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A Method for Field Calibration of a Gyroscope in an Airborne Gravimetry Inertial Stable Platform

By

Amina Daoudi

**A Thesis submitted to the
School of Graduate Studies and Research
in partial fulfilment of the requirements
for the degree of
Master of Engineering**

**Ottawa Carleton Institute for Mechanical and Aerospace Engineering
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**A Method for Field Calibration of a Gyroscope in an Airborne Gravimetry Inertial
Stable Platform**

**submitted by
Amina Daoudi, Ingenieur d'Etat en Fabrication Mecanique
in partial fulfilment of the requirements for
the degree of Master of Engineering**

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May 2000**

ABSTRACT

The calibration of the inertial instruments (accelerometer and gyroscopes) was performed over an inertial laboratory. Sanders Geophysic Limited (SGL) wanted to use the gravimeter gimbal stable platform to calibrate the gyros that needed to be replaced in the field. The replacement necessitates a calibration, in the field, of the new gyro. This thesis discusses the possibility of using the gravimetry platform as a testbed in the field. Three phases were conducted:

Phase I of the thesis consists of describing the gravimeter platform and determining the mechanical error budget.

Phase II describes how to use the platform as a testbed. The gyro is oriented in sixteen different positions and the gyro error terms can be determined easily.

Phase III consists of studying the feasibility of using the platform as a testbed in the field.

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List Of Symbols

α	Tuned Rotor Gyro misalignment angle w.r.t inertial space
α_i	Misalignment angles of the Inner Gimbal, with $i=x,y,z$
β_i	Misalignment angles of the Inner Sensor Flange and the Gimbal Mounting Flange, with $i=x,y,z$
η_i	Misalignment angles between the Mirrors and Cardinal axis, with $i=x,y,z$
θ_{ij}	Misalignment angle of the i Accelerometer input axis about the j system axis
τ_i	Misalignment angles between the Mirrors and the Inner Sensor Flange
ω	Resolver accuracies
B	Bias
C	Transformation matrix
CMT	Contraves Motion Table
DTG	Dynamically Tuned Gyroscope
F	Force
g	Gravity vector
g_i	Gravity component along i axis, with $i=x,y,z$
G	Gravitational acceleration
H	Angular momentum
i	Current
IGA	Inner Gimbal Assembly
IGS	Inner Gimbal Simulator
k_n	Gyro Torquer scale factor for axis n ; $n=1,2,3,4$
K	Acceleration Scale Factor
LSF	Lower Sensor Fixture
m	Mass
M	Applied moment
M_n	Applied moment about axis n ; $n=X,Y$
MU	Mass Umbalance of axis m ; $m=X,Y$
N	Torque
OA	Output Axis
PA	Pendulosity Axis
Q_m	Quadrature of axis m ; $m=X,Y$
R	Resistance
T	Torque
USF	Upper Sensor Fixture
v	Velocity

1 Introduction

1.1 Project Overview

The science of gravimetry is the study of acceleration due to gravity. Gravity is the phenomenon associated with the gravitational force acting on any object that has mass and is situated within the earth's gravitational field. The gravity value changes from one point on Earth to the next. The changes in density of the rocks forming the earth's crust and the thickness of the crust are reflected in the varying gravity field over the earth's surface [05].

Measurement of the earth's gravity field was first performed in 1888. The first method used a pendulum, the best value obtained was 9.809398 m/s^2 . In 1951 another method was used which involved photographing a meter stick falling through a cylindrical vacuum chamber. The most accurate value registered was 9.809280 m/s^2 . The latest method, in use since 1960, involves the launching of an object into the air and tracking it with lasers. The results obtained in 1966 show an average value for g is 9.809260 m/s^2 , which is now considered a universal constant. [07]

Gravity measurements are also useful for mineral and oil exploration, determining the shape and structure of the earth, calibrating accurate weight and pressure measuring equipment, and calculating the trajectory of satellites and rockets. The earth's shape and the height of an observation point above sea level are used to calculate a predicted gravity value. If the predicted gravity is subtracted from the measured gravity value at one point, the resulting value is called a gravity anomaly. Those anomalies are caused by the geological structure size and depth. [07]

There are a few kinds of gravimetry measurement systems that measure gravity at different points on the earth, one being the Lacross Romberg system. Airborne scalar gravimetry is one and it is used to measure the magnitude of gravity (rather than the full gravity vector). The theoretical and experimental work in this field was initiated in 1959, and has accelerated greatly in recent years. Airborne gravimetry has potential as a very effective exploration tool. It has many advantages over sea and land based gravity measurements: it gives virtually unlimited access to areas (e.g., Canadian bush, Amazon, mountains) where other measurement systems cannot access and a large amount of data can be collected very economically and quickly. It can be combined with aerial magnetic measurements and it is less subject to surface gravity changes due to elevation. Geophysics has seen a growth in demand for airborne gravimetric surveys.[04]

Precision inertial instrument availability has made it feasible to build a very precise gravimetry system. The inertial instruments are not the only components to contribute to the construction of a better stabilized platform. Improved electronics, computer engineering, thermal control and the Global Positioning System (GPS), which can be integrated to provide precise altitude

information, have all contributed to the feasibility of a present day airborne gravimeter. [04]

In Canada, gravity surveys to date have been done solely using ground-based gravimeters, which measures gravity at a specific location. Airborne measurements would be less expensive and faster than the presently available survey methods. Sander Geophysics Limited (SGL) has built a prototype airborne gravimetry system using their own internal funds and with sponsorship from the government and oil industries. The goal of SGL is to reach 1 milligal of resolution for the magnitude of the gravity measurement ($1 \text{ milligal} \approx 1 \text{ micro-g}$). The airborne gravimetry system is also designed to be used as a self-calibrating test-bed, which permits the calibration of the inertial instruments in the field. The goal of using the gravimeter as a platform testbed is to save the time that would otherwise be required to send back the inertial instruments to an inertial calibration lab and to reduce the cost of transportation and calibration in a laboratory environment. It also serves to make each geophysics surveys self-sufficient.[13]

1.2 Research Objectives

The goal of this research is to show how the airborne gravimetry inertially stabilized system can be used as a test bed to field calibrate the inertial sensors (i.e., gyroscopes and accelerometers) if one, or at the most two fail during system use. Carleton University activities have included the calibration, test and evaluation of the inertial sensor (QA2000, QA3000 accelerometers and G1200 gyroscopes) error terms, the analysis leading to a theoretical method to determine the platform mechanical errors and to show how to use the platform as a self test bed, in lieu of using a precision test table in a laboratory. This would enable replacement of inertial components and repair of the system piece parts in the field.

First, it was necessary to characterize the performance and behavior of the inertial instruments before integrating the inertial instruments into the platform. The inertial instruments were first tested separately in an inner gimbal simulator at the Navlab (DREO inertial navigation laboratory) using a very accurate Contraves Motion Table (CMT).

The second part of the research consisted of determining the mechanical error budget of the platform. The manufacturing tolerances on each piece part were obtained. The worst and the 'real-world' cases were calculated. Misalignment angles of the platform, determined in the mechanical error budget, would affect the accuracy of the inertial instruments when they are integrated in the gravimetry platform.

The third part of the research attempts to define the relationship of the misalignment angles to each other and attempts to determine how the inertial instrument errors are affected by these platform errors, and also attempts to define a method to calibrate the instruments using a number of inner gimbal platform orientations. The platform is composed of three gimbals embedded one in the other, and each gimbal has one degree of freedom (See table 2-1). Therefore the positioning of the inertial instruments relative to g and the earth's rotational rate depends on the rotation of each gimbal. Rotation matrices were used to determine the relationship between the various mechanical misalignment angles.

1.3 Motivation

Part one consisted of testing of the inertial instruments (i.e., accelerometers and gyros) which was necessary to determine the behavior of the instruments and to characterize the errors. The QA 2000 and QA 3000 Q-flex accelerometers and the G1200 dry, dynamically tuned, two degree of freedom gyros were tested separately in the inner gimbal simulator. The testing was performed in an inertial navigation test laboratory (NAVLAB) using the Contraves Motion Table (CMT), which is accurately aligned with the earth's cardinal axes (North-East-Down). For each test, appropriate equipment was used to control the temperature and collect data. The inertial sensors were installed in the Inner Gimbal Simulator (IGS) and precise (i.e., less than 20 sec of arc) orientations to the gravity vector g and North East Down were determined. The misalignment angles of the sensors about the cardinal axes were obtained through a calibration employing autocollimation and analysis of the sensor outputs.

Before integrating the sensor fixture containing the inertial instruments into the platform, it was necessary to become familiar with the gravimetry plat-

form physical, mechanical and electro-mechanical components and the associated measurement instruments. Therefore, a considerable time was spent at Sander Geophysics Limited (SGL) industrial plant, collecting documents (drawings, assembly procedures, specifications, proposals, etc....). Then, part two, the gravimetry platform mechanical error budget was determined. Since each component has its own misalignment angles, a method was developed, with the assistance of Prof. Staley and Prof. Sinkiewicz, that relates all the errors of the platform components together.

1.4 Thesis Outline

The gravimetry project covers three important tasks performed during the research.

- Inertial instrument testing and evaluation in a controlled laboratory environment
- Determination of the platform mechanical error budget.
- Mathematical development of a method to estimate the inertial sensor errors when the sensors are integrated into the platform.

The testing of the inertial instruments will be briefly described since the goal of the thesis is to determine if the stable gimbal platform can be used as a self test bed.

Chapter two describes the airborne gravimetry system. The mechanical components and electronic equipment is listed and their function is explained.

Chapter three describes the inertial instruments and their applications. The test equipment and test procedures are briefly discussed. A description of the Litton G-1200 gyros, allied signal QA-2000 and QA-3000 accelerometers is given.

Chapter four outlines the platform components which were considered to determine the worse case and real-world scenario of the platform mechanical alignments. The selection of the components is explained in detail along with the determination of the misalignment angles and implementation of rotation transformation matrices.

Chapter five discusses how the gyro error parameters are determined when the gyro is integrated into the gravimetry platform. In this part of the research, the platform is considered to be perfect, without mechanical error.

Chapter six presents a discussion on how to use the platform as a test bed and how the inertial instruments parameters are affected by the platform misalignment angles.

Chapter seven gives a discussion of the results, conclusions and recommendations for future work on the airborne gravimetry platform

2 Airborne Gravimetry System

2.1 History and Background

In medieval times, navigators used maps to travel from point-to-point on the earth. The mapmakers devised a global coordinate system using a grid of latitude and longitude circles so that any position on earth could be defined. In the early 11th century, the magnetic compass came into being, but was not very accurate due to the magnetic poles of the earth. In the 14th century, navigators used the stars to find latitude, and by the 18th century, instruments like the sextant for more accurately measuring the positions of the celestial bodies,

were invented. Knowing longitude was more difficult since the position of the earth relative to the stars depends on the time of the day.

