Univ.-Prof. Dr.-Ing. Prof. h.c. Günter Seeber anlässlich seines 65. Geburtstages
und der Verabschiedung in den Ruhestand. Wissenschaftliche Arbeiten der Fachrichtung
Geodäsie und Geoinformatik der Universität Hannover Nr. 258: 71-79, 2006

Research on Inertial Surveying System Instrumentation for Geodetic Applications in Brazil

Sílvio Rogério Correia de Freitas and Sandro Reginato Soares de Lima

Post-Graduation Course in Geodetic Science, Federal University of Paraná, Brazil

Abstract

Several works related to the research and to the development in the Post-Graduation Course in Geodetic Sciences (CPGCG) have been directed to support technological and methodological innovations. In the last thirty years the development of geodetic instrumentation has faced many challenges in Brazil. More specifically people in the CPGCG have tried to show innovative methods and technologies to geodetic community using a minimum of technical staff and resources. In the next sections there are some instances of international cooperation of CPGCG with other geodetic institutes that deal with innovative research related to inertial technology. The issues described here are the pioneer initiatives in South America since tests with an Inertial Surveying Systems (ISS) developed in 1979, at Curitiba region, to present works in developing low cost inertial instrumentation.

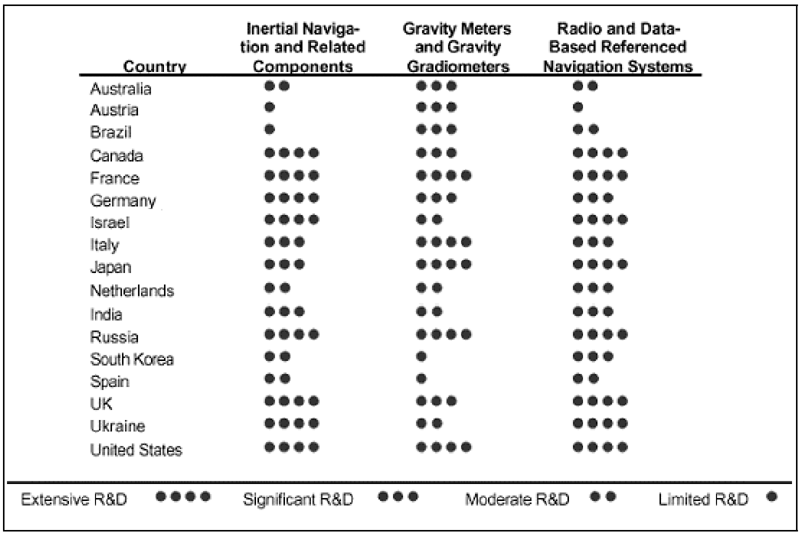
1 Introduction

In Brazil numerous projects deal with or need support from Geodetic Instrumentation and Geodetic Surveying. Several research activities in the Federal University of Paraná were developed in these areas since the 1970's. Because the pioneer work in the CPGCG carried out by Prof. Dr. Camil Gemael who established a lot of contacts with related institutions abroad, the Post-Graduation Program achieved a good experience from international collaboration projects. For instance, in 1979, Prof. Günter Seeber founded the study area related to inertial technology in the CPGCG by giving the first series of lectures on the use of inertial systems in Surveying and Geodesy (Seeber 1979). In the end of the same year, technical people and researchers from American Defense Mapping Agency (DMA) - presently National Imagery and Mapping Agency (NIMA) - brought to Brazil an innovative Inertial Surveying System (ISS) that was applied in tests at the Curitiba region. The surveys carried out in these tests were exploited in an original work about inertial positioners (Freitas 1980). Therefore, since its beginning, this research subject is aimed in CPGCG as one prospective developing for specific instrumentation and optimization techniques with potential to support many geodetic tasks - for instance: alternative to conventional surveying; mobile mapping; and gravimetry. After the first surveying using inertial measurements at Curitiba, some observations employing a gyro-theodolite were used to improve the potential of using the instrument. In this way, further researches were executed considering inertial surveying techniques and its optimization (e.g. Nadal 1982, Schwab 1994). Recently, other experiments using inertial sensors were carried out together with Institut für Erdmessung (IfE) in the Universität Hannover. In this time inertial sensor technology had achieved characteristics that allowed an assumption of low cost development to geodetic instrumentation.

