One such instrument which possesses the potential to isolate survey errors induced by the anomalous gravity field is the moving-base gravity gradiometer.

The gradiometer, which measures the spatial derivatives of the gravity field, is conceived to operate with the inertial survey system in an augmenting role (Ref. 14). The essence of the combination is that the gravity signal provided by the gradiometer allows the inertial system's error identification algorithms to more effectively use the ZUPT data to identify non-gravity errors (e.g., gyro and accelerometer noise). As a result, there is a synergistic reduction of all sources of survey inaccuracy. For this reason the Defense Mapping Agency is pursuing a test program involving the mechanization of a combined inertial/gravity gradiometer survey system.

9. SUMMARY

Inertial survey systems have developed, within the last ten years, into a geodesist's tool which can achieve first order accuracies and operate with unprecedented productivity. They have evolved from providing only position and azimuth data to a capability for gleaning gravity data as well. The position determination portion of this technology is relatively mature. As a result, the thrust of future growth is likely to be directed toward operating refinements rather than improving the sub-meter accuracies already enjoyed.

Inertial gravity field surveys are another matter. This is a young technology which is advancing quickly across the fronts of hardware progress, operating refinements and data reduction improvement. If the past and present are guides, the next few years will see wider use of inertial survey systems working in the gravity field measurement mode.

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