The longitude is measured from Greenwich where longitude is defined to be zero. To determine longitude, the navigator had to know the local time and the Greenwich Mean Time (GMT). It was possible to find the local time by the position of sun, but without a clock set to GMT, it was impossible to know the time at Greenwich. Only near the end of the 18th century was accurate time keeping available at sea with the invention of the marine chronometer.[11]

The process of following a path on a map, through predetermined longitude and latitude, is called Navigation, and the process of orienting the vehicle to follow a selected path is called Guidance. With the advancement of ships and the advent of the airplane, inertial navigation systems began to be developed. Previously, direction and speed were obtained from a magnetic compass and an airspeed indicator. Inertial Navigation Systems (INS) establish an inertial reference frame through the use of gyroscopes and achieve navigation by measuring the three dimensional acceleration with an accelerometer and integrating twice to measure position.[06]

2.2 Inertial System Navigation background:

Navigation involves knowing the present direction and magnitude of motion with respect to other points of reference. To move from point A to point B, the aircraft needs information including heading, speed and attitude. Many devices were invented to aid in this effort including the gyrocompass, airspeed indicator, radar and radio.

When guidance requirements became more complex than a man's abilities to do the job, a need for semiautomatic or automatic guidance developed. However, even in automatic guidance techniques, steering and attitude control are essential.

Inertial navigation defines the orientation of an object (for example: angles of roll, pitch and yaw of an airplane) and acceleration along a given axis. Inertial systems as a practical means of determining vehicle motion between points on earth did not exist much before 1940. The first studies were started during World War two by the military German scientists' who developed the V-2 ballistic rocket missile. The guidance and the control of this rocket employed two two-degree-of-freedom gyros, one to control rolling and yawing motion and

the other to control pitch. It was a very advanced inertial instrument for that time [11].

The primary sensing element in an inertial system is a pendulous proof mass which has one degree of freedom about the input axis. This is referred to as an accelerometer. The proof mass is typically suspended by a quartz flexure hinge between two series-wound torquer coils. When acceleration is applied along the instrument-input axis, the proof mass tends to deflect from its null position in a direction opposite to the direction of the acceleration. This proof mass motion is detected by differential capacitive pickoff circuitry, which produces a signal proportional to the deflection. This signal is fed back into a servo amplifier, which generates a current. The proof mass is moved back to the null position by a magnetic field produced by the current in the torquer coil. The accelerometer output can be determined by measuring the torquer current through a resistor and applying a scale factor conversion [11].

In the early 1950's, the Massachusetts Institute of Technology (MIT) instrumentation lab under the leadership of Prof./Dr. Charles Stark Draper developed the first floated gyroscope. The original idea for the floated gyro came from

Schuler who published a definitive text in 1932 [11]. However it was not used until the early 1950's. This design was called the Hermetic Integrating Gyro (HIG) and was produced in large quantities and became very popular in the navigation field. Then in the mid-1960's, the availability of inertial navigation technology resulted in a proliferation of high performance combat aircraft. At the same time, the Dynamically Tuned Gyro (DTG) was developed. The DTG is a two-axis gyro configuration that does not need flotation fluids. At the end of the 1960's, the DTG became very popular. Many companies such as Litton and Kearfott switched to DTG's from floated gyros.

The inertial sensors have very specific functions. The gyroscope measures the angular rotation rates and establishes an inertial reference frame, and the accelerometers measure the acceleration. Integrating the acceleration output from the accelerometer gives the velocity/speed, and integrating speed gives position/distance traveled. Both gyros and accelerometers are used in Inertial Navigation Systems, and a gimballed platform containing inertial sensors is called an inertial platform or navigation platform. Such a platform may be used by geophysicists to measure the variation of the Gravity. This is done by using the

fact that the inertial system provides a level and stable platform (i.e., 5 arcseconds of angle about X,Y and Z) on which a vertical accelerometer may be mounted, to measure gravity anomalies, which can, in turn give information as to the location of oil or mineral deposits.

2.3 Principal Mechanical Components of the Platform:

The gimbal platform developed by SGL for the gravimetry application consists of three gimbals imbedded one into another. Each gimbal is connected to another gimbal through several mechanical and electrical components. Each gimbal provides a degree of freedom (see Figure 1).

The mechanical components that allow the gimbal to rotate and be connected to each other are ball bearings, twist capsules, resolvers, torque motors and slip rings.

There are two types of bearings in the SGL platform, the miniature duplex bearing (S1724 SO7 313 ZDM) which were installed between the gimbals, one on each side of the gimbal spin axis, and the platform ball bearings azimuth support KA 100 BR3M (40 pounds preload) and KA 025 BR0M (10 pound preload). The 10 pound preload bearing supports the base of the platform and

FIGURE 1. Inertial gimbal platform system

doesn't have any influence on the gimbals. The 40 pound preload bearings support the three gimbals which include the case and the attached piece parts.

Three torque motors are mounted on the platform, each one installed at the junction of two gimbals. These torque motors drive and hold the three axes of the platform stable. The two twist capsules allow ± 90 degrees of rotation about the pitch and roll axis, the slip ring allows ± 360 degrees of rotation about the azimuth (yaw) axis.

Resolvers detect the rotary motion and determine the angular position of the gimbal rotations and their analogue output signal can be converted into a digital signal that can be measured easily. Resolvers contain two opposed coils, one mounted on the resolver shaft, the other stationary. One coil emits an electro-magnetic field, the other has a field induced into it. As the encoder shaft rotates, the current generated through induction varies with the relative position changes of the two coils. By measuring the current generated through induction, resolvers provide precise measurements of the rotors position. Resolvers work well in applications with high vibration, shock, and extreme temperatures. To estimate the failure rate of the resolver, the following factors

were taken into account: Ambient temperature, temperature rise of the unit, type of winding insulation and size of unit. Resolvers are very reliable and robust instruments. The type of resolvers used in the SGL platform are custom built to fit the company requirements. In the platform the resolvers were mounted at the junction of two gimbals and they are used to measure the angular rotation of the gimbals. Their accuracies of 5 arc seconds are normal and accuracies of 3 arc seconds are achievable.[13]

Twist capsules are added to the junction of a pair of gimbals. The twist capsules allow the gimbals to rotate. The limit of rotation is established to ± 90 degrees.

Between the outer gimbal and the base a slip ring is installed. The slip ring allows the outer gimbal, which contains the middle and the inner gimbals, to rotate ± 360 degrees.

2.4 Electronic Equipment of the Platform:

The gravimeter system is an inertial platform made up of three accelerometers and two two-degree-of-freedom gyroscopes. The platform functions are controlled by a set of electronic circuits. Each board performs a specific

function. It is desirable, due to signal-to-noise ratio, shielding, stray wire capacitance, etc....., to keep the electronic cards close to the platform sensors. For that purpose, four cages are mounted on the outer gimbal platform to house the electronic cards. Therefore the integrated electronics are considered as part of the platform. Gyro functions are controlled by several electronic boards, such as the gyro motor excitation, the gyro pick-off excitation, the gyro torque rebalance, and the gyro demodulator which converts the AC output of the gyro pickoffs to DC that is fed into the servo torque motor.

Some other electronic boards are added to the platform to control the remaining electronic devices integrated into the platform. Resolver-to-digital converter board provides the angles of each resolver of the platform in a digital format so that it can be read through software. Temperature controller boards give the absolute temperature at eleven different points on the platform, including accelerometer and gyro temperatures.

Three single board computers are added to control the entire set of electronic boards.

The whole system is connected to an outside platform box which includes the power supplies, the servo amplifiers, stable clock, serial controller and the main processor and data recording equipment.

All the electronic boards are controlled by different software implemented in the computer boards. The software package is needed to execute three principal functions:

- Reading of the accelerometer and gyro outputs.
- Executing gravimeter operation modes.
- Command outputs to the appropriate electro-mechanical drivers.

The stable platform will be used as a test table simulation to calibrate the inertial instruments if there is a gyro failure in the field. For that purpose, software for a test table simulation is written and imbedded into the system.

There are also three slave processors, which interface with the hardware. To provide specific functions. Slave1, reads the resolver angles, X gyro outputs and checks to see if the gimbal rotation is too fast. Slave 2 reads the Y gyro outputs, the gyro motor over-current and monitors the gyro temperatures. Slave

3, reads the accelerometers, registers the temperature inside the platform (eleven temperatures can be recorded) and sends them to the calculator to be displayed. Slave 3, also communicates the information to the calculator which is connected directly to the monitor, and the monitor to the master (see Figure 2, “Serial loop diagram”).[13]

FIGURE 2. Serial loop diagram

The SGL gravimetry platform has two modes, all electronic equipment are used in both modes but in different ways. The first mode, *analogue mode*, is used when the gravimetry platform is used as an airborne gravimetry system and the second mode, *digital mode*, is used when the platform is used as a test-bed. In the analogue mode the inertial stable platform or inner gimbal assembly is held level by 3 analog servo control loops to 5 seconds of arc, while the vertical (QA-3000) accelerometer, the gravimeter, measures the gravity anomalies when the aircraft traverses over the earth (see Figure 5, "Single-axis analogue mode of the gravimeter platform"). During this analog mode the digital mode is open loop. In digital mode, the loop control board receives the demodulated pickoff and sends a DC current to the gyro torquer. The DC current is measured and digitized by an A/D converter to give a digital representation of the gyro input. (see Figure 4, "Single-Axis digital mode of the gravimeter platform").[02]

FIGURE 3. Conceptual of the three axis gimbal platform. [05]

FIGURE 4. Single-Axis digital mode of the gravimeter platform

FIGURE 5. Single-axis analogue mode of the gravimeter platform

2.5 Inertial Instruments

Two important inertial instruments are used in the gravimeter system, the accelerometers and the gyroscopes. Before integrating the instrument into the platform, both instruments were calibrated in an inertial lab, using an accurate motion table. This chapter focuses on the calibration and the leveling of three accelerometers. The calibration of the gyros is discussed in chapter five.

2.5.1 Accelerometers

An accelerometer senses acceleration along a single axis. Inertial navigation depends upon the measurement and integration of linear acceleration to successfully accomplish the function of position and velocity indication. In navigation the accelerometers provide the measurement of vehicle acceleration and gravity in a known reference frame. In this SGL platform the concern is with the vertical accelerometer (i.e., the gravimeter) being able to measure the gravity anomalies and to use the accelerometers to level the platform. Although the three accelerometers along with the gyros can also provide inertial navigation, it is not considered and it is beyond the scope of this thesis.

In this project, the focus was on the Q-flex accelerometers which are used in the SGL gravimetry system.

The elastic quartz flexure suspension gives it nearly perfect turn-on to turn-on repeatability. Its dry, gas damped design makes it very insensitive to the effect of temperature, and design improvements over many years have reduced temperature errors, allowing accurate thermal modeling, although very precise temperature control to $\pm 0.05^\circ$ Celsius is used to attain 1 mgal/1 μ g performance and stability. The time spent between calibration updates has decreased. The bias drift at power turn-on, which impacts system accuracy and response time, continues to decrease. The Q-flex accelerometer is designed to meet high performance standards, (see Figure 6, "Q-flex accelerometer (QA-2000/QA-3000)").

