INERTIAL POSITIONING
PRINCIPLES AND PROCEDURES

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INERTIAL POSITIONING - PRINCIPLES AND PROCEDURES

by

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ABSTRACT

The principle of inertial surveying systems is outlined and its mechanizations are discussed. The different types of platforms including the basic functions of gyros and accelerometers are explained.

Special attention is paid to the disturbing forces and to the error budget of the instruments. Observation schemes and signal processing procedures for on-line filter and for post mission smoothing are presented.

ZUSAMMENFASSUNG

Das Prinzip inertialer Vermessungssysteme und seine Realisierung werden erläutert. Die unterschiedlichen Plattformen einschließlich der Funktionsweise von Kreiseln und Beschleunigungsmessern werden behandelt.

Besondere Aufmerksamkeit wird den Störkräften und dem Fehlerhaushalt der Instrument gewidmet. Beobachtungsverfahren und Signalverarbeitungsmethoden werden dargelegt.

1. INTRODUCTION

Inertial surveying systems (ISS) are modified versions of inertial navigation platforms. In the western world three companies manufacture such instruments which are available on the civil market.

Since 1974/75 the firm LITTON has been selling its Autosurveyor originally designed as the Position and Azimuth Determining System (PADS) for the Artillery of the United States Army. A short time later the British firm FERRANTI presented the Ferranti Inertial Land Surveyor (FILS), which was originally developed as the PADS for the British Army. The GEO-SPIN of the Avionics Division of HONEYWELL which came around 1980 is modified from the SPN/GEANS platform installed in the United States Air Force B-52 bombers.

From the beginning this entirely new principle of geodetic observation has found ample interest in the surveying community. The most attractive properties of ISS are the independence of a line of sight and of external sources of information, and the rapidity of performance. The accuracy ranges between 0.02 and 0.60 m standard deviation depending on the type of instrument, the observation procedure and the density of control points. The high cost between 0.5 and 1.2 million US $ for one ISS, however, makes the use only economical, when the surveying project is sufficiently large.

During the past 10 years this new surveying technology has been used extensively by governmental agencies in the USA and in Canada, and by a number of private companies, which operate in all parts of the world. The main field of application is the establishment of lower order control for cadastral and for mapping projects. The published reports claim that savings of about 50 % in cost and considerably savings in time are typical, so that the instruments pay for themselves within two years.

2. THE BASIC PRINCIPLE

Consider a mass point in space moving along a trajectory as depicted in Fig. 1. If the acceleration a of the point in respect to the coordinate system is measured continuously, then it is possible to compute the way by a double integration over the time.

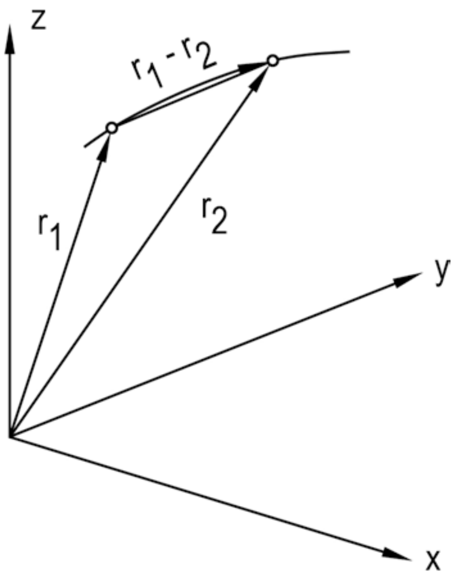

Fig. 1: Motion of a mass point in space

$$r_2 - r_1 = \iint_{t_1}^{t_2} a(t)\, dtdt$$

where the way is defined as the difference vector in the reference frame. Newton's laws of motion provide the basis for the mechanization of the basic idea. The second law gives the well-known relationship between an acting force F, a mass m and the acceleration a

$$F = m \cdot a$$

where the assumption is made that the observation refers to an inertial frame, i.e. a reference frame that is fixed in space.