2 General Remarks about Inertial Surveying Systems for Geodetic Applications

A large improvement for ISS was allowed at the last thirty years because the evolution of devices for navigation based on inertial technology, the development of several techniques for data processing and error control. A quick developing was achieved departing from mechanical gimbaled platforms to the strapdown ones totally based on solid state components. However, all these systems are based on the same fundamental equation of Kinematic Geodesy that relates gravity, inertial acceleration, and specific force (see Moritz 1967, Torge 1989). All the ISS have basis in three basic functions: realization of a local reference frame where inertial accelerations are measured – this function is accomplished by gyros; measuring of inertial forces - accomplished by oriented accelerometers; knowledge or modeling of the gravity field associated with a real time data processing of signal from gyros, accelerometers, and gimbals for obtaining reference information (like velocity, position, etc.) and state errors prediction by Kalman filtering.

Figure 1 presents a fragment of a report about the inertial navigation development level of many countries reported in DoD (2000). It is observed that some countries have an extensive research and development, and other countries have a limited situation. Specifically, since the 1980's, due to international agreement to non-proliferation of armaments, there are direct or indirect restrictions in Brazil for developing inertial technology. Therefore, geodetic areas as instances of applying inertial technology have limited perspectives for official financial support in the country.



Country	Inertial Navigation and Related Components	Gravity Meters and Gravity Gradiometers	Radio and Data-Based Referenced Navigation Systems
Australia	●●	●●●	●●
Austria	●	●●●	●
Brazil	●	●●●	●●
Canada	●●●●	●●●	●●●●
France	●●●●	●●●●	●●●●
Germany	●●●●	●●●	●●●
Israel	●●●●	●●	●●●●
Italy	●●●	●●●●	●●●
Japan	●●●	●●●●	●●●●
Netherlands	●●	●●	●●●
India	●●●	●●	●●●
Russia	●●●●	●●●●	●●●●
South Korea	●●	●	●●●
Spain	●●	●	●●
UK	●●●●	●●●	●●●●
Ukraine	●●●●	●●	●●●●
United States	●●●●	●●●●	●●●●

Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Figure 1: International research comparison by Department of Defense (DoD, 2000)

3 Gimbaled Inertial Surveying System Tests at Curitiba Region

The accuracy and productivity achieved by the gimbaled ISS right away in the 1970's, according Table 1 extracted from Huddle (1976) and Carriere et al. (1977) are impressive if considered the usual methods at that time and even the precision obtained by modern strapdown solid state systems (Schwarz and Glennie 1997). These statements can be confirmed by works developed at CPGCG.

Table 1: Typical ISS position errors (Huddle 1976; Carriere et. al. 1977)

Usual RMS in 1.5 hours Surveying		**Surveying Interval**	**Vehicle Speed**	
Latitude	1.5 m	**Total = 12 hours**	**56 km/h (station wagon)**	**185 km/h (helicopter)**
Longitude	1.5 m			
Height	0.3 m	**Short Period**	**RMS in Position**	
Gravity Anomaly	2 miligal	10 min	0.69 m	3.77 m
Comp. Vertical Deflection	1.5”	5 min	0.12 m	0.48 m
		3 min	0.06 m	0.11 m

A test with an ISS was done at Curitiba, from October 26th to November 16th, 1979, as basis for a Master Dissertation in the CPGCG (Freitas 1980). This test was the first one in southern hemisphere. It allowed a pioneer research in Brazil with inertial technology for geodetic purposes. The used system was one Litton Auto Surveyor System (LASS) lent by Defense Mapping Agency (DMA) that gave all technical support for tests.

The LASS equipment (Figure 2) was developed by Litton Guidance and Control Systems under contract by the DMA - presently National Imagery and Mapping Agency (NIMA), with a cost of more than 1 million of US Dollars. This system had basis on the Position and Azimuth Determination System (PADS) built for military purposes, with basis in a gimbaled tri-dimensional inertial platform Litton LN-15 (Figure 2c) for aeronautical navigation. Its application was conceived to operate in geodetic densification surveys as interpolator according the approach shown in the Figure 3. Other gimbaled ISS with similar performance were Ferranti Inertial Land Surveyor (FILS) and Honeywell Geo Spin.