Two models of Q-flex accelerometers are used in the gravimetry system, QA-2000 and QA-3000. QA-3000 is used as the *gravimeter* due to better performance exceeding the QA-2000 and a better vibration spectrum. The two QA-2000 models are used in conjunction with the QA-3000 for gimbal platform leveling

FIGURE 6. Q-flex accelerometer (QA-2000/QA-3000)

2.6 Installation and Test Equipment

The Contraves Motion Table (CMT) has two degrees of freedom, the tilt axis which is limited to ± 180 degrees and the azimuth axis which can be positioned through ± 360 degrees. The CMT primary axes are aligned with the North - South and East-West cardinal directions. The CMT is aligned to the geographic north direction to an accuracy of better than 8 arcseconds. The CMT rests on the floor on three leveling screws, that allow the table to be leveled when needed. An extremely flat circular plate is mounted by 7 screws on the top of the CMT. This plate supports the Inner Gimbal Simulator (IGS) mounting plate. A breakout panel was used with the IGS and its associated electronic support equipment. The panel receives signals from the electronic boards and sends them to the IGS. The breakout panel allows the removal, replacement or check of the system components, if needed, without dismantling the whole set-up. It also serves as a connection between the instrument rack and the CMT cables. The breakout panel is equipped with switches, one of which serves to provide power to the accelerometers. The panel is attached to the side of a frame, which supports the SGL electronic rack, (see Figure 7, "Multi-Position Inner Gimbal Testing in Inertial Laboratory")

A number of instruments were used for monitoring the experiments and collecting the data. The azimuth angle and the tilt angle were displayed on the MPACS table controller. A fluke thermistor was used to monitor the room temperature during the experiment. Two laboratory quality power supplies (long term stability and low noise) were plugged into the instrument rack. +28Volts was connected to the SGL electronics rack and +35 Volt source was used for the heaters. [24]

Three Datron meters, which provide the A/D conversion, were used to collect the X,Y,Z accelerometer outputs which are displayed in volts. A PDP-11/73 microcomputer was connected to the Datron meters for logging the data. Two high quality $2k\Omega$ resistors in parallel, giving the equivalent of a $1k\Omega$ sense resistor were installed in the accelerometer output and the Datron meters measured the voltage across this sense resistor. These resistors have very low sensitivity to temperature variations (better than 0.6 ppm / $^{\circ}\text{C}$). However a temperature sensor which was connected to the fluke thermistor was installed in the box containing the resistors to monitor the temperature.

Before mounting the Inner Gimbal Simulator (IGS), the breakout panel and the SGL electronic rack, leveling of the CMT was done using bubble levels with

an accuracy of 3 arcseconds. The IGS mounting plate was then fixed on the CMT plate by three screws. The leveling of the IGS mounting plate was done using shims and adjusting the tension of the mounting screws. The surfaces were carefully cleaned with alcohol. The breakout panel was mounted on the side of the frame which was fixed on the top the CMT and supports the SGL electronic rack.

In order to prevent the mounting plate from acting as a heat sink, the IGS was insulated with three quartz washers. The quartz washers were machined very accurately and thus provide a flat mounting surface with minimal contact area to reduce heat transfer. Static balancing of the CMT was performed, after mounting all of the test equipment, through the use of a set of weights and threaded rods. The voltage outputs for the three accelerometers were monitored by the three Datron meters. Data collection software was run during the test to collect the accelerometer outputs from the Datron meters. A personal computer was plugged into the computer card within the SGL electronic rack, through the RS-232 serial link, for monitoring purposes.

2.7 Multiposition Test and Mirror Uncertainty

The QA-2000 accelerometer testing consists of performing a multiposition test. This consists of placing the IGS in six positions that permit some portion of the local gravity vector to be applied to the input axis of the accelerometer. The sensitivity of the accelerometers to temperature change was also tested. The six positions were repeated for six different values of temperature. The six positions shown in Table-1 are sufficient to determine the accelerometer parameters. For each position represented in the Table-1 is the associated azimuth and tilt angle of the Contraves Motion Table (CMT), and the Inner Gimbal Simulator (IGS) coordinate axis which are X, Y and spin axis. [1]

Position	Azimuth (deg)	Tilt (deg)	X	Y	Spin
1	00.0000	180.0000	West	South	Up
2	00.0000	00.0000	West	North	Down
3	00.0000	270.0000	West	Up	North
4	270.0000	270.0000	Up	East	North
5	180.0000	270.0000	East	Down	North
6	90.0000	270.0000	Down	West	North

TABLE 1. Azimuth and Tilt Angles of the Contraves Motion Table and Inner Gimbal Simulator axes orientations for multiposition test.

For each position the voltage outputs for each accelerometer were monitored with the Datron meters (one Datron meter for each accelerometer). Once the table was set up for the position, data logging (LOGDAT) was initiated.

A minimum warm up time of 15 minutes was needed before any data could be collected followed by 10 minutes of data collection. Therefore, the duration of each position test was 25min. [22]

The temperature of the sensors was monitored during the experiment by

Position number	Contraves motion table orientations	X accelerometer axis orientations	Y accelerometer axis orientations	Z accelerometer axis orientations
1
2
3
4

Airborne Gravimetry System

Position number	Contraves motion table orientations	X accelerometer axis orientations	Y accelerometer axis orientations	Z accelerometer axis orientations
5				
6				

TABLE 2. Accelerometer Axis Orientation in Inner Gimbal Simulator

FIGURE 7. Multi-Position Inner Gimbal Testing in Inertial Laboratory

the PC. SGL's WIRETAP program was used for collecting the temperature data. The program was run for 25 minutes for each test, which included sufficient time for the temperature to stabilize the accelerometers.

A complete set of tests (see Figure 11, "Misalignment angles between Cardinal axes, mirror axes and inner flange") was performed three times to provide verification of the measurement and a sense of confidence in the results. On the third set of tests, the room temperature was measured through the PDP-11/73 microcomputer and a LOGTMP data collection task. The same warm up time, and number of samples as used in logdat, were selected in Logtmp.[22]

2.8 Mirror Misalignment Angles:

A theodolite was set up over a brass floor plug which was precisely surveyed to provide a North reference. The azimuth reference was on the roof of a building located 300m from the Navlab.

Position 1

Position 2

Position 3

Position 4

Position 5

Position 6

FIGURE 8. Inner Gimbal Simulator orientations on the Contraves Motion Table

The angle between the reference position and the true North line was 216°51'25''. The theodolite was initialized at this angle. The reference position was chosen to be as far away as possible since the error decreases when the distance between the theodolite and the reference increases.[19]

The error is determined by the parameters shown in table 3:

A	Pointing error=0.0005m @ 300m	= 3.44"
B	Centering error=0.001m @ 300m	= 0.69"
C	Seeks north	= 6.00"
D	Constant factor	= 2.24"
E	T2 theodolite	= 2.45"

TABLE 3. Contraves Motion Table parameters

The total error is

$$\Delta = \sqrt{A^2 + B^2 + C^2 + D^2 + E^2} = 7.71''$$

EQ 1

The measurement of the X mirror angle was performed by pointing the telescope of the theodolite to the center of the mirror. The system coordinate X, Y, Z which was attached to the IGS, corresponds to the true North, East and

FIGURE 9. Theodolite pointing to the inner gimbal

Down directions in the initial position of the CMT. The azimuth and tilt angles of the CMT were stabilized since we had the theodolite reflection through the mirror (see Figure 9, “Theodolite pointing to the inner gimbal”). The same procedure was performed to measure the Y mirror angle. The following steps were used to determine the accelerometer misalignment angles [1]:

Data collection: The digital output of the Datron meters, used as a voltmeter, for six positions and six different temperature values enabled determination of

- Temperature model ($\pm g$).
- Scale Factor and Bias.
- Misalignment Angles.

2.9 The Scale Factor and Bias

For the Z accelerometer the outputs in position 1 and 2 from the multiposition testing (see Figure 7, “Multi-Position Inner Gimbal Testing in Inertial Laboratory”) are defined by the following equations:

$$I_{z1} = K_z(g) + B_z$$

EQ 2

$$I_{z2} = K_z(-g) + B_z$$

EQ 3

Where: I_1 and I_2 are currents obtained from accelerometer positions 1 & 2, K_z is the accelerometer scale factor and B_z is the accelerometer Bias.

By combining the equations 2 and 3, we can solve for the Scale Factor

$$K_z = \frac{I_{z2} - I_{z1}}{2}$$

EQ 4

Similarly the Bias can be defined by:

$$B_{z_g} = \frac{B_z}{K_z} = \frac{I_{z1} + I_{z2}}{I_{z2} - I_{z1}}$$

EQ 5

The same procedure can be used to determine the bias and scale factors for the X and Y accelerometers:

X accelerometer [21]:

$$K_x = \frac{I_{x4} - I_{x6}}{2} \quad \text{EQ 6}$$

$$B_{x_g} = \frac{I_{x4} + I_{x6}}{I_{x4} - I_{x6}} \quad \text{EQ 7}$$

Y accelerometer [21]:

$$K_y = \frac{I_{y5} - I_{y3}}{2} \quad \text{EQ 8}$$

$$B_{y_g} = \frac{I_{y5} + I_{y3}}{I_{y5} - I_{y3}} \quad \text{EQ 9}$$

2.9.1 Misalignment Angle Determination

The generalized accelerometer misalignment matrix is given by:

$$\theta_g = \begin{bmatrix} \theta_{xx} & \theta_{xy} & \theta_{xz} \\ \theta_{yx} & \theta_{yy} & \theta_{yz} \\ \theta_{zx} & \theta_{zy} & \theta_{zz} \end{bmatrix} \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}$$

EQ 10

Where:

θ_{ij} is the misalignment of the i accelerometer input axis about the j system axis, and g_x , g_y , g_z are gravity components in X, Y, Z system axis. Assuming that $\theta_{xx} = \theta_{yy} = \theta_{zz} = 1$, the above equation becomes [21]:

$$\theta_{xz} = \frac{1}{2} \left[\frac{I_{x1}}{k_{x1}} - B_{x1} - \frac{I_{x2}}{K_{x2}} + B_{x2} \right]$$

EQ 11

$$\theta_{yx} = \frac{1}{2} \left[\frac{I_{y4}}{K_{y4}} - B_{y4} - \frac{I_{y6}}{K_{y6}} + B_{y6} \right]$$

EQ 12

$$\theta_{yz} = \frac{1}{2} \left[\frac{I_{y1}}{K_{y1}} - B_{y1} - \frac{I_{y2}}{K_{y2}} + B_{y2} \right]$$

EQ 13

$$\theta_{zx} = \frac{1}{2} \left[\frac{I_{z4}}{K_{z4}} - B_{z4} - \frac{I_{z6}}{K_{z6}} + B_{z6} \right]$$

EQ 14

$$\theta_{zy} = \frac{1}{2} \left[\frac{I_{z3}}{K_{z3}} - B_{z3} - \frac{I_{z5}}{K_{z5}} + B_{z5} \right]$$

EQ 15

$$\theta_{xy} = \frac{1}{2} \left[\frac{I_{x3}}{K_{x3}} - B_{x3} - \frac{I_{x5}}{K_{x5}} + B_{x5} \right]$$

EQ 16

3 Platform Mechanical Assembly Error

3.1 Introduction

The gyro stabilized airborne gravimetry platform, which will be used by SGL as a testbed for the calibration of the inertial sensors (gyroscopes and accelerometers), is composed of three gimbals, three highly precise accelerometers and two gyros, electronics, accurate temperature control and accurate mechanical platform pieces. The gimbal platform system was initially built to measure the gravity anomalies when mounted in an aircraft. If, during a survey, a break-

down of an inertial sensor occurs, the gimbal platform could be used as a calibration testbed, an inertial instrument could be removed and replaced, and then recalibrated without significantly delaying the survey by several months and without sending the instruments back to an inertial laboratory for calibration and alignment.