3. INERTIAL PLATFORMS

In order to apply the basic principle for the fixing of positions on the earth, it is necessary to mechanize a measurement frame with known orientation in respect to an inertial reference frame. In this system three accelerometers can be used to measure the three components of acceleration. The realization of this idea is the so-called inertial platform. It is basically a stable element on which three mutually orthogonal accelerometers and three single-degree of freedom gyros (or two two-degrees of freedom gyros) are mounted. The platform is isolated from its case and from the host vehicle, on which it is being carried, by a system of three or four gimbals, see Fig. 2.

The gyros control the attitude of the platform in respect to the inertial reference frame, thus providing the rotational information needed to perform the transformation of the signals from the inertial frame to a geodetic coordinate system. The principle of a gimbal mounted two-degrees of freedom gyro is depicted in Fig. 3.

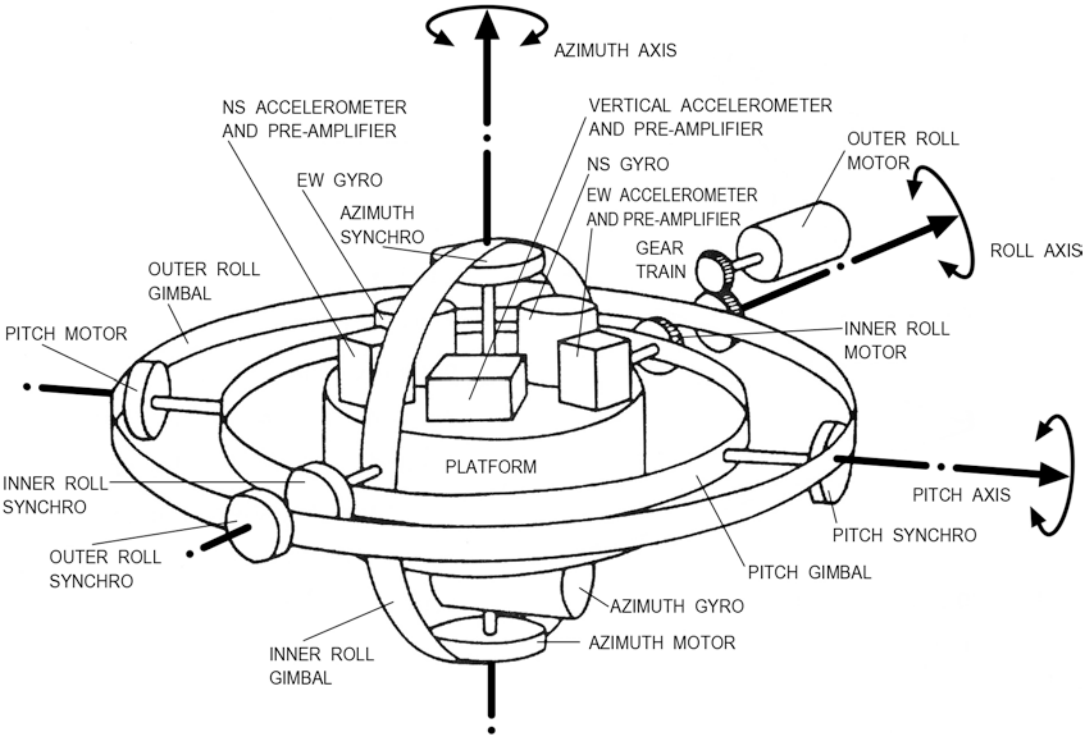

Fig. 2: Schematic of a Gimballed Platform (FILS), Deren (1981)

