

INERTIAL SURVEY SYSTEM (ISS)

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ABSTRACT

In April 1979, the National Geodetic Survey used an inertial survey system (ISS) to establish second-order horizontal control along the Louisiana Gulf Coast in support of hydrography. The ISS, successfully installed in a NOAA Bell 204 helicopter, established or checked the position of 106 stations along the coast in 6 days.

This paper will discuss inertial technology, operational scenarios, various operational limitations, and how the inertial system was and could be utilized to support hydrographic operations.

INTRODUCTION

Development of inertial platform technology is relatively new. Its beginning can probably be traced to research done by Charles DRAPER of the Massachusetts Institute of Technology (MIT) as early as 1938, although the first real application can be traced to the German V-2 Rocket Program. After World War II, both the Instrumentation Laboratory of MIT under the direction of Charles DRAPER and the Redstone Arsenal under the direction of Dr. W. von BRAUN began intensive development work on more precise inertial navigation platforms. Unquestionably,

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high-precision systems have evolved from this early exploratory research. Inertial systems are indispensable to missile guidance, have safely taken explorers to the Moon, and are used daily throughout the world for the safe navigation of commercial aircraft.

DEFINITIONS OF TERMS

In order to understand the mechanics of an inertial survey system (ISS) a few basic definitions are presented first.

Inertia

Inertia is the tendency of a body (mass) to resist acceleration. Inertia is the tendency of a body at rest to remain at rest, or a body in motion at a constant velocity to remain at that velocity and travel in a straight line. Therefore, anytime a body at rest begins to move, or a body in motion deviates either in speed or direction from that motion, an acceleration has occurred.

Inertial Reference Frame

An inertial reference frame is any frame of reference to which the Newtonian law of motion, "force equals mass times acceleration" is valid.

Gyroscope

A gyroscope is a rapidly spinning body (mass) having one to three axes of angular freedom. The spin axis itself provides one degree of freedom for the spinning mass. The remaining degrees of freedom are provided by the axes of the supporting gimbals. A gyroscope of three degrees of freedom allows the spin axis to be oriented in any direction. The spin axis in a three degree of freedom gyroscope will maintain a particular orientation even though the entire gimbaled system is put into motion. The gyroscope spin axis thereby acts according to inertia and can be used to provide a fixed reference system relative to some beginning known orientation. Gyro compasses are special purpose gyroscopes in that their spin axis becomes aligned with the rotational axis of the Earth. The Earth-related orientation produced by a gyrocompass is dependent on the phenomena of precession, gravity, and Earth rotation in conjunction with gyroscopic motion.

To mechanize a stable reference frame, gyroscopes of one-three degrees of freedom, gyroscopes of two-two degrees of freedom, or gyroscopes of three-one degrees of freedom are necessary. Single gyroscope systems tend to be the least stable and are subject to more random drift errors. Three-one degree of freedom gyroscopes are most stable but hardest to mechanize because of production tole-

rances and space limitations. Two-two degree of freedom gyroscope systems are a happy medium, although one axis will be redundant. This feature is not entirely desirable due to the correlations which develop between certain corrections during processing.

The reference system generated may be space oriented or Earth related. The space-oriented reference frame is one in which the initial orientation of the ISS is not important so long as its relation to an Earth coordinate system is determinable at the beginning of survey operations. An Earth-related reference system can be obtained directly by using gyrocompasses in lieu of gyroscopes. In this latter system the reference frame will be automatically oriented north and normal to the geoid (vertical). The duplicated coordinate axis is normally the vertical axis, because its orientation is most sensitive to motion and position on the Earth's surface.

Accelerometer

An accelerometer is an electro-mechanical device for measuring accelerations acting upon the inertial platform. A single degree of freedom accelerometer is normally composed of a tube with a highly machined steel ball inside, which can move with little or no rolling friction. The ball is mechanically restrained in the center of the tube by being sandwiched between two steel springs. The compression of one spring and simultaneous expansion of the other can be used to measure acceleration. That is, if the ball is governed by inertia, it would normally remain at rest within the tube unless acted upon by some external acceleration. Since springs have a very small compression range in which they deform in a linear manner the ball is also kept in the center of the run with the aid of an electromagnetic force as well as the spring tension. The amount of current supplied to the electromagnet necessary to keep the ball from moving is a function of the acceleration. If one knows the acceleration of a body then the double integration of acceleration with respect to a given amount of time yields the distance a body travels in that amount of time.

Inertial Platform

An inertial platform is a unique sensor used for position and velocity determinations of a moving vehicle from measurements of the vehicle's accelerations. The basic components of the platform are its accelerometers for measuring the total acceleration, the gyroscopes for mechanizing a coordinate system, and an on-time digital computer for real-time processing and control of the system. Some platforms are two-dimensional devices, such as the shipboard systems where elevation is known, and some are three-dimensional sensors analogous to missiles and geodetic use.