3.2 Errors

It is standard procedure to specify or describe the accuracy of an inertial system in terms of instrument and system errors. When used as a gravimeter system or a testbed, the inertial platform has to be very accurate. The required performance is discussed in the following sections. For an aircraft being navigated by an inertial system, it is desirable that the system compute aircraft position with respect to the earth very precisely. While it would be ideal for position indication to be perfect, a certain amount of error is expected since the measurement instruments are not perfect. While the system is used as a testbed, the ideal is to have the same results as would be obtained using the Contraves Motion Table in a laboratory. However, considering the fact that

mechanical and electromechanical pieces are built with certain tolerances, obtaining a perfect system is impossible.

Several sources of errors exist in inertial platform systems. Gyro error terms, accelerometers error terms, platform mechanical component tolerances and initial alignment angles are some examples of errors that exist. Estimates were made of the amount of error a source will contribute when the entire system is installed in the environment in which it will be used, and these contributions are totaled and compared to an overall error allowance for the system. Through this procedure the relative contribution of each error source was determined and used to establish specifications for the allowable error of each component. The process by which the various error sources are obtained and used to calculate the total error of the system is called error analysis. In the design phase of an inertial system the overall accuracy requirement has usually been predetermined. The task is to assemble the various components of the inertial system and associated equipment into a configuration which provides the desired results with the required accuracy.

Considering all of the sources of error which exist in the system, an error bud-

get must be adopted such that when the different system components are assembled together the overall effect of the errors will not exceed the expected final error. Thus, error analyses are performed which result in the establishment of an *error budget*.

For a testbed simulator, different types of error sources were considered including:

- Errors in construction, particularly in mechanical alignment
- Errors in the inertial instruments
- Computer and electronics errors

When the platform is used as a gravimeter, additional errors must be considered.

In this thesis, discussion will be limited to the testbed simulator errors. In the following discussion each major source of error will be listed and the propagation of the error in the inertial platform system will be described. This project is limited to the mechanical and inertial errors which will determine whether the platform system can be used as a testbed. The computer errors such as analog and digital computer errors, computer equation errors etc. are not consid-

ered.

3.3 Mechanical Component Consideration

An uncertainty parameter tolerance study was conducted of the expected accuracy of the gimbaled platform axes alignment given manufacturing tolerances, bearing inaccuracies, resolver inaccuracies, etc. The study attempted to determine if the gimbaled platform itself can be used as a test bed to measure the prominent sensor errors including gyro and accelerometer misalignment with respect to platform reference axes (mirrors). The airborne system consists of an assembly of three gimbals embedded into one another and mounted on a vibration isolated base. Each gimbal provides a degree of freedom about one axis. The following table shows the degree of freedom of each gimbal

	Rotation axis	Rotation angle
Outer Gimbal	Z axis	360° around Z axis
Middle Gimbal	Y, Z axes	190° around Y axis
Inner Gimbal	X, Y, Z axes	190° around X axis

TABLE 4. Gimbal rotation axis and rotation angles

Each gimbal is attached to the other gimbal by several mechanical and electrical components. Some of these piece parts will contribute to the platform mis-

alignment and/or error budget. Figure 10, “Airborne gravimetry platform mechanical components” defines the different piece parts that are considered in the error budget determination.

FIGURE 10. Airborne gravimetry platform mechanical components

In determining the mechanical error budget the most important parts to consider are, the ball bearing tolerances, the direct pieces in contact with the bearings and the mounting flange in the inner gimbal. The remaining pieces will

not directly affect the misalignment, however they will be defined for completeness to show that they were initially considered.

The duplex bearing used between the inner and the middle gimbals is the same as the one installed between the middle and the outer gimbal but the bearings installed in the azimuth axis are different. For each bearing the worst case will be considered to get the angular tolerance that could affect the axes alignment of the platform. Parallel alignment could also be a factor but that will be discussed later.

The second determination is how to relate the mechanical error budget with the electrical angular output of the resolvers. An optical calibration using a theodolite was performed once the Inner Sensor Assembly (ISA) was installed in the platform. The platform has eleven holes that allow visual access to mirrors which are installed in the ISA. There are two holes on each gimbal, one hole on each cover of the gimbal.

Another requirement was to perform multiposition tests on the Inner Gimbal Simulator (IGS) containing two QA-2000 accelerometers, one QA-3000 accel-

erometer and two G1200 gyros. The testing was performed at the DREO NAV-LAB using the Contraves Motion Table (CMT). These results were compared to the results obtained previous research during testing of a CSG-2 gyro which is very similar to the G1200.

3.4 Misalignment Angles

3.4.1 Mechanical Component Consideration

Before starting the error budget determination, the following observation was made.

The slip ring and the twist capsules are mounted in the gimbal rotational pieces and do not come in contact with the gimbal or support any load. Therefore the slip ring and the twist capsule were not considered in the error budget. The gimbal cover weight and the distortion when tightening the cover screws were assumed negligible, so they do not change the axis alignment of the gimbals. The resolvers and the stop ring were not connected to the main assembly, so their mechanical tolerances were not included in the error budget. The friction of the sliding surfaces was assumed to be negligible. Therefore the three sets of ball bearings (BB), shaft mounts to BB inside diameter surface, housing

mounts to BB outside diameter surface and mounting flanges are the piece parts considered when determining the error budget.

The first consideration was the bearings installed in the inner and the middle gimbal rotational axes, which are the X and Y axes. For each axis, there are two ball bearings, one on each side of the gimbal. The worst case condition was full maximum tolerance on one side and full minimum on the other side (see Appendix A). The inner gimbal rotates around the X axis when the middle and the outer gimbals are in their stationary position. The misalignment angle of the inner gimbal is taken about the X axis (see Figure 15, "Misalignment angles of the inner gimbal"). The middle gimbal rotates around the Y axis, the misalignment angle is about the Y axis (see Figure 16, "Misalignment angle of the middle gimbal"). The tolerances of the housing axis and the shaft axis are added to the bearing tolerances. To determine the largest misalignment angle, the minimum diameter of the inner and middle gimbal is the one to consider. For the platform azimuth table and the mounting flange, the misalignment angles are about the X and Y axes, because there are circular components (see Figure 17, "Misalignment angle of the platform azimuth table"). The mechanical error budget was calculated, and the results are shown in the Appendix A.

3.5 Relation Between the Mechanical Error Budget and the Rotation of the Gimbals

When the inertial instruments are integrated into the platform, it is necessary that the orientation of the instruments sensitive axes be known so that the measured outputs can be resolved into a set of navigation coordinate axes. In the gimbal platform, each part of the system generates its own random error; the mechanical components, the inertial instrument, the computer and electronics. These errors are independent of each other, which means the cause of the error in one component is not related to the cause of the error in other components. While the error in one component is positive the error in another component can be negative. The case becomes very complex if we try to add all the errors of all components together. All errors depend on the orientation of the cardinal frame and the reference frame. Therefore, before further discussion of the errors, the frames and arbitrary position of the reference frame must be defined.

A coordinate frame is defined by three unit vectors that are mutually perpendicular to one another in the right-hand sense. The vectors are called axes and

pass through a common point called the origin (0,0,0). The physical location of the origin is considered in this project to be arbitrary. The coordinate frames of the different components of the gimbal platform are defined as follows:

1) The “C” frame is the cardinal frame used for position location definition. It is defined so that its axes are fixed to the earth and aligned with East-North-Down axes.

2) The “R” frame is the reference frame which will be considered to be accurately aligned with the Cardinal frame.

3) The “B” frame is the mirror of the base of the platform frame. It is essential to know the position of the platform before performing any test. A mirror was mounted on the base of the platform, and an autocollimation was executed to determine the absolute orientation of the platform.

4) Each gimbal platform has its own frame, the “O” frame is related to the outer gimbal, the “M” frame to the middle gimbal, and the “I” frame to the inner gimbal.

5) There are three resolvers mounted in the platform. Each resolver was assigned a frame which is called R with a subscript number. R_1 refers to the resolver mounted between the inner and the middle gimbal, R_2 refers to the resolver mounted between the middle and the outer gimbal, and R_3 for the azimuth resolver mounted in the base.

6) The S_s and M_s frame are respectively the inner sensor frame and the mirror frame. Three mirrors are mounted on the inner sensor block, one on each coordinate axis. Each axis was named M_{sx} , M_{sy} , M_{sz} axes. These axes are important because their alignment with the cardinal frame is directly determined by autocollimation. Eleven holes in the platform allow us to see the inside mirrors at certain orientations of the gimbals.

The direction cosine matrix is defined as a square matrix whose columns are an orthogonal set of unit vectors, each equal to a unit vector along a coordinate axis of frame A_2 as projected onto the axes of coordinate frame A_1 : Depending on the rotation axis, the cosine matrix is [3]:

$$z = \begin{bmatrix} \cos & \sin & 0 \\ -\sin & \cos & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

EQ 17

It is necessary to determine the transformation from the reference frame to the other frames since the inertial sensors provide information in different coordinate frames.

Rotation Matrices:

The misalignment angles between the cardinal axis and the mirror, which are installed in the sensor fixture, were determined by autocollimation. The misalignment angles between the accelerometers and the cardinal axis were determined from the multiposition tests. The misalignment between the accelerometer axes and the mounting surface and then the mounting surface needed to be determined and the mounting surface with respect to the mirrors. Starting from the misalignment angles between the mirrors and the flange of the inner gimbal (or of the inner sensor):

X, Y, Z are the cardinal axis parallel to the North-East-Down axes. X_m, Y_m and Z_m are the mirror axes. η_x, η_y and η_z are the misalignment angles between the mirror and the cardinal axis when the mirrors are oriented to the North-East-Down direction (see Figure 11, "Misalignment angles between Cardinal axes, mirror axes and inner flange").

X_f, Y_f and Z_f are the flange axes and the misalignment angles between the mirrors and the inner sensor flange are τ_x, τ_y and τ_z . Therefore

$$(\tau_x)_x (\tau_y)_y (\tau_z)_z (\eta_x)_x (\eta_y)_y (\eta_z)_z \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

EQ 18

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \tau_x \\ 0 & -\tau_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -\tau_y \\ 0 & 1 & 0 \\ \tau_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \tau_z & 0 \\ -\tau_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \eta_x \\ 0 & -\eta_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -\eta_y \\ 0 & 1 & 0 \\ \eta_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \eta_z & 0 \\ -\eta_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

EQ 19

FIGURE 11. Misalignment angles between Cardinal axes, mirror axes and inner flange

3.6 Misalignment Angles Between the Inner Sensor Flange and the Inner Gimbal Mounting Flange:

The tolerances of the inner gimbal mounting flange are known. Because all matrices can not be written on one line, an attempt to simplify the writing by using the new axes name instead of the entire set of matrices. $\beta_x, \beta_y, \beta_z$ are the angles of the inner sensor flange and the inner gimbal mounting flange (see Figure 12, “Misalignment angles between the inner sensor flange and the inner gimbal flange”).

$$(\beta_x)_x (\beta_y)_y (\beta_z)_z \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}$$

EQ 20

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \beta_x \\ 0 & -\beta_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -\beta_y \\ 0 & 1 & 0 \\ \beta_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \beta_z & 0 \\ -\beta_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}$$

EQ 21

FIGURE 12. Misalignment angles between the inner sensor flange and the inner gimbal flange

3.7 Misalignment Angles Between the Inner Gimbal and the Middle Gimbal:

A rotation introduces misalignment angles since the inner gimbal rotates around the middle gimbal through the resolver. The resolver has its own accuracy which is considered in the gimbal rotation. This transformation includes the misalignment angles of the mounting surface of the inertial instruments, the mirrors, the inner sensor flange, the mounting flange, the inner gimbal mechanical error budget and the resolver accuracy.