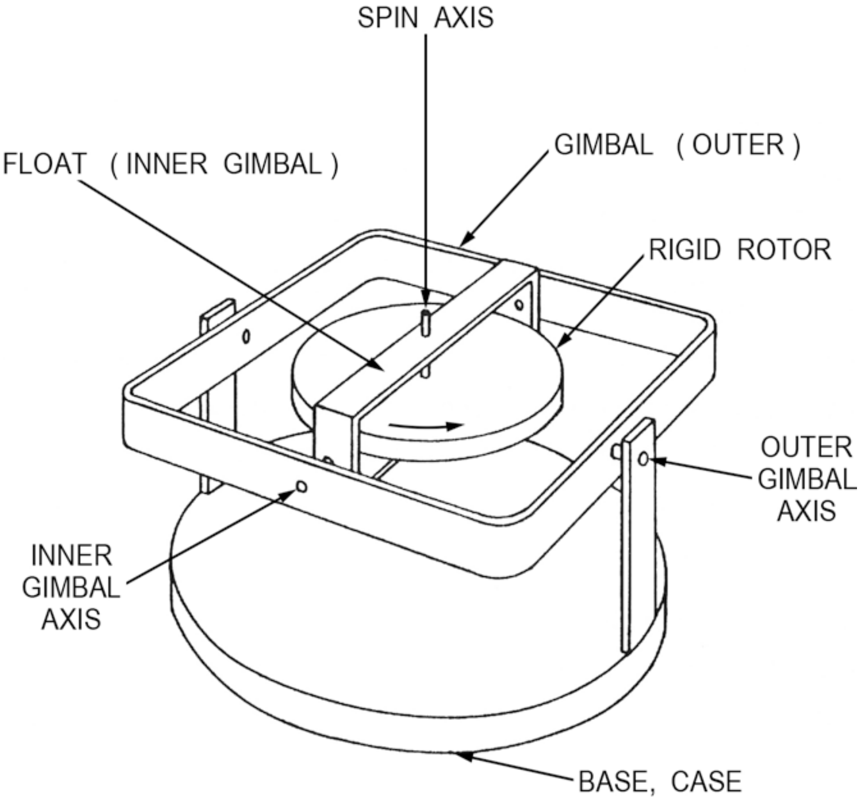

Fig. 3: Gimbal mounted TDF Gyro, Rüeger (1982)

When the rotor is spinning fast and no disturbing torque is applied, then the spin axis will preserve indefinitely its orientation in inertial space. If on the other hand a torque acts upon the outer gimbal axis, an angular rate precession of the inner gimbal (float) about its axis results. Thus the gyro can be used to stabilize the platform or to manipulate its attitude in any desired way.

The accelerometers are precision measuring devices containing a mass that is coupled to a case through an elastic or an electromagnetic constraint. Actually it senses the specific force being the resultant of the inertial reaction force due to vehicle accelerations and of the gravitational and various disturbing forces. Fig. 4 shows in a simplified manner the principle of an accelerometer.