Physically speaking, the inertial platform is a flat plate oriented into a coordinate system by a pair of gyroscopes with three single degree of freedom accelerometers aligned along the coordinate system's axes. The ISS designed by Litton Industries orients the plate carrying the accelerometers into an Earth-

related coordinate system; i.e., latitude, longitude, and elevation, by using two-degree of freedom gyrocompasses having a redundant vertical axis and one axis each orientated north and east. The plate carries the accelerometers such that there is one accelerometer oriented north, east, and vertical. The accelerometers, therefore, sense all accelerations in their north, east, and vertical components. The integration period is 16 milliseconds; therefore every 16 milliseconds a change in latitude, longitude, and elevation is measured. If we know where the system was located at a given point in time, we can transport it to some new location and by summing all the increments of latitude, longitude, and elevation, and assuming no error during transit, we will know the location of the new point.

SYSTEM ACCURACY

From a surveying accuracy viewpoint, inertial systems can be classified into three categories: low, moderate, and high precision. These categories and typical parameter measurement accuracies for the four items of interest to the surveyor are shown in table 1. Note that an inertial system not only yields position but also elevation, gravity, and deflection of the vertical (difference between the gravity normal and astronomic normal).

Achievement of these accuracies is a function of both inertial system precision (including both hardware and software capabilities) and survey mission scenario.

Results from the Louisiana Traverse Task Number 83621178 are within the High Precision category of table 1.

TABLE 1
Inertial Survey System accuracy

Inertial survey system precision class	Position control (1σ)		Gravity measurement error (1σ)	
	Horizontal (m)	Vertical (m)	Anomaly (milligals)	Vertical deflection (Arc-seconds, north & east)
Low	> 3	> 3	> 5	> 5
Moderate	1 to 3	1 to 3	2 to 5	> 1.5 to 5
High	< 0.5	< 0.5	< 2	< 1.5

ISS SURVEY SCENARIO

At the outset of the mission, the system is allowed 30 to 50 minutes to sense the local vertical, to orient itself automatically to astronomic north, and to perform an on-site calibration. Here the system's accelerometer signal, the drift of

the axes, and so on, are monitored to detect the degree of platform change from an actual static state. These estimates are then used in the software component of the system as a model to predict the performance of the platform during the survey.

As the vehicle begins to move, accelerations relative to the initial orientation are doubly integrated into geodetic position changes. This is done every 16-milliseconds and, almost instantly, the axes of the platform are rotated to conform with the corresponding spheroid orientation of the new site. This process is repeated continuously at 16-millisecond intervals until there is a need to update the platform errors. To achieve the update, the vehicle is brought to a complete stop for 30 seconds and allowed to seek the local vertical again. Because the navigation was performed on the spheroid, the angular change of the platform axes required to bring it to the local vertical represent the magnitude of the deflection from the vertical. Also, any residual velocity exhibited by the system in this "zero velocity" state is used to update platform errors. These "stop" operations continue until the system reaches the first station of the traverse and, eventually, the last. The gravity measurement is obtained from the system by recording the vertical accelerometer output at each stop, after the system has reoriented itself to the local vertical. With the systems currently available, the velocity updating process is repeated every 3 to 5 minutes. Since the system obtains its starting coordinates from some known point and computes its accumulated errors by completing a traverse on another known point, all those points established between the known points are actually obtained by the process of interpolation.

Traverses should be run twice, with one running in each direction of the traverse. Closed loop traverses are not acceptable, because the solution of system errors is not determinable from only one known control point.

SURVEY APPLICATIONS

Inertial survey systems are very useful for establishing second- and third-order horizontal control. The system is capable of establishing control at speeds which are only limited to that of the transporting vehicle. On-line processing of data assists the pilot in navigating between control points, thereby maximizing survey time by minimizing transit time. Some unique survey applications of the system will now be discussed.

1. Recover and check control. The unique ability of the inertial system to navigate to a point whose coordinates are known permits economical recovery and checking of existing control. Search time at the site should be kept to a minimum and is economically controlled by the cost of return for further search without the inertial system and the probability of a successful recovery balanced against the need for the control. This is usually the first phase in a large project and normally takes 5 to 10 minutes per point (\$40-\$80).

In the Louisiana Coastal Traverse, three stations were considered "Most Likely Destroyed" during the last 20 years but were found within 5 minutes of

landing at the station sites. Six other stations were positively confirmed as destroyed using the system (one station would be directly under the foundation of a house, four lie out in the Gulf of Mexico, and one in the middle of a manmade channel).