$\alpha_x, \alpha_y, \alpha_z$ are the errors of the inner gimbal of the platform

ω_y, ω_z are the accuracies of the resolvers mounted between the inner gimbal and the middle gimbal.

δ is the rotation angle of the inner gimbal. Since the rotation is produced around the X axes, we note the rotation angle $(\delta)_x$.

$$(\delta)_x (\omega_y)_y (\omega_z)_z (\alpha_x)_x (\alpha_y)_y (\alpha_z)_z \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix}$$

EQ 22

$$(\delta)_x \begin{bmatrix} 1 & 0 & -\omega_{1y} \\ 0 & 1 & 0 \\ \omega_{1y} & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \omega_{1z} & 0 \\ -\omega_{1z} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \alpha_x \\ 0 & -\alpha_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -\alpha_y \\ 0 & 1 & 0 \\ \alpha_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \alpha_z & 0 \\ -\alpha_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix}$$

EQ 23

3.8 Misalignment Between the Middle Gimbal and the Outer Gimbal

The middle gimbal rotates around the Y axis. There is a resolver between the middle and the outer gimbal that measures the angles. This resolver is the same type as the one used for the inner and middle gimbal. In this rotation we have to consider the error of the middle gimbal and the resolver. The resolver rotates about the X and Z axis, so that the error is called ω_{2x} and ω_{2z} , the plane is X_{r2} , Y_{r2} and Z_{r2}

The second error to consider is the error of the middle gimbal obtained in the error budget analysis. The axis are X_m , Y_m and Z_m misaligned with the resolver axis about ϕ_x , ϕ_y and ϕ_z .

$$(\theta)_y (\omega_{2x})_x (\omega_{2z})_z (\phi_x)_x (\phi_y)_y (\phi_z)_z \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix}$$

EQ 24

$$\begin{bmatrix} 1 & 0 & \theta_y \\ 0 & 1 & 0 \\ -\theta_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \omega_{2x} \\ 0 & \omega_{2x} & 1 \end{bmatrix} \begin{bmatrix} 1 & \omega_{2z} & 0 \\ -\omega_{2z} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & \phi_x \\ 0 & \phi_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & \phi_y \\ 0 & 1 & 0 \\ -\phi_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & \phi_z & 0 \\ -\phi_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} = \begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix}$$

EQ 25

3.9 Rotation of the Outer Gimbal about the Platform Azimuth Table

The outer gimbal rotates about the Z axis, and its misalignment angles have been determined through the mechanical error budget in real and worst case scenarios (see appendix A). Between the outer gimbal and the azimuth table, a very high precision resolver is installed. That resolver indicates the orientation of the outer gimbal with respect to the reference frame. It can also be used to

position the gimbal to the desired orientation. The resolver has its own errors that can affect the outer gimbal misalignment. Its tolerances are given by the manufacturers and will be directly included in this rotation transformation:

$${}^{(\varphi)}_z({\omega}_{3x})_x({\omega}_{3y})_y({\lambda})_x({\lambda})_y({\lambda})_z \begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix} = \begin{bmatrix} x_5 \\ y_5 \\ z_5 \end{bmatrix}$$

EQ 26

$${}^{(\varphi)}_x \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & {\omega}_{3x} \\ 0 & -{\omega}_{3x} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -{\omega}_{3y} \\ 0 & 1 & 0 \\ {\omega}_{3y} & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & {\lambda}_x \\ 0 & -{\lambda}_x & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & -{\lambda}_y \\ 0 & 1 & 0 \\ {\lambda}_y & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & {\lambda}_z & 0 \\ -{\lambda}_z & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix} = \begin{bmatrix} x_5 \\ y_5 \\ z_5 \end{bmatrix}$$

EQ 27

The development of the above equations are very complex. The product of these matrices will end up with a large equation containing many unknowns. Since the exact value of the misalignment angles can not been determined, a simplification is needed in this case. Since the angles are very small, the prod-

uct of two angles is negligible. The Sine of a small angle is equal to the angle, and the Cosine is equal to one. Given the fact that the angles are very small, the matrix product is commutative.

The last equation ends up adding all the misalignment angles of the entire platform. The best approach to solve the equation is to add up all the errors to determine the total error, the value of sigma will give a significant estimate of the probable error. Thus, the usual way of combining the 1-sigma errors when they are independent is to determine the Root Mean Square (RMS).

The final equation is:

$$\begin{aligned} &(\tau_x)_x (\tau_y)_y (\tau_z)_z (\eta_x)_x (\eta_y)_y (\eta_z)_z (\beta_x)_x (\beta_y)_y (\beta_z)_z (\delta)_x \\ &(\omega_{1y})_y (\omega_{1z})_z (\alpha_x)_x (\alpha_y)_y (\alpha_z)_z (\theta)_y (\omega_{2x})_x (\omega_{2z})_z \\ &(\phi_x)_x (\phi_y)_y (\phi_z)_z (\varphi)_z (\omega_{3x})_x (\omega_{3y})_y (\lambda)_x (\lambda)_y (\lambda)_z = (X, Y, Z) \end{aligned}$$

EQ 28

RMS axis x:

$$X = \sqrt{(\tau_x)^2 + (\eta_x)^2 + (\beta_x)^2 + (\alpha_x)^2 + (\phi_x)^2 + (\omega_x)^2}$$

EQ 29

RMS axis y:

$$Y = \sqrt{(\tau_y)^2 + (\eta_y)^2 + (\beta_y)^2 + (\alpha_y)^2 + (\phi_y)^2 + (\omega_{2y})^2}$$

EQ 30

RMS axis z:

$$Z = \sqrt{(\tau_z)^2 + (\eta_z)^2 + (\beta_z)^2 + (\alpha_z)^2 + (\phi_z)^2}$$

EQ 31

4 Feasibility of Using the Platform as a Testbed for Sensor Calibration

4.1 Precision of the Gimbal Platform:

Sensor calibration during the development of the SGL gravimeter was performed in an inertial navigation laboratory. A very accurate motion table was used for the testing. The testing consisted of mounting the sensors, which are mounted in the inner gimbal simulator, such that their axes could be oriented in all possible directions. In the field, the gimbal platform would be used in lieu of the Contraves motion table used in the NAVLAB. The risk of con-

tamination in the field during replacement of the sensor in the platform will not be considered in this project, and to simplify our development, we will consider that the mounting of the sensors in the field was done in conformance to the norms, thus no mounting misalignment errors would occur. To calibrate the sensors using the platform, we have to make sure that a maximum number of sensor orientations can be performed in order to eliminate some errors.

The main purpose of this thesis is to determine if the SGL platform can be used as a testbed to calibrate one or two of the inertial instruments (accelerometers and gyroscopes).

4.2 Gyro¹Errors

The calibration of the gyro is primarily dependent on the gimbal platform accuracy and stability when it is used as a testbed. Ideally the gimbal platform should behave as the Contraves table in the NAVLAB. The gyros used for geophysical survey in the gimbal platform are high precision, dynamically tuned, two degree-of-freedom gyroscopes (DTG's). The two degree-of-free-

1.

dom gyroscope allows the spin axis to have two degrees of rotational freedom with respect to the case of the gyroscope. The invariance of the angular momentum vector of the spinning rotor of the gyro in the absence of external torques provides the means of attitude control of the platform. Therefore, a small misalignment angle of any part of the gimbal platform can affect the gyro calibration. When the platform is assembled, adjoining parts are accurately aligned. However, some misalignment angles, due to assembly, will be unavoidably introduced. This misalignment could affect the gyro calibration.

During a geophysics survey, the inner stable member (ISM), containing the gyros and accelerometers, is isolated from the vehicle rotation by the three gimbals. The ISM does not rotate with the vehicle (the aircraft), its orientation remains fixed in inertial space. The platform outer case is attached to the vehicle. The gimbal platform displacements with respect to the vehicle are referred to as inner gimbal (roll), middle gimbal (pitch) and outer gimbal (yaw). The outer gimbal and the middle gimbal are disturbed by the vehicle and the inner gimbal (stable member) will remain fixed at its null position. The gyros are used to maintain the platform inertial orientation by sensing the platform rotations caused by vehicle rotation about the pitch, roll and yaw axes. The gyros

mounted on the inner gimbal sense a rotation of the vehicle about the roll, pitch or yaw axes and output a signal which is proportional to the angular motion and is used by the gimbal electronics to drive the displaced gimbals to null the gyro outputs. The ISM will remain levelled and undisturbed, maintaining its inertial orientation while the gimbals respond to vehicle motions. The platform has to be aligned before performing any data collection. The inner gimbal, which contains the inertial instruments, is aligned using the three accelerometers mounted on it. Each accelerometer is mounted along one platform axis. One accelerometer measures the acceleration along the platform's X axis, the second one on the Y axis and the third one on the Z axis. When the accelerometer experiences an acceleration along its input axis, it causes a pendulous mass displacement. This displacement is measured by a pick-off device, which generates an electrical signal that is proportional to the input acceleration. This signal is then amplified and sent to a rebalance loop and then to a torquer within the accelerometer, which repositions the proof mass to its null position. Before performing the calibrations of the gyros in the gimbal platform, the gyro errors must be defined. The most common and important errors are: the Bias " B ", the Quadrature term " Q ", the Mass Unbalance " MU " and Scale

Factor “ k ”.

Each gyro is oriented so that its spin axis is perpendicular to the gravity vector and the X axis aligned with the gravity vector. In a perfect condition, the spinning mass is balanced in the plane of the wheel. However, if there is a small imperfection in mass distribution, a torque, which is proportional to the mass and the lever arm, will be caused about the Y axis. This will induce a precession rate about the X axis due to the fundamental law of precession. This is known as Mass Unbalance Drift, given the symbol MU_x , when it is applied along the X axis. In order to counteract its effect, a torque equal in magnitude is applied to the output axis Y in the opposite direction.

Similar assumptions can be made when the Y input axis is aligned with the gravity vector.

The other major error is the Quadrature mass unbalance, which is known as the g-sensitive effect. The given symbols are Q_x and Q_y , about each axis, respectively. The Dynamically Turned Gyro (DTG), has two gimbals attached together by four flexures, two of them connect the rotor to the gimbal, and the other two connect the gimbal to the shaft. These fixtures are not perfect, they are always loaded by tension or compression. Since torques are being applied

to the wheel, precession occurs.

Torques are caused by the acceleration along one axis (X axis for example), and that acceleration would create a drift along the other axis (Y axis). Since these errors are generated by the gravity or acceleration applied along one axis, they are known as g-sensitive drifts.

There are other types of drift errors that can occur in Dynamically Tuned Gyros but they are beyond the scope of this thesis.[1]

To determine the error parameters of the gyros, sixteen positions with respect to g must be oriented by the gimbal platform, which are the same orientations achieved in the laboratory on the Contraves Motion Table. The error parameters that must be evaluated for the calibration of a gyro are as follows:

Bias (B_d), Scale factor (k), Mass umbalance (MU), Spin axis g sensitive drift term $D(x)$, Quadrature umbalance (Q) and the angles between the gyro input axis and one of the gimbal axes. Determination of these error parameters is achieved through gimbal repositioning. It is assumed that the platform frame is aligned with the reference frame, and based on the platform frame (the base), the gyro parameters were determined. The parameters are defined as follow:

MU occurs in the equation when the input axis is aligned with g .

Q occurs in equation when the opposite axis to the input axis is aligned with g

D(X) occurs in the equation when the gyro spin axis is aligned with g .