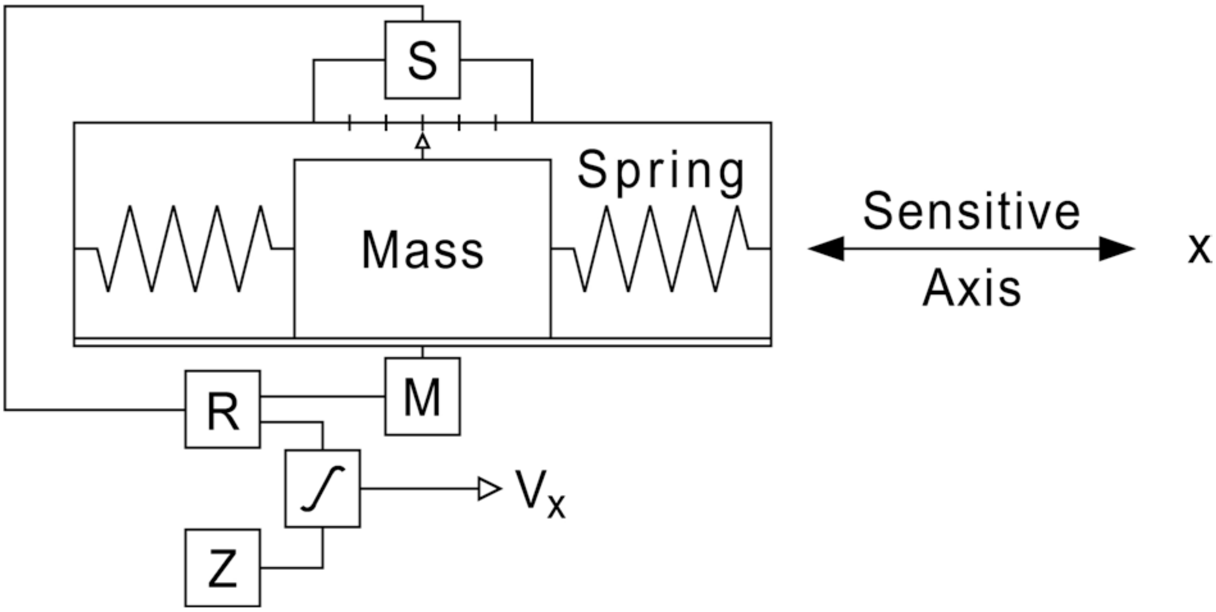

Fig. 4: Schematic of an Accelerometer

Three types of inertial platforms have been developed which differ in the way of control of the accelerometer triad.

The space-stabilized platform maintains its orientation between two alignments. Thus the accelerations refer to a frame which is fixed in space. The conversion of the position differences into a geodetic coordinate system is carried out by on-line transformations. The GEO-SPIN of Honeywell is an example of a space-stabilized system.

The local-level platform is continuously torqued to keep the z - axis parallel to the local normal of the reference ellipsoid and to hold its horizontal axes always pointing towards north and east, respectively. This type of platform control is realized in the Litton Autosurveyor and in the Ferranti Inertial Land Surveyor.

The strap-down platform follows all movements of the host vehicle. The rotations are sensed by gyros and accounted for computationally. No strap-down platform has been modified so far for geodetic position fixing.

4. THE ERROR BUDGET

The implementation of the very simple principle of inertial positioning requires the overcoming of a number of difficulties originating from the fact that the earth rotates, that the measurements are performed in the earth gravity field and that the mechanical and the electronic realization cannot be accomplished without small biases. Consequently the measured acceleration is the sum of the signal and various bias and noise terms

$$F = a_r + \sum a_d + g + \sum b_I + \sum \varepsilon \ , \quad m = 1$$

These terms can be grouped according to the way they are dealt with.

The first group, $\sum a_d$, consists of systematic effects which are completely known and can therefore be compensated for by strict mathematical corrections. The Coriolis, the centripetal and the tangential accelerations belong to this group. They occur since the measurements are carried out on the rotating earth. The influence of the gravity field, g, on the sensor output can be considered here as well. The normal gravity is compensated strictly. The remaining gravity disturbances belong to the second group, being formed by systematic effects which vary with time or position and can be estimated during the mission. Especially instrumental biases, $\sum b_I$, as zero offsets, scale factors, gyro drifts, non-orthogonality of sensitive axes and alignment errors pertain to this group. First estimates of these biases are computed in the pre-mission calibration phase. A Kalman-filter or similar approximation procedures are employed to update these instrumental errors for proper correction of the signals. If these biases are not controlled on-line they grow rapidly since the double integration of the signals amplifies all disturbances dramatically. The observations necessary for the filter are taken at regular stops in intervals of 3 - 5 minutes. In the absence of vehicle accelerations the corrected signals of the horizontal sensors should be zero. The actual readings are used to update the filter (zero velocity update: ZUPT).

The third group of errors, $\sum \varepsilon$, is formed by random noise and by pseudo-random errors remaining after applying estimated corrections and reductions. These errors propagate statistically. They are accounted for in post-mission smoothing and adjustment procedures. Additional self-calibrating parameters are estimated if the error pattern is of systematic nature.

5. OBSERVATION PROCEDURES

Inertial surveying systems are usually operated from a helicopter or a land vehicle, but there are also applications using vessels and aeroplanes.