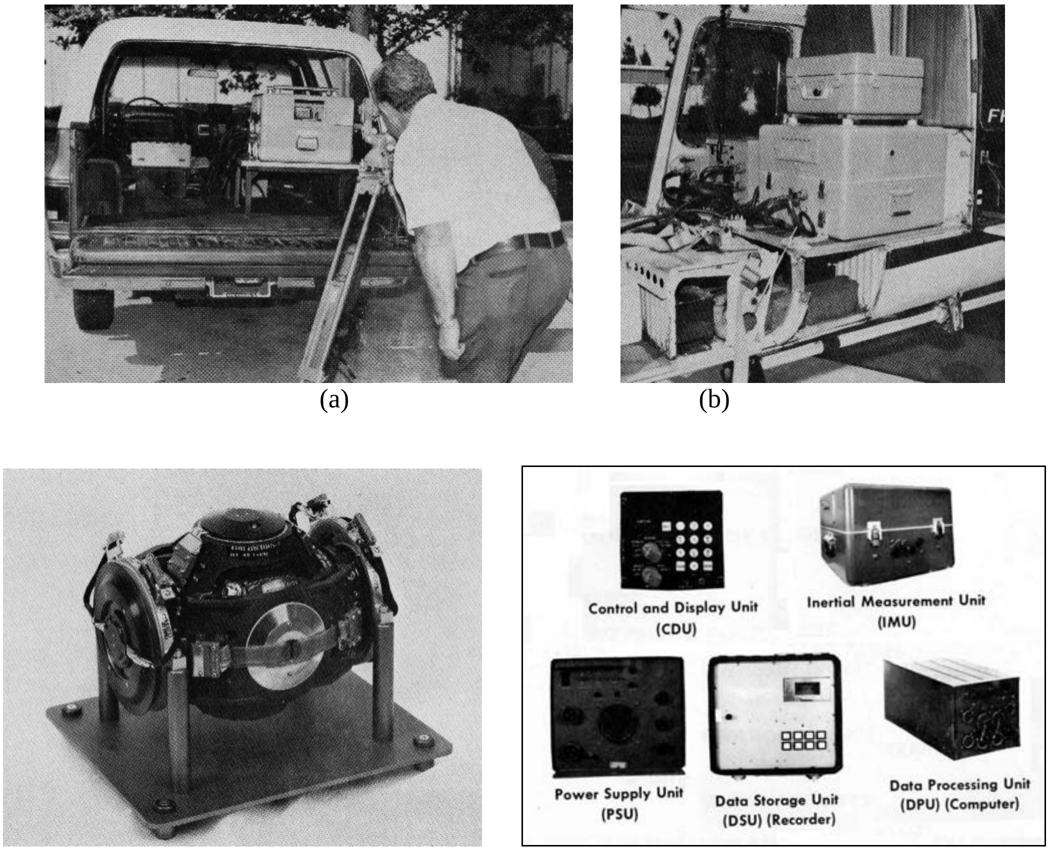
The operation of a gimbaled ISS like LASS is based on some special procedures (see Torge 1989) like: dynamic calibration in the beginning of each project (usually 7 to 15 work days) on reference N-S and E-W baselines with 5 to 10 km with relative precision better than 1:100.000; section initialization with static calibration each work day; periodical updating procedures aiming to reduce position errors (Zero Velocity Update - ZUPT). There are some operational restriction in using ISS determined mainly by instrument drifts and error estimation. There are several challenges for planning a survey with the LASS whose put limits in using the system. However its productivity is exceptional when the survey is adequately planned. The basic restrictions to be accomplished are the following:

a) Due the heading sensitivity of mechanical platforms, the strategy for surveying is constrained in traverse form between known points restrict in lateral developing in an edge at thirty percent of the length between extremes;

b) Maximum interval between ZUPT procedures of 5 minutes;

c) Ideal traverse length of 45km for terrestrial survey (e.g. LASS in a station wagon –Figure 2a) and 150km for aerial survey (LASS in an helicopter – Figure 2b);

d) Time interval for closing the traverse restrict to about 3 hours.