2. **Densification.** Horizontal control can be established as a portion of the project or as an end in itself. The use of established geodetic control or Doppler satellites for the basic control from which the ISS established secondary control has been extremely successful. In Louisiana, eight previously established stations were used to control the inertial system, which in turn established or checked the position of 72 other control points.

In a future project, being planned for the St. Marys River, seven horizontal control points would be established by Doppler Translocation (Short Arc Method) which, in turn, will be used by the ISS to establish approximately 120 new control points (including most fixed aids to navigation).

Another future project would utilize an inertial system within a framework of first-order geodetic control. The ISS would traverse both N-S and E-W through all new control points. This new procedure will hopefully improve the survey precision to better than 1:50 000.

3. **Aerial photo control** has been a major use of the system. The sparse spacing of the points and the requirement that they lay within the overlap exploit several advantages of the inertial system. Provided the project size is adequate, no other survey system can compete economically in this field. Maximum savings are dependent upon early planning, but costs have averaged one-half to two-thirds of conventional surveying. In featureless terrain, panels should be set and positioned at the same time using the ISS prior to taking the photos, whereas on many projects with identifiable features, photos may be flown when conditions are ideal and establishment of coordinates on photo-identifiable points accomplished later.

During the first 15 months of ISS operation in Canada, 1908 second-order stations were positioned for mapping control.

4. The NOS could most effectively use an ISS for establishing hydrographic control. The ISS can establish Third-Order, Class I control to a density of one station per 3 kilometers (km). The control is independent of line of sight or strength of figure. This means the control is put exactly where it is needed without any need for further breakdown. With the proper planning, the locations of all electronic navigation sites, fixed aids to navigation, landmarks for charts, and calibration points may be established in one survey. The system can establish the control in a very short period of time (approximately 20 stations/day). The system is capable of working in any weather conditions and is limited only by the operational limits of the transporting vehicle. Any conventional four-wheel drive, half-ton truck, 1000-pound payload helicopter, or any of various all-terrain vehicles may transport the system so long as the vehicle is capable of coming to a stable zero velocity stop. The system can be easily air freighted to remote locations and then installed in a vehicle near the survey area. One ISS could support all NOS requirements for hydrographic and coastal mapping control.

LOUISIANA COAST INERTIAL SURVEY

The Coastal Louisiana Traverse performed at the request of the Office of Marine Surveys and Maps (MS&M) to provide second-order control at 7- to 10-km spacing was accomplished by a contract with Span International, Inc.

NGS Field Party G-18 set all the station marks and performed the necessary ground work in February 1979. Transportation for the ground work and eventual survey was supported by the NOAA Bell 204 E helicopter. The ISS was chosen because the terrain was totally unacceptable for classical work involving Bilby Towers.

On April 1, 1979, the inertial system was ready to begin survey operations. Six days later the entire survey comprising 106 stations was completed. Subsequent analysis had shown that all stations are within Second-Order, Class II specifications with 50 percent of the stations exceeding 1:50 000 or Second-Order, Class I specifications. The average station spacing was 7.1 km with a total traverse distance of 453 km (one way). The entire survey was performed at a cost of \$1300 per station.

NGS may need to perform a second-order control survey along the St. Marys River at the request of MS&M. As currently reconnoitered, the proposed classical survey establishing approximately 30 new stations will fulfil MS&M's requirements for 7- to 10-km station spacing. If, however, a combination Doppler-ISS survey was performed with the average station spacing reduced to 1 to 3 km, all hydrographic control requirements could be met, including the location of all fixed aids to navigation and landmarks for charts. The control could be placed over sufficient numbers of photo-identifiable points to allow photogrammetric compilation of the shoreline detail. The Doppler translocation of Short Arc Methods will establish sufficient control at a precision of 1:50 000 to control inertial surveys at precisions of both 1:20 000 and 1:10 000. Proposals are currently being sent to two companies. The inertial system would be carried in a hover craft from point to point. This mode of transportation would be unique. The Canadian Government has expressed interest in the project and offered their expertise in planning and processing of the data.

The purchase of an inertial system has become more attractive to NOS due to the recent introduction of the Honeywell Geo-Spin System. The combination of such an inertial system and the NOAA Bell 204 E helicopter would give NOS the ability to support control surveys within NGS, NOS, and NOAA. The system would also be used to support the U.S. Coast Guard's need to locate fixed aids to navigation along the east coast. The initial investment is great - \$500K to \$850K for the equipment plus \$50K per year for maintenance; however, this cost will be offset by a decrease in the cost per control point and in the number of costly delays often suffered by the hydrographic ships due to lack of control.