A mission begins with a platform alignment which is carried out automatically under computer control. When the position, the elevation and additional parameters for time, coordinate system etc. have been entered into the instrument, the platform is levelled to the gravity field by use of the horizontal accelerometers and it is aligned to the local astronomical coordinate system by a technique known as gyrocompassing. During this process of alignment an initial calibration is being performed to estimate the actual biases and drift rates of gyros and accelerometers. For this pre-mission alignment/calibration 30 - 60 minutes are needed. At the same time the system attains its operating temperature which has to be maintained during the whole mission. While for the Autosurveyor and the GEO-SPIN usually one alignment at the beginning of a working day suffices, it is necessary to repeat the procedure for the FILS every 90 - 120 minutes. A re-alignment is necessary for all platforms after a switch off or break down of the system.

The mission commences in the survey mode over a known control point and proceeds by driving along the traverse stopping at all points where geodetic parameters are required and between points for ZUPTs if the spacing is too wide. The internal measurements for a ZUPT of for a coordinate fix last 20 - 30 seconds. If it is not possible to centre the reference point of the platform on the survey mark it is required to measure the excentricity in position and height. Efficient auxiliary equipment has been developed for this purpose, so that the stops are usually shorter than two minutes. The mission must be terminated over a known control point, different from the starting point.

At the terminal station the differences between the predicted and the known coordinates are used by a smoother to compute corrected coordinates for all intermediate points. Since most of the systematic errors are functions of the time or the distance travelled very simple on-line smoothing models are applied. As a protection against gross errors and for the elimination of course dependent biases all traverses are run forward and reverse.

Independent of the type of the ISS the following rules are to be considered in order to get most accurate results

- the time between control points should not exceed two hours
- the traverses should be fairly straight
- the points should be evenly spaced
- ZUPT stops should be made every three minutes.

6. POST MISSION PROCEDURES

The two terminal points of a traverse do not provide enough information to develop a sophisticated error model. To this end a higher degree of redundancy is necessary, which is achieved by combining traverses to a network with a sufficient number of cross-overs. In the ideal design all points belong to two traverses, thus creating a network of grid pattern. Fig. 5 shows as an example the network "Ebersberger Forst" which has been established to test different inertial platforms (CASPARY, BORUTTA, KÖNIG, 1985).

The method of modelling systematic errors in a post mission adjustment is similar to the well known self calibration approach in photogrammetry. The problem is mainly one of selecting suitable nuisance parameters to absorb efficiently the systematic errors. Simulation studies with different observation schemes using both, polynomial error models and those based on known error sources, have been published by HANNAH and PAVLIS 1980 and ARDEN and SCHWARZ 1983.