(a) (b)

(c) (d)

Figure 2: a) LNSS Assembly for Terrestrial Surveying with possibility of azimuth transference; b) LNSS Assembly for Aerial Surveying; c) Gimbaled platform Litton LN-15; d) LASS Assembly and Command Devices

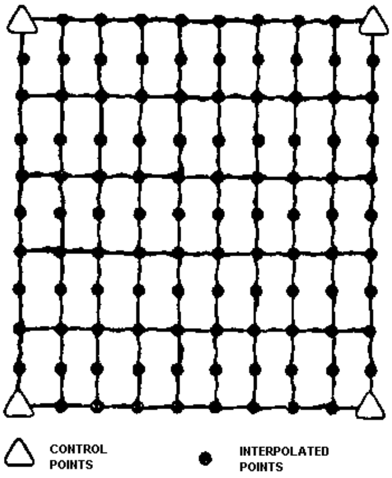


Figure 3: Ideal survey solution for interpolating new control points using an ISS (Freitas 1980)

Figure 4 shows the calibration lines and the traverses developed in the tests that happened at Curitiba with the LASS that operating in a station wagon (Figure 2a). Extreme conditions were imposed in the tests, like traverses with severe changes in azimuths, height variation until about 900m, time for closing traverses up 5 hours. In the 1979 Curitiba tests were realized 338 measurements on 93 intermediary observed points on 10 traverses (several with only one measurement on lines without target points in Figure 4). The total time span of the tests was 50h 33 min, including in this survey time 6 hours of static calibration. If considered that each observation could result in a new control point, these fulfillments resulted in a mean time of 9 minutes for observing a new point. The obtained results are in the table 2.