B bias appears in all equations, K scale factor as well.

α is the misalignment angles between X system axis and a given gyro input axis

β is the misalignment angle between Y system axis and a given gyro input axis

γ is the misalignment angle between Z system axis and a given gyro input axis.

For each gyro there are two input axis, X and Y axis. There are two gyros in the platform, one called X gyro, which is mounted on X axes of the inner gimbal platform, and the second one called Y gyro, which is mounted on Y axes of the inner gimbal. The summary below shows the differences between the axes:

Gyro X, X input axis

Gyro X, Y input axis

Gyro Y, X input axis

Gyro Y, Y input axis

The platform co-ordinate frame also called the system co-ordinate frame has an X, Y and Z. The system co-ordinate frame is: X_s , Y_s and Z_s .

The misalignment angles of the gyro input axes with respect to the system axes are also included in the gyro equations. They are determined as follows:

α is the misalignment between X_s and a given gyro input axis.

β is misalignment between Y_s and a given gyro input axis.

γ is misalignment between Z_s and a given input axis.

FIGURE 13. Gyro axis orientation about cardinal frame

Position	X axis	Y axis	Z axis	Resol.1	Resol.2	Resol.3
1	West	South	Up	0	180	+/-90
2	North	West	Up	0	180	+/-90
3	East	North	Up	0	180	+/-90
4	South	East	Up	0	180	+/-90
5	West	Up	North	180	0	+/-90
6	Down	West	North	180	0	+/-90
7	East	Down	North	180	0	+/-90
8	Up	East	North	180	0	+/-90
9	West	North	Down	0	0	Depends
10	South	West	Down	0	0	+/-90
11	East	South	Down	0	0	+/-90
12	North	East	Down	0	0	+/-90
13	West	Down	South	0	180	+/-90
14	Up	West	South	0	180	+/-90
15	East	Up	South	0	180	+/-90
16	Down	East	South	0	180	+/-90

TABLE 5. Inner sensor axis orientation while integrated in the platform, and the resolver outputs

Positions of the inner gimbal axes into the gravimeter platform	Axis orientation of G1200 (Gx)	Axis orientation of G1200 (Gy)
1
2
3
4
5

TABLE 6. Gx and Gy axis orientations within the inertial gimbal platform. Each gyro has x and y input axis.

Positions of the inner gimbal axes into the gravimeter platform	Axis orientation of G1200 (Gx)	Axis orientation of G1200 (Gy)
6
7
8
9
10
11

TABLE 6. Gx and Gy axis orientations within the inertial gimbal platform. Each gyro has x and y input axis.

Positions of the inner gimbal axes into the gravimeter platform	Axis orientation of G1200 (Gx)	Axis orientation of G1200 (Gy)
12
13
14
15
16

TABLE 6. Gx and Gy axis orientations within the inertial gimbal platform. Each gyro has x and y input axis.

Positions			Direction of gyro axes			Acceleration a longaxis g			Earth rate	
#			Spin	X	Y	Spin	X	Y	X	Y
1			Up	W	S	1	0	0	0	$-\omega_e \cos \lambda$
2			Up	N	W	1	0	0	$\omega_e \cos \lambda$	0
3			Up	E	N	1	0	0	0	$\omega_e \cos \lambda$
4			Up	S	E	1	0	0	$-\omega_e \cos \lambda$	0
5			N	W	Up	0	0	1	0	$\omega_e \sin \lambda$
6			N	Dn	W	0	-1	0	$-\omega_e \sin \lambda$	0
7			N	E	Dn	0	0	-1	0	$-\omega_e \sin \lambda$
8			N	Up	E	0	1	0	$\omega_e \sin \lambda$	0
9			Dn	W	N	-1	0	0	0	$\omega_e \sin \lambda$
10			Dn	S	W	-1	0	0	$-\omega_e \sin \lambda$	0
11			Dn	E	S	-1	0	0	0	$-\omega_e \sin \lambda$
12			Dn	N	E	-1	0	0	$\omega_e \sin \lambda$	0
13			S	W	Dn	0	0	-1	0	$\omega_e \cos \lambda$
14			S	Up	W	0	1	0	$-\omega_e \cos \lambda$	0
15			S	E	Up	0	0	1	0	$-\omega_e \cos \lambda$
16			S	Dn	E	0	-1	0	$\omega_e \cos \lambda$	0

TABLE 7. Definition of gyroscope axes positions, in a perfect gravimeter testbed, for 16 position test

Equations of GYRO Y, X input

Position 1 $k_3[w_e \sin \lambda \cos \gamma_3 - w_e \cos \lambda \cos \beta_3 + B_3 - D(X)_{S3}] = I_1$

EQ 32

Position 2 $k_3[w_e \sin \lambda \cos \gamma_3 + w_e \cos \lambda \cos \alpha_3 + B_3 - D(X)_{S3}] = I_2$

EQ 33

Position3 $k_3[w_e \sin \lambda \cos \gamma_3 + w_e \cos \lambda \cos \beta_3 + B_3] = I_3$

EQ 34

Position 4 $k_3[w_e \sin \lambda \cos \gamma_3 - w_e \cos \lambda \cos \alpha_3 + B_3 + D(X)_{S3}] = I_4$

EQ 35

Position 5 $k_3[w_e \cos \lambda \cos \gamma_3 + w_e \sin \lambda \cos \beta_3 + B_3 + Q_3] = I_5$

EQ 36

$$\text{Position 6} \quad k_3[w_e \cos \lambda \cos \gamma_3 - w_e \sin \lambda \cos \alpha_3 + B_3 - MU_3] = I_6$$

EQ 37

$$\text{Position 7} \quad k_3[w_e \cos \lambda \cos \gamma_3 - w_e \sin \lambda \cos \beta_3 + B_3 + Q_3] = I_7$$

EQ 38

$$\text{Position 8} \quad k_3[w_e \cos \lambda \cos \gamma_3 + w_e \sin \lambda \cos \alpha_3 + B_3 + MU_3] = I_8$$

EQ 39

$$\text{Position 9} \quad k_3[-w_e \sin \lambda \cos \gamma_3 + w_e \cos \lambda \cos \beta_3 + B_3] = I_9$$

EQ 40

$$\text{Position 10} \quad k_3[-w_e \sin \lambda \cos \gamma_3 - w_e \cos \lambda \cos \alpha_3 + B_3 + D(X)_{S3}] = I_{10}$$

EQ 41

$$\text{Position 11} \quad k_3[-w_e \sin \lambda \cos \gamma_3 - w_e \cos \lambda \cos \beta_3 + B_3] = I_{11}$$

EQ 42

$$\text{Position 12} \quad k_3[-w_e \sin \lambda \cos \gamma_3 + w_e \cos \lambda \cos \alpha_3 + B_3] = I_{12}$$

EQ 43

$$\text{Position 13} \quad k_3[-w_e \cos \lambda \cos \gamma_3 - w_e \sin \lambda \cos \beta_3 + B_3 - Q_3] = I_{13}$$

EQ 44

$$\text{Position 14} \quad k_3[-w_e \cos \lambda \cos \gamma_3 + w_e \sin \lambda \cos \alpha_3 + B_3 - MU_3] = I$$

EQ 45

$$\text{Position 15} \quad k_3[-w_e \cos \lambda \cos \gamma_3 + w_e \sin \lambda \cos \beta_3 + B_3 - Q_3] = I_{15}$$

EQ 46

$$\text{Position 16} \quad k_3[-w_e \cos \lambda \cos \gamma_3 - w_e \sin \lambda \cos \alpha_3 + B_3 - MU_3] = I_{16}$$

EQ 47

FIGURE 14. Gyro axis orientations about the inner gimbal axis

Gyro X, X input axis

Position 1 $k_1 [w_e \sin \lambda \cos \gamma_1 - w_e \cos \lambda \cos \beta_1 + B_1 - D(X)_{s1}] = I_1$

EQ 48

Position 2 $k_1 [w_e \sin \lambda \cos \gamma_1 + w_e \cos \lambda \cos \alpha_1 + B_1] = I_2$

EQ 49

Position3 $k_1 [w_e \sin \lambda \cos \gamma_1 + w_e \cos \lambda \cos \beta_1 + B_1 + D(X)_{s1}] = I_3$

EQ 50

Position 4 $k_1 [w_e \sin \lambda \cos \gamma_1 - w_e \cos \lambda \cos \alpha_1 + B_1] = I_4$

EQ 51

Position5 $k_1 [w_e \cos \lambda \cos \gamma_1 + w_e \sin \lambda \cos \beta_1 + B_1 - MU_1] = I_5$

EQ 52

Position 6 $k_1 [w_e \cos \lambda \cos \gamma_1 - w_e \sin \lambda \cos \alpha_1 + B_1 - Q_1] = I_6$

EQ 53

Position 7 $k_1 [w_e \cos \lambda \cos \gamma_1 - w_e \sin \lambda \cos \beta_1 + B_1 + MU_1] = I_7$

EQ 54

Position 8 $k_1[w_e \sin \lambda \cos \gamma_1 + w_e \sin \lambda \cos \alpha_1 + B_1 - Q_1] = I_8$

EQ 55

Position 9 $k_1[-w_e \sin \lambda \cos \gamma_1 + w_e \cos \lambda \cos \beta_1 + B_1 + D(X)_{S1}] = I_9$

EQ 56

Position 10 $k_1[-w_e \sin \lambda \cos \gamma_1 - w_e \cos \lambda \cos \alpha_1 + B_1] = I_{10}$

EQ 57

Position 11 $k_1[-w_e \sin \lambda \cos \gamma_1 - w_e \cos \lambda \cos \beta_1 + B_1 - D(X)_{S1}] = I_{11}$

EQ 58

Position 12 $k_1[-w_e \sin \lambda \cos \gamma_1 + w_e \cos \lambda \cos \alpha_1 + B_1] = I_{12}$

EQ 59

Position 13 $k_1[-w_e \cos \lambda \cos \gamma_1 - w_e \sin \lambda \cos \beta_1 + B_1 + Q_1] = I_{13}$

EQ 60

Position 14 $k_1[-w_e \cos \lambda \cos \gamma_1 + w_e \sin \lambda \cos \alpha_1 + B_1 + Q_1] = I_{14}$

EQ 61

Position 15 $k_1[-w_e \cos \lambda \cos \gamma_1 + w_e \sin \lambda \cos \beta_1 + B_1 - MU_1] = I_{15}$

EQ 62

Position 16

$$k_1[-w_e \cos \lambda \cos \gamma_1 - w_e \sin \lambda \cos \alpha_1 + B_1 + Q_1] = I_{16}$$

EQ 63

Gyro X, Y input axis

Position 1 $k_2[w_e \sin \lambda \cos \gamma_2 - w_e \cos \lambda \cos \beta_2 + B_2 - MU_2] = I_1$

EQ 64

Position 2 $k_2[w_e \sin \lambda \cos \gamma_2 + w_e \cos \lambda \cos \alpha_2 + B_2 - MU_2] = I_2$

EQ 65

Position 3 $k_2[w_e \sin \lambda \cos \gamma_2 + w_e \cos \lambda \cos \beta_2 + B_2 - MU_2] = I_3$

EQ 66

Position 4 $k_2[w_e \sin \lambda \cos \gamma_2 - w_e \cos \lambda \cos \alpha_2 + B_2 - MU_2] = I_4$