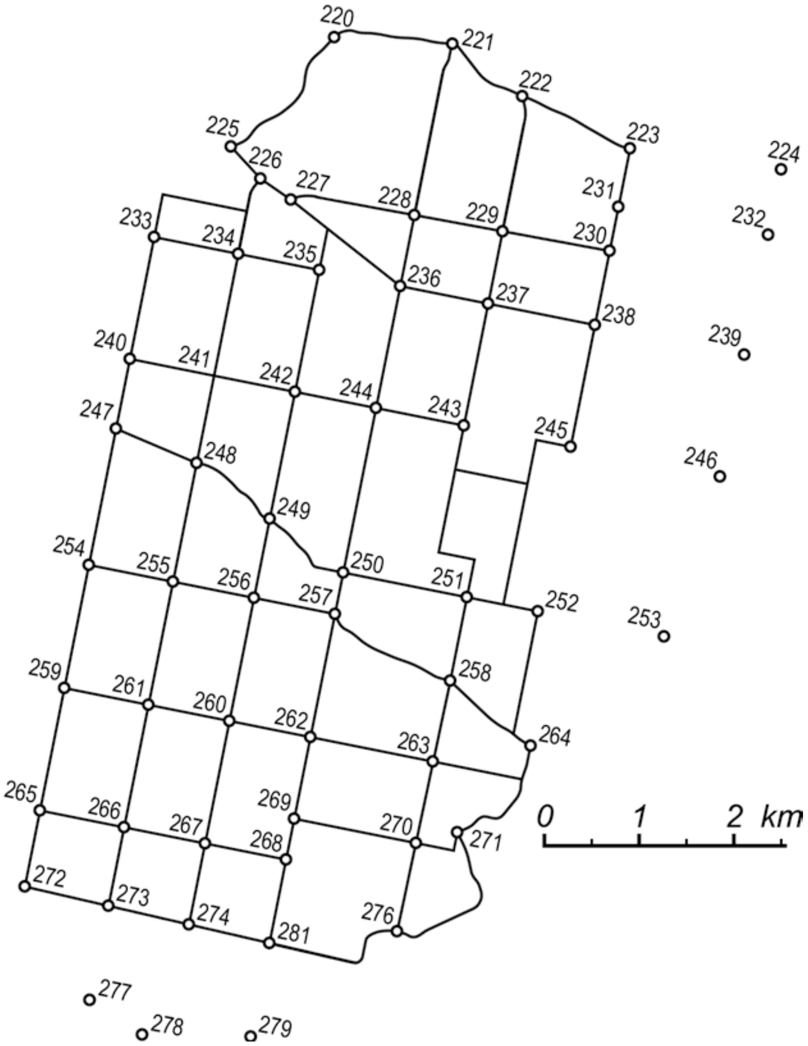

Fig. 5: Test network "Ebersberger Forst"

7. CONCLUSION

The inertial surveying systems being in use during the last 10 years proved their capability for a variety of geodetic applications. They have established their place in the geodetic arsenal, and their use is most successful if projects of sufficient extent are considered. Since progress in the electronic industry has been tremendous in this time it appears that a second generation of platforms is due. The users hope for improved instruments with more accurate sensors, being compacter, less power requiring and less expensive. This would open new fields for a much wider application of inertial surveying systems.

8. REFERENCES

ARDEN, I.A.G., SCHWARZ, K.P.: ***Optimizing Field Procedures for Inertial Network.*** XVIII. General Assembly of the IUUG, Hamburg, 1983

BOEDECKER, G.: ***Inertialvermessung.*** Beitrag zum IX. Internationalen Kurs für Ingenieurvermessung, 1984, A 17

CASPARY, W.: ***Inertiale Vermessungssysteme.*** Vermessungswesen und Raumordnung, S. 169-189, 1983

CASPARY, W., BORUTTA, H., KÖNIG, R.: ***Network Densification by Inertial Positioning.*** 7th Symposium on Geodetic Computations, Cracow, June 18 - 21, 1985

DEREN, G.: ***The Ferranti Inertial Land Surveyor and its Applications.*** Proceedings 2nd ISS-Symposium, Banff, 1981

GONTHIER, M.: ***Smoothing procedures for inertial survey systems of local level type.*** UCSE Reports Number 20008, 1984

HANNAH, J.: ***Inertial surveying systems and their use in geodetic positioning.*** Journal of the surveying engineering, p. 39-48, 1984

HANNAH, J., PAVLIS, D.E.: ***Post Mission Adjustment Techniques for Inertial Surveys.*** Report of the Department of Geodetic Science and Surveying No. 305, Ohio State University

MILBERT, D.G.: ***Inert 1: A Program for Planning and Simultaneous Adjustment of Inertial Surveys.*** Proceedings ASCM 42nd Meeting, S. 173-183, 1982

MUELLER, I.I.: ***Inertial Survey Systems in the Geodetic Arsenal.*** 2nd ISS, Banff, 1981

MÜLLER, HANNAH, PAVLIS: ***Inertial technology for surveying.*** FIG XVI. International Congress Montreux, 501.4, 1981

ROOF, E.F.: ***Inertial survey applications to civil works.*** U.S. Army Corps of Engineering ETL - 0309, 1983

RÜEGER, J.M.: ***Inertial Sensors, Part I: Gyroscopes.*** Edited by K.P. Schwarz, Division of Surveying Engineering, Publ. 1982

RÜEGER, J.M.: ***Evaluation of an Inertial Surveying System.*** Australian Surveyor, p. 78-98, 1984

SCHWARZ, K.O.: ***Inertial Surveying and Geodesy.*** Review of Geophysics and Space Physics, Vol. 21, No. 878-890, 1983