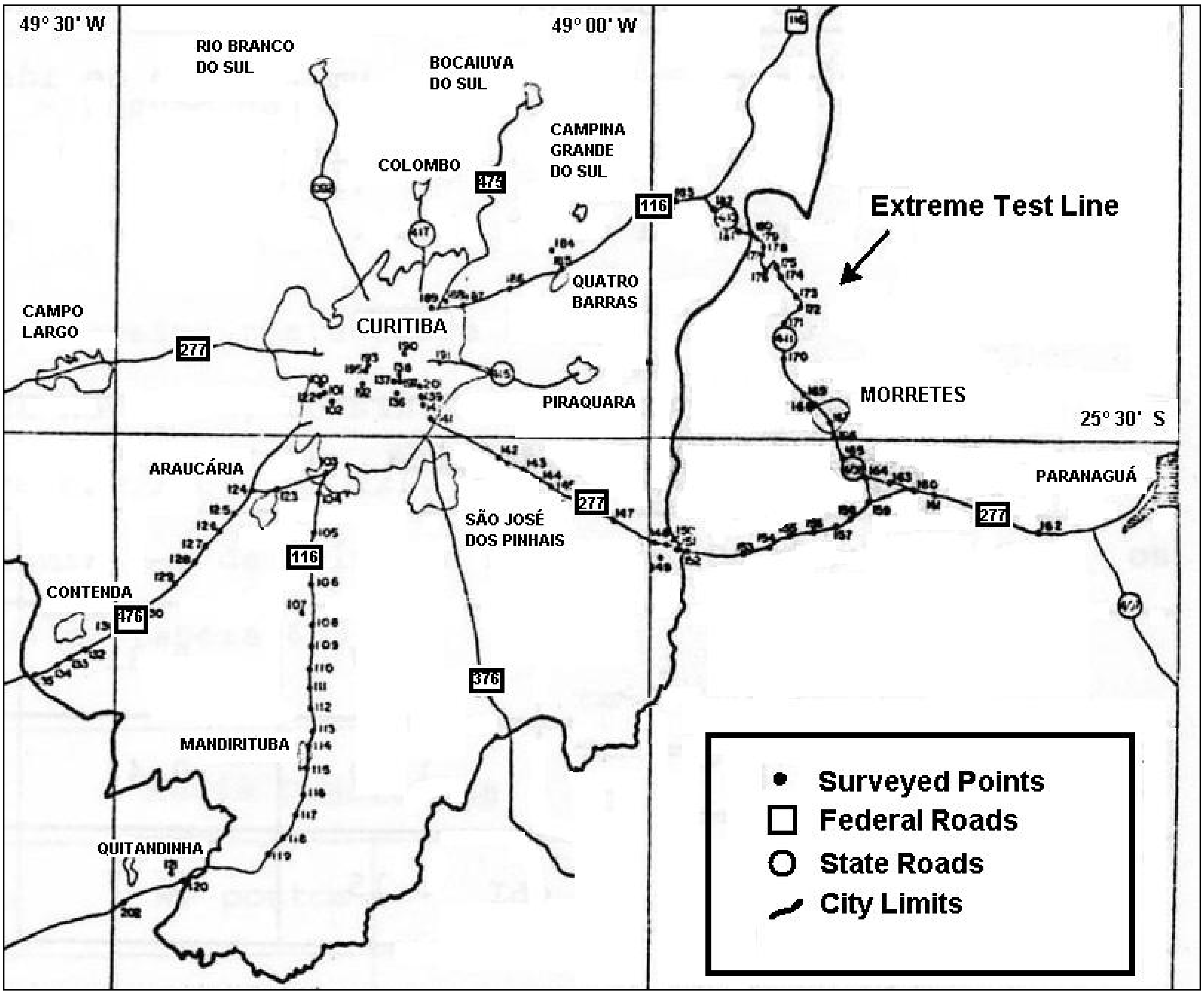


Figure 4: Curitiba region – test lines (Freitas 1980)

The acquired data were processed after the tests both in the CPGCG and in the DMA, with different strategies in considering the injunction of data in start and closing traverse points. As the LASS allowed introduction of latitude, longitude, height, components of the vertical deflection, and gravity anomaly information in different points, several strategies were possible for adjusting the traverses, according to Freitas (1980) who described several results to the experiments at Curitiba.

Table 2: Curitiba Tests – Some results obtained by Freitas (1980)

Parameters	**Number of Test Points / Observations**	**Standard Deviation (σ)**	**Number of Control Points / Observations**	**RMS**		
				forward	**backward**	**global**
Latitude	46 / 240	0.12 m	7 / 42	0.87 m	0.78 m	0.81 m
Longitude	46 / 240	0.18 m	7 / 42	0.90 m	0.75 m	0.81 m
Height	45 / 228	0.06 m	34 / 176	0.23 m	0.25 m	0.22 m
Free-Air Anomaly	43 / 234	0.57 miligal	39 / 220	1.02 miligal	1.24 miligal	0.90 miligal

Obs: weighted values = number of observations at a point.

Freitas (1980) considered that his better results came of his strategies of starting and closing survey lines, and data processing with smoothing technique, even considering the imposed severe conditions on testing (e.g. the target line in Figure 4 having survey time up 5 hours on line with 68 km, strong changes in azimuth and height).

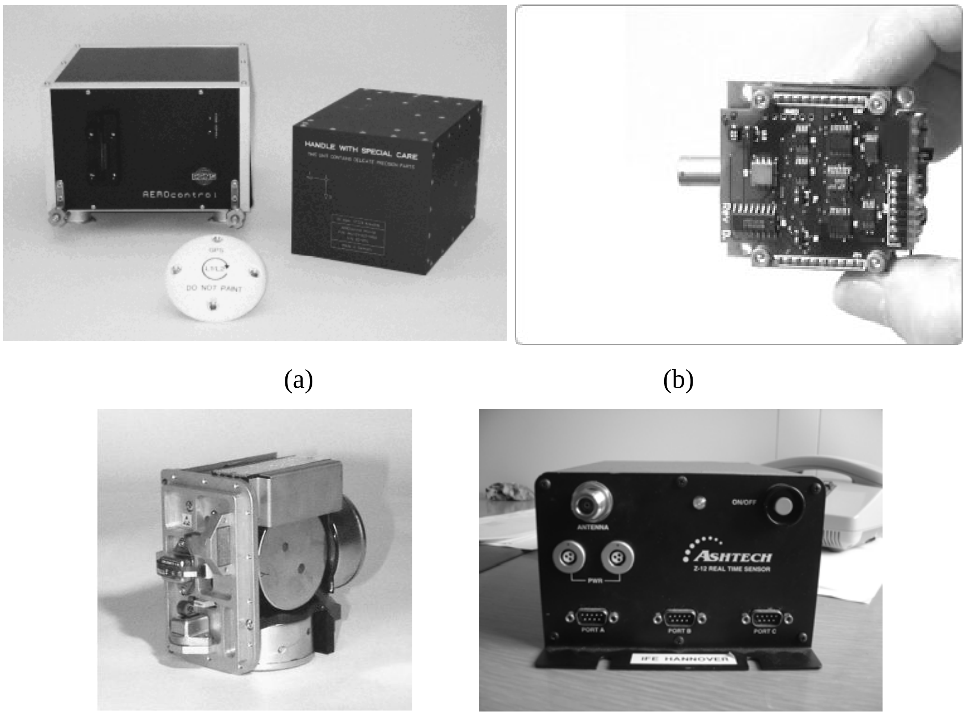
4 Low Cost Strapdown Inertial Measurement Unit

Nowadays, the horizons for applying inertial platforms in Geodesy are strongly different from those of the 1970's. Platforms are thought mainly as additional or complementary control device for other survey systems.