EQ 67

Position 5 $k_2[w_e \cos \lambda \cos \gamma_2 + w_e \sin \lambda \cos \beta_2 + B_2] = I_5$

EQ 68

Position 6 $k_2[w_e \cos \lambda \cos \gamma_2 - w_e \sin \lambda \cos \alpha_2 + B_2] = I_6$

EQ 69

Position 7 $k_2[w_e \cos \lambda \cos \gamma_2 - w_e \sin \lambda \cos \beta_2 + B_2] = I_7$

EQ 70

Position 8 $k_2[w_e \cos \lambda \cos \gamma_2 + w_e \sin \lambda \cos \alpha_2 + B_2] = I_8$

EQ 71

Position 9 $k_2[-w_e \sin \lambda \cos \gamma_2 + w_e \cos \lambda \cos \beta_2 + B_2 + MU_2] = I_9$

EQ 72

Position 10 $k_2[-w_e \sin \lambda \cos \gamma_2 - w_e \cos \lambda \cos \alpha_2 + B_2 + MU_2] = I_{10}$

EQ 73

Position 11 $k_2[-w_e \sin \lambda \cos \gamma_2 - w_e \cos \lambda \cos \beta_2 + B_2 + MU_2] = I_{11}$

EQ 74

Position 12 $k_2[-w_e \sin \lambda \cos \gamma_2 + w_e \cos \lambda \cos \alpha_2 + B_2 + MU_2] = I_{12}$

EQ 75

Position 13 $k_2[-w_e \cos \lambda \cos \gamma_2 - w_e \sin \lambda \cos \beta_2 + B_2] = I_{13}$

EQ 76

Position 14 $k_2[-w_e \cos \lambda \cos \gamma_2 + w_e \sin \lambda \cos \alpha_2 + B_2] = I_{14}$

EQ 77

Position 15 $k_2[-w_e \cos \lambda \cos \gamma_2 + w_e \sin \lambda \cos \beta_2 + B_2] = I_{15}$

EQ 78

Position 16

$$k_2[-w_e \cos \lambda \cos \gamma_2 - w_e \sin \lambda \cos \alpha_2 + B_2] = I_{16}$$

EQ 79

Gyro Y, Y axis

Position 1 $k_4[w_c \sin \lambda \cos \gamma_4 - w_c \cos \lambda \cos \beta_4 + B_4 - MU_4] = I_1$

EQ 80

Position 2 $k_4[w_c \sin \lambda \cos \gamma_4 + w_c \cos \lambda \cos \alpha_4 + B_4 - MU_4] = I_2$

EQ 81

Position 3 $k_4[w_c \sin \lambda \cos \gamma_4 + w_c \cos \lambda \cos \beta_4 + B_4 - MU_4] = I_3$

EQ 82

Position 4 $k_4[w_c \sin \lambda \cos \gamma_4 - w_c \cos \lambda \cos \alpha_4 + B_4] = I_4$

EQ 83

Position 5 $k_4[w_c \cos \lambda \cos \gamma_4 + w_c \sin \lambda \cos \beta_4 + B_4] = I_5$

EQ 84

Position 6 $k_4[w_c \cos \lambda \cos \gamma_4 - w_c \sin \lambda \cos \alpha_4 + B_4] = I_6$

EQ 85

Position 7 $k_4[w_c \cos \lambda \cos \gamma_4 - w_c \sin \lambda \cos \beta_4 + B_4] = I_7$

EQ 86

$$\text{Position 8} \quad k_4[w_e \cos \lambda \cos \gamma_4 + w_e \sin \lambda \cos \alpha_4 + B_4] = I_8$$

EQ 87

$$\text{Position 9} \quad k_4[-w_e \sin \lambda \cos \gamma_4 + w_e \cos \lambda \cos \beta_4 + B_4 + MU_4] = I_9$$

EQ 88

$$\text{Position 10} \quad k_4[-w_e \sin \lambda \cos \gamma_4 - w_e \cos \lambda \cos \alpha_4 + B_4 + MU_4] = I_{10}$$

EQ 89

$$\text{Position 11} \quad k_4[-w_e \sin \lambda \cos \gamma_4 - w_e \cos \lambda \cos \beta_4 + B_4 + MU_4] = I_{11}$$

EQ 90

$$\text{Position 12} \quad k_4[-w_e \sin \lambda \cos \gamma_4 + w_e \cos \lambda \cos \alpha_4 + B_4 + MU_4] = I_{12}$$

EQ 91

$$\text{Position 13} \quad k_4[-w_e \cos \lambda \cos \gamma_4 - w_e \sin \lambda \cos \beta_4 + B_4] = I_{13}$$

EQ 92

$$\text{Position 14} \quad k_4[-w_e \cos \lambda \cos \gamma_4 + w_e \sin \lambda \cos \alpha_4 + B_4] = I_{14}$$

EQ 93

$$\text{Position 15} \quad k_4[-w_e \cos \lambda \cos \gamma_4 + w_e \sin \lambda \cos \beta_4 + B_4] = I_{15}$$

EQ 94

Position 16

$$k_2[-w_c \cos \lambda \cos \gamma_4 - w_c \sin \lambda \cos \alpha_4 + B_4] = I_{16}$$

EQ 95

5 Feasibility of using the platform for inertial sensor calibration

Using the inertial gravimetry platform as a testbed for sensor calibration is very complex. To calibrate a high accuracy instrument, a very accurate test platform is needed. A very clean, contamination free and stable environment is also essential. The definition of a good calibration depends upon a clear understanding of the accuracy requirements and the expected stability of the instruments being calibrated. In the laboratory environment, it was shown that the gyro bias stability was as low as 0.0015 deg/h for the CSG-2, and that

the accuracy of the accelerometers were within 1 milligal. The gimbal platform mechanical errors, with inaccurate platform orientation would excite error sources, specially misalignments, which, if not properly compensated, the bias of the accelerometer and the gyro error parameters could be significant. Many other parameters can affect the inertial instrument calibration in the field, such as dust, humidity, the platform initial orientation about the cardinal axis and the imprecise alignment during inertial instrument replacement. When one of the inertial sensors integrated in the platform is damaged during a survey, in the normal situation the inertial platform would be sent back to an inertial laboratory so that the inertial instrument can be removed without contamination of the platform. One of the most important tasks before installing or removing an instrument in/out of the gimbal platform is to make sure that the contact surfaces of the inner stable member and the inertial instruments have been carefully cleaned. In the field, it is very difficult to perform this task. Once the covers of the gimbals are removed, the gimbal assembly could get contaminated. However, this contamination can be reduced if the inertial instrument replacement is performed carefully in a positive laminar flow assembly area. A space for this operation in the aircraft should be planned in advance if all

possible.

An accurate calibration necessitates an accurate orientation of the testbed (gravimetry platform) to the Cardinal frame. Optical references are used additional to the gyrocompassing of the inertial system orientation. In the field, some errors can occur during the testbed axis orientation, and in this case the calibration of the inertial instruments is not accurate if the instrument positions are not precise. We can minimize some of those errors that occur during the platform reorientation by using adequate instruments and position methods, but we can not eliminate them completely. In our this project, it is assumed that the reference frame of the platform is aligned with the cardinal frame in order to avoid very complicated equations and that the multipositioning of the gimbal during calibration are precise and accurate.

5.1 Field calibration techniques

During the research, the gravimeter platform manufacturing was in process, as well as the measurement equipment. Therefore, our project is confined to a theoretical method; no testing on the gravimetry platform was performed. The inertial sensors were calibrated in the inertial laboratory (NAVLAB), only.

Calibrating the same inertial sensors in a gravimetry system is very challenging since not only will the platform errors occur but additional parameters will interfere with the sensor calibration. Certain assumptions are made, as previously stated, to study the possibility to use the gravimetry platform in the field as a testbed. In the next part of this chapter, the possible steps and approaches which will allow the use of the gravimetry system as a testbed are discussed.

5.1.1 Inertial instrument mounting and platform levelling

As was mentioned above, the recommended place to uninstall and install any inertial instruments would be a clean area, dust free, in the SGL airplane or van. It is very important to make sure that contact surfaces are cleaned with alcohol. The joint surfaces of the platform can be contaminated as well as the platform if not worked on in a clean area. The first requirement is to make sure that the inertial sensors and the gravimeter platform are kept in dust free environment. Another error that can occur during the sensor mounting on the sensor block is the tightening or torquing down of the accelerometers. In the laboratory, sometimes this task is time consuming and it requires the attention of an experienced technician. In the field, one should to make sure that the

technician has all the equipment and the clean environment to perform the sensor mounting. When the accelerometer is not mounted properly on the sensor block, a misalignment angle will have to be included in the accelerometer equation development and that makes the task more difficult since it is impossible to easily evaluate that misalignment angle.

Once the mounting of inertial sensors and the sensor block is done properly, the next step is to level the platform. A support rack was designed by SGL engineers, such that the entire platform can be installed. The rack allows the technician to level the platform to a certain accuracy. Once the inertial instruments are mounted and the three gimbals are covered, the technician can then start the leveling process. The platform is mounted on the rack after making sure that the contact surfaces have been cleaned. The support rack is equipped with three screws which will allow the levelling. The top cover of the outer gimbal has a small flat area where we can put a bubble level. To start levelling, a 30arcsecond bubble level is recommended. The bubble level is put on different positions on the surface, then rotated and checked, if 30 arcseconds is achieved, the same procedure is repeated with 20 arcseconds and 10 arcseconds bubble levels. A minimum of 10 arcseconds of levelling is achieved.

The assumptions made to study the feasibility of using the gravimetry as a test-bed are:

- Assume that the gimbal platform and the inertial sensors are contamination free.
- Assume that the outer gimbal case is leveled to 10 arcseconds or better.

5.1.2 Platform axis orientation

The platform axis orientation depends on optical references and gyrocompassing. First, the gyrocompassing is used to locate the exact area of testing. That will permit aligning the platform reference axis to the cardinal axis. Gyrocompassing can be performed in many ways, and it will be discussed in this project. Then, mirror alignment (optical references) will be performed. The mirror placed on the external surface of the platform base will be the most important one to start with. An autocollimation will be performed in the field using the theodolite. The same procedure used in the inertial laboratory NAV-LAB (see Figure 9, "Theodolite pointing to the inner gimbal") will be used for autocollimation in the field to allow for alignment of the gravimeter platform to the geographic frame

5.2 Gyro calibration in the gravimetry platform

This part will be the combination of chapter four and chapter five. In chapter four, we discussed the mechanical error budget of the platform. The important platform components that can interfere with the gyro calibration were considered, but some factors were ignored such as the friction and the gimbal cover weight. Using the rotation matrices, the root mean square value of misalignment angles about each platform axis is achieved. In chapter five, it is assumed that the platform can be repositioned to all orientations required and the platform is aligned with the cardinal frame. The gyro error parameters should duplicate those obtained in the NAVLAB. In the real world scenario, the gyro parameters will be affected by the platform errors. To determine the gyro errors, sixteen separated orientations are needed positions, and one equation for each position is created; this resulted in sixteen equations for each gyro output axis at a given orientation. Therefore we are going to select some positions that would allow us to have the g term aligned with only one axis of one gyro will be considered.