Since 2001, low cost inertial sensors are evaluated at CPGCG. Specifically, Analog Devices Microelectromechanical System (MEMS) series of sensors had been analyzed in laboratory at LAIG (Geodetic Instrumentation Laboratory) with the purpose of identifying their potential properties to the utilization in geodetic surveying.

In August, 2004, some field experiments of inertial positioning were executed at Hannover in a cooperation partnership of the Institut für Erdmessung (IfE) in the Univertsität Hannover and CPGCG, with supervision from Prof. Günter Seeber. An Inertial Navigation System (INS) designed by IGI GmbH and an Inertial Measurement Unit (IMU) designed by MicroStrain, Inc. (see Figure 5a and 5b) were mounted simultaneously in a terrestrial vehicle. These inertial navigation instruments have inertial sensors assembled to build instances of strapdown platforms.

It is important to remark that IGI-system utilizes expensive and high precision Fiber Optic Gyroscopes (FOG) (Figure 5c) and the MicroStrain unit makes use of low cost inertial sensors (MEMS-based gyroscopes and accelerometers from Analog Devices, Inc.) and that characteristic clearly distinguishes these two inertial units.



(a) (b)

(c) (d)

Figure 5: a) IGI-system; b) MicroStrain MEMS-IMU; c) inertial sensors array; d) Ashtech Z-12 GPS receiver

Several modern mobile Multisensor Mapping Systems (MMS) utilize INS units and GPS receptors together image acquisition sensors in terrestrial (van) or aerial platforms. Therefore, an Ashtech Z-12 GPS receiver module (Figure 5d) was planned to be used with the IGI-system and an antenna was installed on the roof of the vehicle by means a special mechanical structure. That GPS receiver was responsible for high precision observables (e.g., time, pseudo-ranges, and carrier phases).

IGI-system was designed to use its proprietary software called AeroOffice to GPS/INS integration, but to gain knowledge of the integration steps other independent routines based on Kalman filter estimation were developed in the CPGCG (Lima 2005). Two areas were used to the experiments execution: initially the streets near the IfE (with many obstructions to GPS satellite signals) were surveyed and later the Schützenplatz area (more favorable to satellite tracking) was utilized.

These experiments were part of the development of kinematic processes for evaluation of low cost GPS/INS integration and therefore the main purpose of the MEMS-IMU experiment was testing of the procedure of using the high precision IGI-system observations as a reference to IMU evaluation (Lima 2005). At the urban canyon trajectory the presence of severe GPS satellite signals multipath was continuous in the first experiments area, therefore the later experiments had better performance.

5 Inertial Surveying Systems Performances

At the present time, both inertial positioning systems (gimbaled and strapdown) under investigation have several possibilities of use in geodetic surveying. Table 3 describes some differences and similarities between these inertial platforms.

Table 3: Comparison of inertial navigation platforms

Inertial Positioner	**LASS (ISS)**	**MEMS (IMU)**
Platform structure	Gimbaled	Strapdown
Geodetic applications	Gravimetry; Positioning;	MMS; Bathymetry;
Observation Processing	Kalman filter	Kalman filter
Order of precision in positioning (tolerances)	Sub-meter	Meter
Comparative cost	High	Low

In relation to the inertial positioning experiments, static gimbaled system calibration interval used a number of hours to be completed and the initialization process requires external references to align the platform with the reference orientation and gravity field. On the other side, modern strapdown units require less time to initialization and GPS/INS process eliminates the ZUPT procedure used for periodic observation corrections in the gimbaled system case, and the need of most of external references for static calibration.

With IGI and MEMS units was possible to acquire comparable acceleration observations, however rotation rate ones were very different because FOG sensors have superior performance when compared to MEMS rotation rate sensors. Observations of both systems were processed using Kalman filter algorithm strategies. Experiments using gimbaled system showed precisions in the terrestrial surface positioning in longitude and latitude around 0.8m (LASS). With GPS observables synergy strapdown units obtained performance in the terrestrial surface positioning around 0.2m and 3m, respectively to high precision and low cost units.

6 Conclusions

Since 1979, a pioneer research in Brazil based on inertial surveying experiments showed the potential use in geodetic surveying applications. Operations planning of different inertial navigation systems were fundamental to experiment success mainly in the choice of test areas and initialization procedures. A significant result is that final costs were estimated in around fifty percent of conventional methods. Historically, Doppler receivers were planned to be used with gimbaled systems, therefore, synergy with GPS receivers are the modern choice to integration of spatial observations.

To try preview the future research at CPGCG/UFPR in relation to Inertial Positioning and Gravimetry it can be possible to see perspectives to execution of gravimetric measurements using gimbaled apparatus to stabilize relative analogical (LaCoste & Romberg) or digital (Scintrex) gravimeters. Nowadays, low cost MEMS sensors are used in Multisensor Mapping System (MMS) and to establish spatial orientation to Augmented Reality (AR) in real world sceneries. Other potential research subjects are that related to geodetic applications in engineering, mainly in monitoring movements and vibrations.

Finally DMA/NIMA, IfE/Universität Hannover and CPGCG/UFPR instances of cooperation are considered fundamental to the research and development of instrumentation and applications in the geodetic survey area.

Acknowledgements

In this work the authors want to celebrate the successful career of Prof Dr. Günter Seeber in the Institut für Erdmessung (IfE). The authors acknowledge the fundamental collaboration of Prof. Dr. Jürgen Müller (IfE director), Dr. Christian Hirt, Dipl. -Ing. Olaf Bielenberg, Dipl. -Ing. Ortwin Krüger.

The authors also acknowledge DAAD (Deutscher Akademischer Austausch Dienst) and CNPQ (Conselho Nacional de Desenvolvimento Cientifico e Tecnológico) for the financial support (CNPQ project n. 474344/03-7).

References

Carriere, R.J.; Kouba, J.; Penney, R.C. (1977). Experience with the inertial survey system at geodetic survey of Canada. In: International Symposium on Inertial Technology for Surveying and Geodesy, April 27-28, 1976. Institute of Navigation.

Department of Defense - DoD (2000). Militarily critical technologies. Part III: Developing critical technologies. Section 16: Positioning, navigation, and time technology. Report of Defense Threat Reduction Agency. Dulles.

Freitas, Sílvio R. C. de (1980). Inertial Surveyors (*in portuguese*). CPGCG dissertation. Federal University of Paraná - UFPR. Curitiba.

Huddle, James R. (1976). Navigation to surveying accuracy with an inertial system. In: National Aerospace Symposium Proceedings, April 27-28, 1976. Institute of Navigation.

Lima, Sandro R. S. de (2005). GPS/INS integration using MEMS based inertial sensors (*in portuguese*). CPGCG thesis. Federal University of Paraná - UFPR. Curitiba.

Moritz, Helmut (1967). Kinematical Geodesy. Columbus: 1967. Report AFCRL-67-0626, AD666052, Department of Geodetic Science, The Ohio State University.

Nadal, Carlos A. (1982). Instrumental constants determination of gyro-theodolite (*in portuguese*). CPGCG dissertation. Federal University of Paraná - UFPR. Curitiba.

Schwab, Silvia H. S. (1994). Fourier analysis in gyro theodolite determinations (*in portuguese*). CPGCG dissertation. Federal University of Paraná - UFPR. Curitiba.

Schwarz, K.P., and Glennie, C. (1997). Improving accuracy and reliability of airborne gravimetry by multiple sensor configuration. In: Geodesy on the move, Springer, Berlin, pp. 11-17.

Seeber, Günter (1979). The use of Inertial Systems in Surveying and Geodesy. Lectures notes. CPGCG, Federal University of Paraná - UFPR. Curitiba

Seeber, Günter (1993). Satellite Geodesy: foundations, methods, and applications. Berlin: Walter de Gruyter.

Torge, Wolfgang (1989). Gravimetry. Walter de Gruyter, Berlin.