Once the platform is bolted to the support and then oriented using the optical reference and the gyrocompassing accomplished, other factors will have to be checked. The electronic equipment will be placed as close as possible to the platform to avoid any signal loss. In the inertial lab, inertial sensor calibration can last up to two weeks, because of the number of the positions performed and the repeatability of the test. In the field, the technician can not afford that much time to calibrate, therefore a minimum of positions will be suggested for a maximum of three hours of testing. Because of the complexity of the platform, we will have to limit the gimbal platform rotations. This limitation is defined further within the gyro equations. The temperature inside the platform has to be maintained stable at 60° Celsius, $\pm 0.05^{\circ}\text{C}$. The sensor cool down sensitivity and shift in value can impose a problem. The technician has to check, several times, that the temperature is stable.

5.3 Theoretical approach to calibrate the gyros within the gimbal platform

When the gyro equations were developed in Chapter five, the platform was considered as perfect as the Contraves Motion Table which is precisely aligned with the cardinal axis and the mechanical components of the table are perfectly aligned and few misalignment angles can occur during test. In the platform the mechanical error budget makes the gyro calibration complex. The gyro equations are developed about one gyro axis. The output of that axis is affected by the platform errors about the three axis of the platform, that means it is impossible to consider only misalignment angle about one axis.

The misalignment angles of the gimbal platform angles, determined in the error budget, are called X_p Y_p and Z_p about the reference frame which is assumed to be perfectly aligned with the cardinal frame. The gimbal misalignment angles are considered to be known since they are determined using the manufacture tolerances. Therefore, we do not need to have extract equations or extract positions to calibrate the gyros. With the same positions we used in Chapter five for gyro calibration within perfect gravimeter platform, the gyro parameters can be determined. The value of each gyro parameter about one

gyro input axis, will depend on the misalignment angles of platform about the three axes. There is another parameter that can make the resolution of the equations very difficult, it is the gravity vector, which can be comprised of three direction cosine matrices which when solved create many non-linear equations. As we did in the chapter 5 the gravity term will be considered perfectly aligned with the Z axis. The same gyro parameters used in Chapter 5 will be included in the equation, such as the bias B, the scale factor K, the mass unbalance MU, the g sensitive term D(x) and the quadrature Q. The transformation matrix used in to determine the direction of the torque vector which causes the drift term, based on the orientation of the gravity vector, is used in the same way as used in the Chapter 5, the only added part in the gyro equation is the platform misalignment angles. The following formulation would apply:

$$MU(\phi)(\psi)C_{\tau}$$

EQ 96

6 Results and Conclusions

Using the gravimeter platform as a testbed for gyro calibration is a complex project. After getting familiar with the inertial instruments and testing them in an inertial laboratory, the gravimeter platform has to be understood as well, so that the error budget of the platform could be determined. The error budget is the primary factor that would affect the calibration of the gyros. It is also a complex step, since all components of the platform will contribute to the misalignment of the platform. The mechanical components that had the largest

effect on the misalignment were selected, the others were assumed to have a minimum contribution and then categorized as negligible, such as the friction and the gimbal cover weight. All the component errors add together on each axis. The root Mean Square value is determined on each axis of the gimbal platform after using the rotation matrices. This part is considered to be reliable. The RMS can be numerically determined, knowing all tolerances of each component.

A calibration of the two gyros was performed for the gravimeter platform, and the testing environment was considered to be similar to the inertial laboratory environment. Sixteen gyro equations for each gyro and each axis of the gyro were formulated. All gyro error parameters can be determined from these equations that evolve out of each gyro reorientation with respect to g .

The challenging part of this project was to define a mathematical method which would allow us to extract data from multiposition tests and conclude that the gravimeter platform could be used as a testbed. In the field, the conditions for an accurate calibration assumed that the reference frame of the platform was perfectly aligned with the Cardinal frame. It was also assumed that

the instruments or platform were not contaminated during replacement. The testing is performed in a static environment.

The three accelerometers mounted in the platform, one accelerometer on each platform axes, are used to level the platform during the gyro calibration in the field. The calibrations of the accelerometers in the field is another subject for another research project. In this project we focus on the gyro calibration after one gyro is replaced in the gravimeter platform.

The G-1200 gyro calibration was performed in the laboratory environment (NAVLAB), not in the platform. Error parameter values were measured and evaluated. It was assumed that the gimbal platform was perfectly aligned, and the positions equivalent to the positions obtained in the inertial laboratory during gyro calibration. Since the testing of the actual gimbal platform was not possible to perform, the research was oriented to the platform mechanical error effect on the gyro calibration. The mechanical error budget was determined for two cases of scenario, the worse case scenario and the real world case scenario. The real case scenario will be considered for the calibration of the G-1200 gyros into the platform. The mechanical error budget was determined by using

the Root Square Sum (RSS) of the errors of each platform component that can interfere with the gyro calibration. A selection of the components was done, and some assumptions made. In the real case scenario, the sensor fixture of the inner gimbal platform seems to have the highest misalignment angle, $0^{\circ}01'1.1''$, because of the mechanical tolerances of the ball bearing. The lowest misalignment angles are the azimuth misalignment angles, $0^{\circ}00'0.39''$, because of the low manufacturing tolerances of the spacers and the rotational base. These errors will add together when they are mounted in the platform, and the accuracy of each gimbal orientation, measured by the resolvers, will depend on the mechanical error budget, which is in fact the misalignment angles of the gimbal platform. To add these errors all together, the rotation matrices were used. The misalignment angle about each axis of the platform was determined with the RSS. These angles can be determined numerically once we know the resolver accuracies.

6.1 Recommendations:

In the real world scenario, many parameters would effect gyro calibration using the platform as a testbed in the field.

a- The first step recommended is to remove one of the good gyros from the stable platform, while the platform is in the NAVLAB or at SGL in the positive laminar flow, semi-clean environment. The same gyro should than be reinstalled into the ISA and the gimbal system should be oriented through the various multipositions described previously to level the platform and reorient the gyro through the 16 positions to get the various error parameters for calibration.

b- Repeat step a with a different gyro.

c- Assuming the recalibration of both the good and different gyro in the platform proved the method of testing described in this thesis, then the same test should be repeated outside/outdoors of SGL, as in the parking lot in a van, to simulate in the field test conditions.

d- If these previous test calibrations work than the platform test calibration should be tried in actual field tests.

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APPENDIX A: Gimbal Platform Misalignment Angles

A-1 Inner gimbal

The adjoining parts of the inner gimbal will affect the misalignment of the gimbal while it is mounted in the gravimeter platform. The adjoining components are the ball bearings, the housing motor and the shaft motor.

FIGURE 15. Misalignment angles of the inner gimbal

	Tolerances	RMS
Ball bearing duplex [ref. GRV-1020 rev.B]	± 0.0002 in	0.000283
Housing motor inner axis [ref. GRV-1019 rev.B]	± 0.0002 in	0.000283
Shaft motor inner axis [ref. GRV-1022 rev.A]	± 0.0002 in	0.000283

TABLE 8. Tolerances of the ball bearings, the housing motor and the shaft motor of the platform inner gimbal

To determine the total tolerance of the assembly, the Root Square Sum (RSS) is used:

$$RSS = \sqrt{X_1^2 + X_2^2 + X_3^2}$$

A-1

The misalignment angle is calculated by dividing the RSS by the radius of the inner gimbal. For the real case scenario the average radius is considered.

$$\tan \alpha = RSS \frac{1}{radius}$$

A-2

Real case scenario

$$\alpha = \alpha = 0.00589^\circ = 0^\circ 00' 21.2''$$

A-3

Worse case scenario:

Results and Conclusions

$$\alpha = 3 \bullet 0.00589 = 0^{\circ}01'3.61''$$

EQ 4

A-2 Middle gimbal:

FIGURE 16. Misalignment angle of the middle gimbal

The same method is applied for the determination of the middle gimbal misalignment angle. The middle gimbal has the same pivot mechanical components as the inner gimbal. The misalignment angles are a little different because of the radius values, which are obviously different.

Results and Conclusions

	Tolerances	RMS
Ball bearing duplex [ref. GRV-1024 rev.B]	± 0.0002 in	0.000283
Housing motor middle axis[ref.GRV-1019rev.B]	± 0.0002 in	0.000283
Shaft motor middle axis [ref. GRV-1022 rev.A]	± 0.0002 in	0.000283

TABLE 9. Tolerances of the ball bearings, the housing motor and the shaft motor of the platform middle gimbal

Misalignment angles are:

Real case scenario

$$\phi_r = \phi_v = 0^{\circ}00'14.51''$$

A 5

Worse case scenario

$$\phi_x = \phi_y = 3 \bullet 0^{\circ}00'14.51'' = 0^{\circ}00'43.53''$$

A 6

A-3 Azimuth misalignment angle:

FIGURE 17. Misalignment angle of the platform azimuth table

The misalignment angle of the azimuth table depends on the tolerance of the bearing spacers, the bearings and the rotational base. The bearing considered was the KA 1000 BR3M 40 pounds preload bearings.

	Tolerances	RMS
Ball bearing	± 0.0005 in	0.000707
[ref. GRV1027 rev. B]		

Spacers [ref. GRV-1029 rev. B]	± 0.0002 in	0.000283
Rotational base [ref. GRV-1028 rev.B]	± 0.0001 in	0.000142

TABLE 10. Tolerances of the ball bearings, the spacers and the platform rotational base

Misalignment angles are:

Real case scenario

$$\lambda_x = \lambda_y = 0^{\circ}00'0.39'' \quad \mathbf{A\ 7}$$

Worse case scenario

$$\lambda_x = \lambda_y = 3 * 0^{\circ}00'0.39'' = 0^{\circ}00'1.16'' \quad \mathbf{A\ 8}$$

A-4 Sensor fixture flange misalignment angles:

FIGURE 18. Misalignment angles of the sensor fixture flange

The sensor fixture flange supports the inner sensor block which contains the inertial instruments. The accuracy of the mounting of the inner sensor depends on the manufacturing tolerances of the inner gimbal flange and the sensor fixture flange.

	Tolerances	RMS
Inner gimbal flange //	$\pm 0.0005\text{in}$	0.000707
[GRV-1001]		
Sensor fixture flange	$\pm 0.0005\text{in}$	0.000707
[GRV-1001]		

TABLE 11. Tolerances of the inner gimbal flange and the sensor fixture flange

Misalignment angles:

Real case scenario

$$\beta_x = \beta_y = 0^\circ 01' 1.1''$$

A-9

Worse case scenario

$$\beta_x = \beta_y = 3 * 0^\circ 01' 1.1'' = 0^\circ 03' 3.3''$$

A-10

APPENDIX B:

	QA-2000-010	QA-2000-020
Input Range	25g	
Bias (Nominal)	<4mg	
Bias (Composite Error)	<550 μg	<220 μg
Modeling Residual	<100 μg	<60 μg
B.T.C	<30 μg	<30 μg
Scale Factor	1.2 to 1.46 mA/g	
S.F (Composite Error)	<600 ppm	<500 ppm
Modeling Residual	<200 ppm	<125 ppm
S.F.T.C.	<180 ppm/C	
Linearity	<50 $\mu\text{g/g}^2$	<40 $\mu\text{g/g}^2$
Axis Misalignment	<2 mrad (0.002 rad=	
A.A Composite Error	<105 μrad	<100 μrad
RC<500Hz	<60 $\mu\text{g/g}^2$	<40 $\mu\text{g/g}^2$
Input Voltage	+ 13 to 18 VDC	
Input Current	<20 mA	
Temperature Range	-55 to +95	
Weight	<80 grams (72,5 grams)	

Table B-1: Performance and specifications for QA-2000 accelerometers (horizontal)